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Long Period Comets with TRAPPIST Telescopes

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Abstract

Comets are among the most pristine remnants of the early Solar System, preserving valuable information about the conditions that prevailed during its formation. Studying their physical and chemical properties, as well as their evolution, provides crucial insights into the processes that shaped the Solar System and its planetary bodies. Rich in volatile compounds and complex organic molecules, comets may have played a significant role in delivering water, prebiotic materials, and noble gases from the interstellar environment to the early Earth, potentially contributing to the emergence of life.

Although dozens of potentially observable comets reach perihelion every year, only a small fraction are studied in any detail. Except for extensive astrometric surveys and monitoring of apparent visual magnitudes, homogeneous datasets on comet composition are scarce. Nowadays, it is more and more difficult to obtain observation time on the ever larger and fewer telescopes available. Only a couple of nights at most will usually be available for a given team to get the detailed chemical information for only one comet, at one given heliocentric distance, usually close to perihelion when the comet is most active. However, comets vary unpredictably for a variety of reasons. Observing them on a limited number of nights could then provide a biased view of their composition and evolution.

Comparison of the measurements of different comets, and even of the same comet observed at different times by different teams using different techniques, is then a very risky matter because of systematic effects. Gathering homogeneous physical data on as large a sample as possible is then very important. Even for comets not studied in detail, homogeneous data are invaluable for understanding the distribution of physical and chemical properties. Only with this information will we be able to infer general conclusions from the detailed information obtained for the very few well-observed comets.

This is exactly my goal with the TRAPPIST telescopes, which I use 50% of their observing time for a photometric and astrometric survey in both the southern and northern hemispheres. Thanks to the large amount of telescope time available on both telescopes for this project, we collected a unique data set of thousands of photometric measurements of dozens of Jupiter-family comets and more than 40 long-period comets (including the dynamically new), in addition to the third interstellar comet 3I/ATLAS, which was discovered in 2025. To make these observations possible, telescopes are equipped with large, high-quality cometary narrow-band filters. Those filters were built by NASA for the observation campaign of the great comet Hale-Bopp. They isolate small spectral regions where the given cometary species are mostly emitting (emission bands produced by resonance fluorescence of the molecules in the UV sunlight), as well as nearby continuum regions (the dust-reflected solar spectrum). From the different gaseous species production rates, I derive the relative molecular abundances, such as CN/OH because water is usually the reference species, but also other ratios such as CN/C₂, etc.

The comparison of those ratios from comet to comet allows finding/confirming compositional groups of comets (comet taxonomy) and possibly a link with their dynamical properties

(namely their reservoir of origin). The variations with heliocentric distance will also give important information about ice sublimation, while possible variations for a given comet during a given night could reveal some heterogeneity of the ice in the nucleus. The dust production is also estimated using the quantity $Af\rho$, a parameter that is relatively independent of the size of the aperture and of the wavelength. Dust is a very important part of coma chemistry, and correlations will be searched for, such as the dust-to-gas ratio to heliocentric distance, abundance ratios, dynamical types, etc.

The first study in this work focuses on comet C/2017 K2 (PanSTARRS), a dynamically new comet that displayed remarkable activity at unusually large heliocentric distances. Combining nearly eight years of TRAPPIST photometric monitoring, comprising more than 270 nights and over 2200 images, with high-resolution spectroscopy from UVES and CRIRES⁺ at the Very Large Telescope, we trace the evolution of its brightness, colors, and gas production rates (OH, CN, C₂, C₃) across a wide range of heliocentric distances. The comet exhibits a smooth, outburst-free brightening, stable optical colors, and a gradual increase in molecular activity approaching perihelion. Combined optical and infrared data identify HCN as the primary source of CN and C₂H₂ photodissociation as the dominant source of C₂, while a transient pre-perihelion dip in activity is attributed to partial depletion of near-surface supervolatile ices, followed by a resurgence driven by water-ice sublimation within ~ 3 au.

The second study presents a comparative photometric analysis of eight long-period comets observed between 2010 and 2024, four returning LPCs and four DNCs, examining light curves, broad-band colors, magnitude slopes, the dust proxy $Af\rho$, and gas production rates. DNCs show activity emerging well beyond 3–5 au before perihelion, systematically lower pre-perihelion activity indices ($n \sim 1\text{--}3$ versus $n \sim 5\text{--}13$ for LPCs), and elevated dust and gas production at large distances, consistent with supervolatile-dominated activity. LPCs, in contrast, brighten steeply only within ~ 3 au, consistent with water-ice-driven activity following volatile depletion from prior perihelion passages. Broad-band colors show no significant separation between the two classes, and comet C/2009 P1 (LPC-like DNC behavior), underscoring that individual thermal history, rather than dynamical classification alone, governs the observed activity.

Together, these results confirm that DNCs are compositionally more pristine than the returning LPCs and establish a quantitative framework linking activity onset, dust and gas production, and thermal processing to dynamical history. This framework directly supports the preparation and scientific exploitation of the ESA Comet Interceptor mission, and motivates continued long-term, multiwavelength monitoring of returning LPCs and DNCs.

Chapter 1

General Introduction

1.1 Historical and scientific context of comets

The name comet originates from the Latin *comēta* and the Greek *κομητης*, both referring to “long hair” and evoking the luminous tails that characterize these bodies. Today, comets are recognized as some of the most ancient remnants of the Solar System, preserving ices and dust that have remained largely unaltered since their formation 4.6 billion years ago. Because they contain such pristine material, comets act as natural archives of the early Solar System and provide essential information about the conditions that prevailed during the epoch of planetary formation. Observational campaigns, conducted from the ground and from space, and covering the full extent of their orbital paths, are therefore crucial for disentangling the original properties of cometary nuclei from the effects of long-term evolutionary processes.

The human perception of comets has evolved dramatically over millennia. The earliest known records date back to Chinese astronomers in 2316 BC, who carefully documented their appearances and even associated the form of cometary tails with terrestrial events such as disease or conflict (Ho, 1962). In Mesopotamia, Babylonian and Chaldean scholars noted their recurrent appearances on clay tablets and regarded them as planetary-type celestial bodies. In contrast, Aristotle (384–322 BC) described them as meteorological phenomena produced in Earth’s atmosphere.

A breakthrough came during the sixteenth century. Copernicus suggested that comets followed orbits around the Sun, an idea that would later gain traction. Tycho Brahe’s precise parallax measurements of comet C/1577 V1 at Uraniborg observatory in 1577 provided compelling evidence that comets were indeed celestial objects lying far beyond the Moon (Festou et al., 2004). This discovery refuted the Aristotelian atmospheric interpretation and set the stage for new dynamical theories. In the following century, Galileo supported the heliocentric view, while Kepler attempted to model cometary trajectories, though he mistakenly envisioned them as linear paths through interstellar space. It was Newton (1687) who provided the correct theoretical framework: his law of gravitation demonstrated that comets move under solar attraction and can follow elliptical, parabolic, or hyperbolic orbits. Soon after, Halley applied Newton’s laws to a set of comets and identified their periodic nature. His successful prediction of the return of comet 1P/Halley in 1758 definitively established the astronomical nature of comets and their orbital regularity.

From that period onward, scientific interest in comets gradually shifted from purely orbital studies toward physical and compositional investigations. By the nineteenth century, Bessel (1836) had associated cometary tails with the influence of solar radiation. The first spectroscopic studies, performed by Donati (1864) and Huggins (1868), revealed emissions from di-

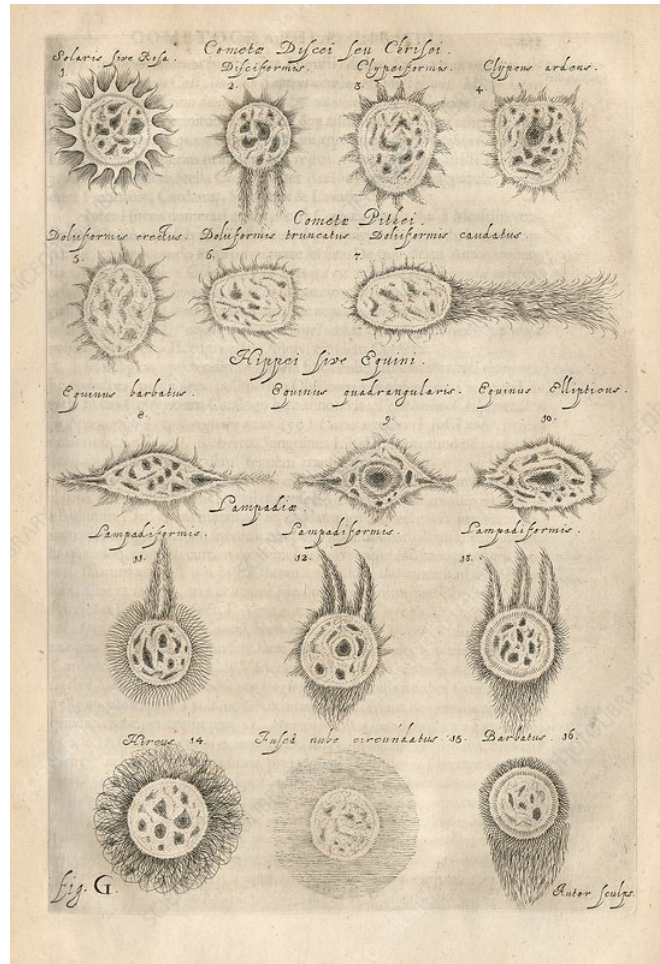


Figure 1.1: Types of comets. Illustration from *Cometographia* (Hevelius, 1668), by the Polish astronomer Johannes Hevelius, showing different types of comets.

atomic carbon (C_2) in cometary comae. In the twentieth century, advances in spectroscopy and photometry deepened the understanding of cometary nuclei and their gaseous environments. Wurm (1943) proposed the distinction between primary molecules released from the nucleus and secondary products created in the coma through photochemistry. Whipple (1950) introduced the influential “dirty snowball” model, describing nuclei as icy-dusty aggregates, while Oort (1950) inferred the existence of a distant reservoir of long-period comets, now known as the Oort Cloud. Shortly thereafter, Biermann (1951) demonstrated that the dynamics of plasma tails are driven by interactions with the solar wind, completing the foundations of the modern physical picture of comets.

1.2 Dynamical origins and classification of comets

Cometary nuclei accreted in the cold outer regions of the protoplanetary disk through coagulation of dust and condensation of volatiles. Their retention of abundant ices implies formation at large heliocentric distances, broadly within the giant-planet zone (roughly 5–30 au). Early dynamical evolution of the nascent Solar System was highly active: gravitational interactions with the giant planets scattered a large fraction of the original planetesimal population away from its formation locations, populating distant reservoirs that continue to supply observable comets today (e.g., Gomes et al. (2005); Tsiganis et al. (2005)).

Modern taxonomy groups cometary populations according to dynamical behavior and inferred source regions. Two principal reservoirs dominate: the trans-Neptunian region (commonly referred to as the Kuiper Belt and its scattered-disk extension) and the distant, roughly spherical Oort Cloud (Fig. 1.2). Dynamical classification commonly uses the Tisserand parameter with respect to Jupiter,

$$T_j = \frac{a_j}{a} + 2\sqrt{\frac{a}{a_j}(1 - e^2)\cos(i)} \quad (1.1)$$

where a , e , and i are the semi-major axis (in au), eccentricity, and inclination (in degrees) of the orbit, respectively, while $a_j = 5.2$ au is the semi-major axis of the orbit of Jupiter. In practice, this quantity separates populations with distinct dynamical histories: objects with $T_j > 2$ are generally associated with the ecliptic population (low inclinations and Kuiper-belt origins), while $T_j < 2$ identifies nearly isotropic comets that are typically linked to the Oort Cloud.

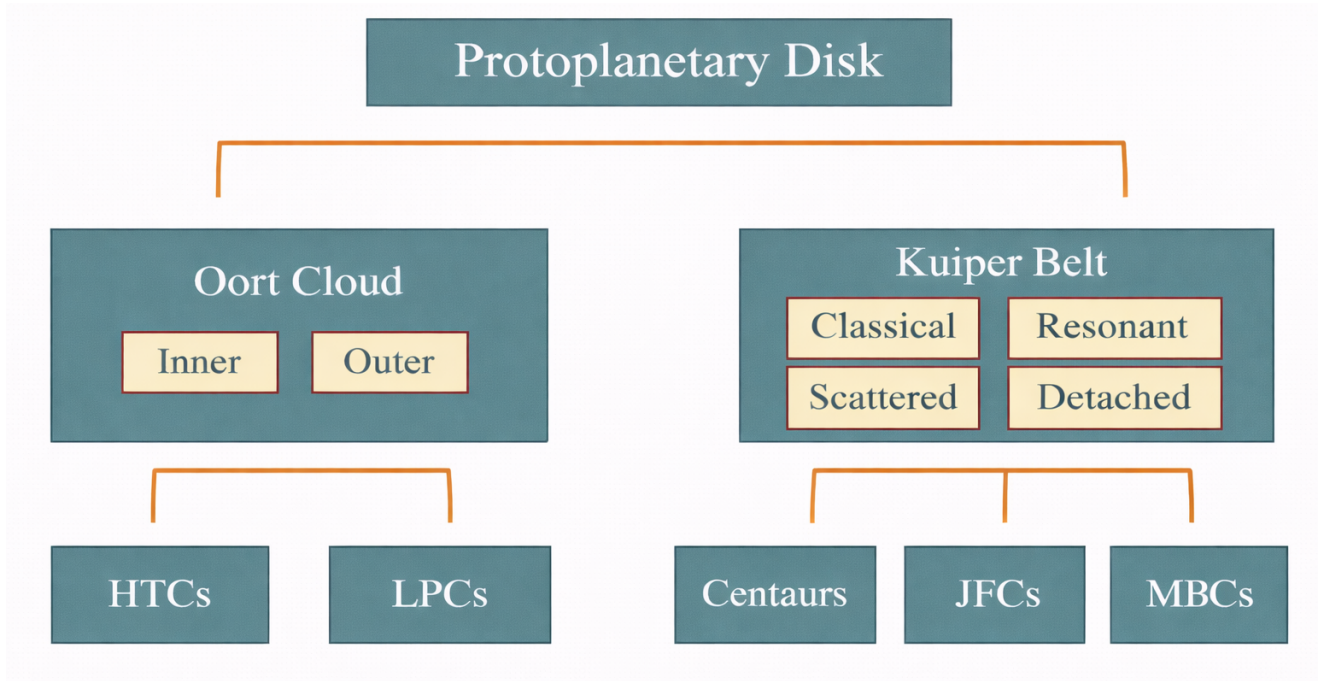


Figure 1.2: Flowchart of Comet Populations and Their Dynamic Origins. Credits: [Jewitt \(2015\)](#), adapted and modified by the author.

Nearly isotropic comets (NICs) exhibit broad inclination distributions and include long-period comets (LPCs; typically defined as those with semi-major axes $a > 40$ au) and Halley-type comets (HTCs, with $a < 40$ au). The Oort Cloud, first postulated on dynamical grounds by Öpik and later quantified by [Oort \(1950\)](#), is a distant, roughly spherical reservoir extending from $\sim 10^4$ au to several 10^5 au. Comets are injected into observable orbits from the Oort Cloud by perturbations from passing stars and galactic tides. Objects whose orbits carry them into the inner Solar System for the first time since their emplacement in the Cloud are commonly classified as *dynamically new comets*, often defined by original semi-major axes $a_{\text{orig}} \gtrsim 10^4$ au. Estimates of the Oort Cloud’s population and total mass remain uncertain, but both dynamical models and observational constraints indicate a vast reservoir, with values spanning several orders of magnitude.

The trans-Neptunian region supplies the ecliptic family of comets. The Kuiper Belt extends roughly from Neptune’s orbit at ~ 30 au out to ~ 50 au and contains distinct dynamical

subclasses: resonant objects locked in mean-motion resonances with Neptune (e.g., Pluto), a dynamically “cold” low-inclination population, and a dynamically “hot” component with larger inclinations. Beyond the classical belt, the Scattered Disk hosts bodies on more eccentric, Neptune-interacting orbits (semi-major axes often > 50 au) and is thought to be the dominant source of Jupiter-family comets (JFCs), which are characterized by low inclinations and aphelia near Jupiter. In addition to these outer Solar System sources, a small population of active objects known as main-belt comets (MBCs) resides within the asteroid belt, exhibiting comet-like activity likely driven by the sublimation of near-surface volatiles or impact-triggered exposure of ice. Current formation scenarios, most notably the Nice model, invoke early planetary migration and a phase of dynamical instability that scattered material outward and populated the Oort Cloud, the Scattered Disk, and the Kuiper Belt from a common planetesimal disk (e.g., [Gomes et al. 2005](#); [Levison et al. 2008](#)). Although this framework explains many large-scale features of the small-body populations, detailed comparisons between model predictions and observations continue to refine aspects of the picture.

Among these populations, and because of their pristine nature, long-period comets (LPCs) and dynamically new comets (DNCs) constitute the primary focus of this thesis. Long-period comets, conventionally defined as those with orbital periods greater than 200 years and typically with semi-major axes $a > 40$ au, originate predominantly from the Oort Cloud, a distant and roughly spherical reservoir of icy bodies extending from ~ 2000 au to 200 000 au ([Oort, 1950](#)). The Oort Cloud is thought to have been populated early in Solar System history when planetesimals formed in the giant-planet region were scattered outward by gravitational interactions, with a fraction subsequently trapped at large heliocentric distances under the combined effects of planetary scattering and galactic perturbations ([Dones et al., 2004](#); [Kaib and Quinn, 2009](#)). LPCs that make repeated passages through the inner Solar System are distinguished from dynamically new comets, which represent first-time visitors from the Oort Cloud. Dynamically new comets are often defined by an original semi-major axis $a_{\text{orig}} \gtrsim 10^4$ au, placing them at the outermost edge of the Oort Cloud and indicating that they are being injected into observable orbits for the first time, mainly due to perturbations from passing stars or galactic tides ([Rickman et al., 2008](#); [Fernández et al., 2015](#)). Because DNCs have not undergone repeated perihelion passages, they are considered to retain the most pristine ices and dust from the epoch of Solar System formation. Their physical and chemical study, therefore, provides a unique window into the initial conditions of the protoplanetary disk.

The distinction between LPCs and DNCs is not merely semantic but has profound implications for cometary science. LPCs that have undergone multiple perihelion passages may have already experienced significant surface evolution, including the formation of refractory mantles, loss of highly volatile species, and morphological reshaping due to repeated sublimation-driven activity. By contrast, DNCs are more likely to display vigorous outgassing at large heliocentric distances, beyond 15 au like comet C/2017 K2 (PanSTARRS) ([Jewitt et al., 2017](#); [Hmiddouch et al., 2025](#)), or even beyond 25 au like comet C/2014 UN271 (Bernardinelli-Bernstein) ([Bernardinelli et al., 2021a,b](#)), because of the sublimation of supervolatile ices such as CO and CO₂ ([Jewitt et al., 2017](#)). Observational evidence suggests that these first-time comets may have brighter comae, higher dust-to-gas ratios, and more extended activity compared to evolved LPCs. However, their study remains challenging because of their rarity and unpredictability: DNCs are detected only when perturbations succeed in sending them into the inner Solar System, and many are discovered with short lead times before perihelion. Despite these difficulties, their importance is paramount. Dynamically new comets provide perhaps the best available probes of primordial Solar System material, while LPCs allow us to trace the long-term dynamical and evolutionary pathways of Oort Cloud objects.

From a dynamical perspective, the injection of LPCs and DNCs into observable orbits

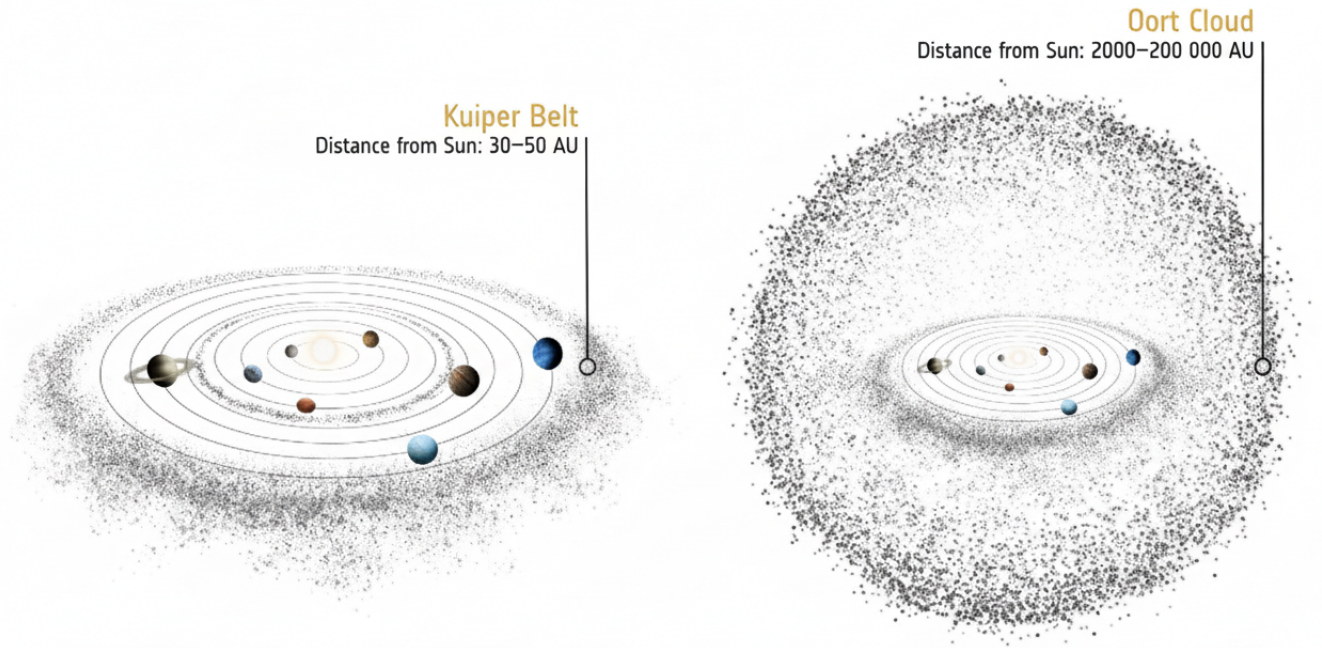


Figure 1.3: Artist view of the Oort Cloud and the Kuiper Belt. Credits: ESA, adapted and modified by the author.

is controlled by a delicate balance between external perturbations and planetary scattering. Galactic tides, arising from the gravitational field of the Milky Way, can gradually modify the perihelia of distant Oort Cloud objects. At the same time, passing stars can provide stochastic kicks that significantly alter orbital energies and inclinations. Once a comet’s perihelion is reduced to within a few astronomical units, planetary perturbations, particularly from Jupiter and Saturn, dominate its subsequent evolution, determining whether the object becomes a returning LPC, is ejected from the Solar System, or is eventually transferred into a shorter-period family such as the Halley-types or Jupiter-family comets (Levison et al., 2002; Kaib and Quinn, 2009; Jewitt, 2022). This dynamical interplay highlights the central role of LPCs and DNCs as tracers of both the Oort Cloud population and the broader dynamical environment of the Solar System.

In the context of this thesis, special emphasis is placed on the study of long-period and dynamically new comets. By combining photometric monitoring and compositional studies, we aim to characterize their activity patterns, gas and dust production rates, and compositional diversity. This dual approach is essential for disentangling evolutionary effects from primordial signatures. LPCs serve as laboratories for studying evolutionary processing over repeated passages, while DNCs provide benchmarks of relatively unaltered material, allowing for a comparative analysis between evolved and pristine bodies. Such a systematic investigation not only advances our understanding of cometary physics and chemistry but also contributes directly to broader goals, including the identification of suitable targets for future cometary missions such as ESA’s *Comet Interceptor* mission (Jones et al., 2024). LPCs and DNCs are not only key to unraveling the dynamical history of the Oort Cloud but also provide the foundation for probing the early conditions of the Solar System.

1.3 The physical makeup of comets

1.3.1 The nucleus

Cometary nuclei are the solid cores from which all observable cometary activity originates, through the sublimation of volatile ices and subsequent release of gas and dust into the coma under solar heating. Despite being the central component of a comet, nuclei remain extremely difficult to observe directly. Their small sizes (typically a few kilometers in radius), low albedos, and the bright surrounding coma that develops when the comet approaches the Sun make ground-based and space-based observations highly challenging. Only in favorable cases, such as at large heliocentric distances when the coma is weak, observations can provide constraints on bulk parameters like the effective radius, albedo, or color indices of nuclei (Lamy et al., 2004b; Meech et al., 2004). Much of our most reliable knowledge, however, comes from spacecraft encounters and in situ observations, which have revolutionized our understanding of these bodies. Since 1986, several comets have been visited by space missions, with eight distinct cometary nuclei imaged in situ, 1P/Halley (Keller et al., 1986), 19P/Borrelly (Soderblom, 2002), 81P/Wild 2 (Brownlee et al., 2004), 9P/Tempel 1 (A’Hearn et al., 2005), 103P/Hartley 2 (Thomas et al., 2013), and most comprehensively 67P/Churyumov-Gerasimenko with ESA’s *Rosetta* mission (Jorda et al., 2016). These encounters have revealed a striking morphological diversity: some nuclei are elongated, some nearly spheroidal, and others, like comet 67P, exhibit a bilobate “rubber-duck” shape, which is now widely interpreted as the result of a gentle merger between two primordial planetesimals. Surface features such as cliffs, pits, valleys, and layered terrains have been documented, along with discrete jets of gas and dust emanating from localized active regions rather than the entire surface. These observations confirm that nuclei are not homogeneous spheres of ice, but instead complex and heterogeneous objects with varied geological and compositional histories.

The internal structure and composition of cometary nuclei have long been the subject of debate. Early hypotheses, such as Lyttleton’s “sandbank” model (Lyttleton, 1948), envisioned comets as loose swarms of dust particles bound by gravity, but this model failed to explain observed non-gravitational accelerations in cometary orbits. A breakthrough came with Whipple’s “dirty snowball” model (Whipple, 1950, 1951, 1955), which described nuclei as monolithic conglomerates of ices and rocky material. This model successfully accounted for a wide range of cometary behaviors, including the non-gravitational motion of comets such as 2P/Encke, and became the prevailing paradigm for decades. Subsequent refinements introduced variations, including the “fluffy aggregate” model (Donn et al., 1985), in which nuclei are tenuous assemblages of icy grains; the “primordial rubble pile” (Weissman, 1986), which envisions nuclei as aggregates of small icy planetesimals with high porosity and low strength; and the “icy-glue” model (Gombosi and Houpis, 1986), in which refractory boulders are bound together by volatile ices acting as a cement. Belton et al. (2007) proposed a layered model in which nuclei consist of a central core surrounded by alternating layers of ice and dust. The *Rosetta* mission provided unprecedented constraints on nucleus properties, with the Radio Science Investigation (RSI) instrument measuring the mass of comet 67P to be $\sim 1 \times 10^{13}$ kg and its bulk density to be 470 ± 45 kg m⁻³ (Sierks et al., 2015), implying a highly porous internal structure consistent with the rubble-pile or fluffy-aggregate scenarios. These findings strongly suggest that cometary nuclei are primordial relics composed of weakly bound aggregates rather than compact monolithic bodies, preserving a record of the early stages of Solar System formation.

The surfaces of nuclei are among the darkest in the Solar System, with geometric albedos typically in the range 0.02–0.06 (Millis et al., 1985; Sagdeev et al., 1986; Lamy et al., 2004a;

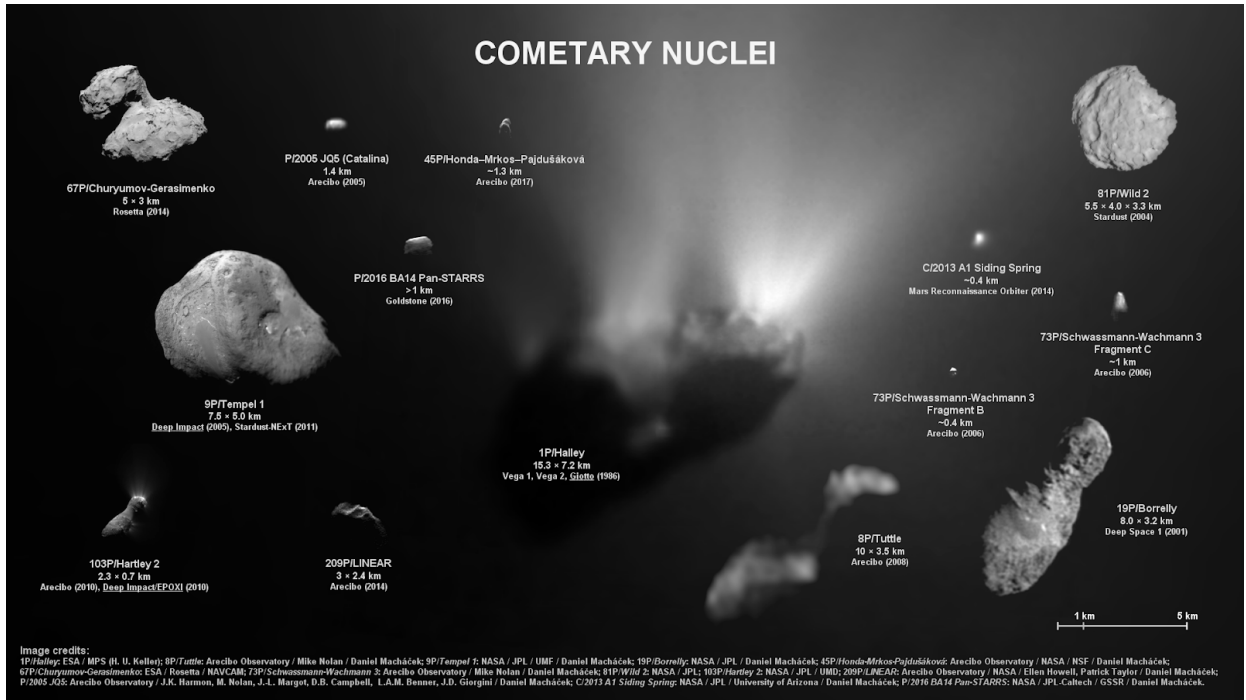


Figure 1.4: Collage of cometary nuclei imaged by spacecraft and planetary radars, shown to scale. When viewed at full size, the resolution reaches 25 meters per pixel. Image credits for each nucleus are provided directly within the collage.

Keller and Jorda, 2001). For instance, measurements of comet Halley from the Vega spacecraft revealed an albedo of about 0.04. At the same time, instruments aboard *Rosetta* measured a value of 0.06 for comet 67P (Bieler et al., 2015), consistent with previous estimates for other comets. The very low reflectivity is attributed to an outer layer of complex organic macromolecules mixed with refractory dust, which masks the underlying ices. Compositional studies reveal that cometary nuclei are composed predominantly of H_2O ice (typically $\sim 80\%$), with significant contributions from CO_2 and CO (10–20%), along with dozens of minor volatile species, including CH_3OH , NH_3 , HCN , and more complex organic molecules. The detection of molecular oxygen (O_2) in comet 67P (Bieler et al., 2015) was a surprising result, raising questions about the chemical environment of the early Solar System and the preservation of primordial species. Morphological studies also show evidence of depressions and pits that may have formed through sublimation-driven collapse, impacts, or a combination of processes. Many of these structures are associated with active regions, confirming that sublimation is spatially heterogeneous. Indeed, gas and dust production rates measured in comae are often lower than expected if the entire surface were freely sublimating, implying that only a fraction of the nucleus surface is active at any given time. The presence of discrete jets and seasonal modulation of activity further emphasizes the localized and temporally variable nature of cometary outgassing.

Finally, the rotational properties of nuclei play a critical role in governing their activity and evolution. Rotation periods can be constrained through lightcurve analysis at large heliocentric distances, monitoring of recurrent coma features, or direct imaging by spacecraft. Observed spin periods span from a few hours, as in the case of comet 10P/Tempel 2 (A’Hearn et al., 1989; Jewitt and Luu, 1989; Sekanina, 1991) and comet Hyakutake (1996 B2) (Schleicher and Osip 2002; Schleicher and Woodney 2003), to more than a day for larger bodies such as 9P/Tempel 1 (Belton and Melosh, 2009) and comet Halley (Belton et al., 1991). Nuclei may also exhibit complex rotational states involving precession or tumbling, as observed for comet 103P/Hartley 2. Importantly, rotation periods are not static: they can evolve due to torques generated by anisotropic outgassing (Whipple, 1982), changes in the moment of inertia

caused by erosion or fragmentation (Boehnhardt, 2004), or collisions with other small bodies. A striking example is comet 41P/Tuttle-Giacobini-Kresak, whose rotation period was observed to increase by 26 hours in only two months (Bodewits et al., 2018; Moulane et al., 2018). These rotational changes can have profound implications for the evolution of cometary activity, as the illumination of active regions varies with spin state, driving the observed diversity in activity patterns and long-term evolution. Together, the study of cometary nuclei through their morphology, composition, activity, and rotational dynamics provides a unique window into the conditions of the protoplanetary disk and the processes that shaped the early Solar System.

1.3.2 The coma

When a comet approaches the inner regions of the Solar System, solar heating causes the sublimation of the volatile ices within its nucleus. The gas released in this process carries entrained dust grains into space, forming a diffuse atmosphere around the nucleus known as the *coma*. The coma is a transient, extensive envelope composed of gas and dust, whose size can vary greatly depending on the comet’s heliocentric distance and activity level. For comets near 1 au from the Sun, the coma can extend over several hundred thousand kilometres, while the hydrogen envelope may reach several million kilometres. The onset of activity, however, can begin much farther from the Sun (beyond 3 au) due to the sublimation of highly volatile species such as CO and CO₂ (Jewitt et al., 2017). As the comet moves inward, the increasing solar flux heats the surface layers, and H₂O sublimation becomes the dominant driver of activity within ~ 3 au.

Gas molecules escaping from the nucleus typically exhibit outflow velocities around 0.8 km s^{-1} at 1 au (Bockelée-Morvan et al., 1990; Biver et al., 1999), although near-nucleus velocities can be somewhat lower (Lee et al., 2015). The region closest to the nucleus, known as the *inner coma*, is characterized by frequent molecular collisions and chemical interactions. This collision-dominated zone can extend up to several thousand kilometres, depending on the comet’s gas production rate and distance from the Sun. Beyond this region, the coma becomes increasingly rarefied, and photochemical processes, primarily photodissociation and ionization by solar UV photons, dominate the evolution of its constituents.

The species directly released from the nucleus are called *parent molecules*. These molecules, primarily H₂O, CO₂, and CO, emit radiation through fluorescence processes at ultraviolet, infrared, or radio wavelengths. Water, the most abundant parent molecule, was first directly detected in cometary comae in the 1980s from infrared and in situ measurements of comet 1P/Halley (Mumma et al., 1986; Weaver et al., 1986; Krankowsky et al., 1986). Alongside these major volatiles, numerous other molecules have been identified, including CHO-bearing species (e.g., CH₃OH, H₂CO, HCOOH), hydrocarbons (CH₄, C₂H₂, C₂H₆), sulfur compounds (CS₂, OCS), and nitrogen-bearing species (NH₃, HCN) (Cochran et al., 2015). The relative abundance of these compounds generally decreases with increasing molecular complexity. Under the influence of solar UV radiation, parent species undergo photodissociation, producing smaller daughter molecules, radicals, and ions, such as CN, OH, C₂, C₃, CH, and NH₂. These secondary species are primarily responsible for the rich emission spectra observed at optical wavelengths.

The second major constituent of the coma is the *dust component*. Dust grains are lifted from the surface by the drag force of sublimating gas and are composed of a mixture of silicates, carbonaceous materials, and organic compounds. In-situ measurements, sample-return missions such as the *Stardust mission* to comet 81P/Wild 2 (Brownlee et al., 2003; Sandford et al., 2021), and spectroscopic observations have revealed that cometary dust typically consists of silicates (pyroxene, olivine), amorphous carbon, metals, and sulfides, as well as carbon-hydrogen-oxygen-

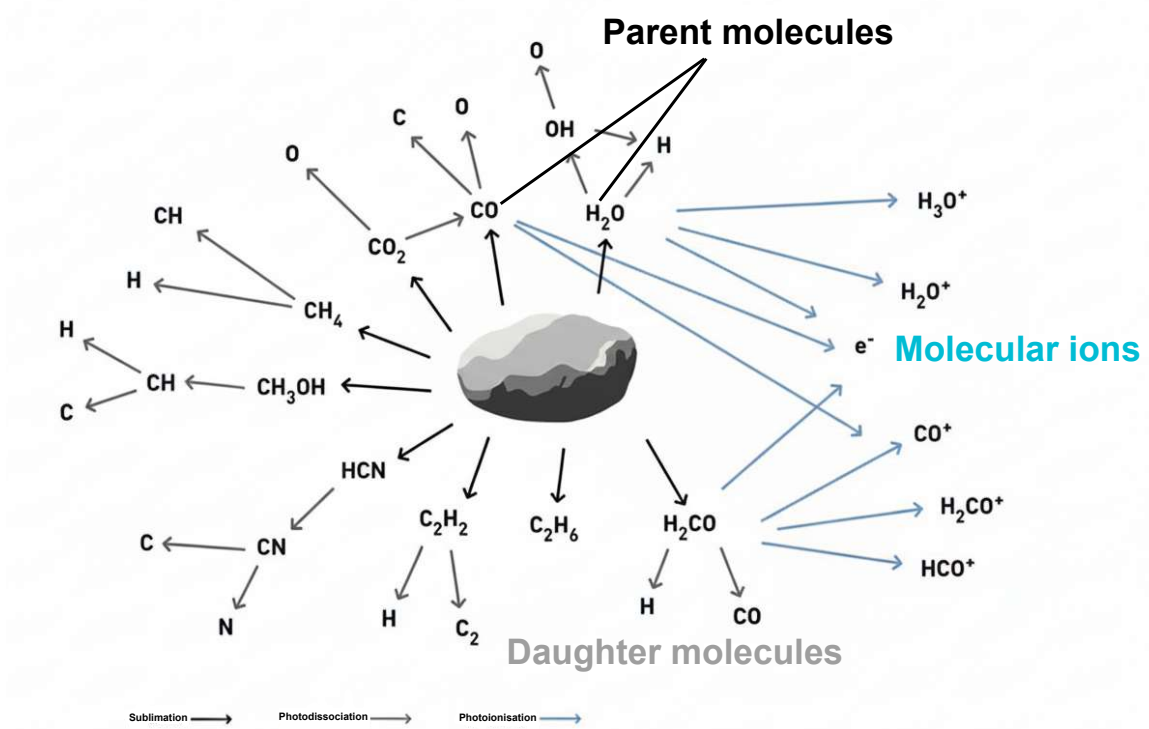


Figure 1.5: Schematic representation of the principal physical and chemical processes in the cometary coma, including sublimation, photodissociation, and photoionisation. Credits: DLR website, adapted and modified by the author.

nitrogen (CHON) compounds (Schulz et al., 2015). Dust grains are generally dark and porous, with low albedo and density, suggesting that they are fluffy aggregates rather than compact particles. Their expansion velocities are significantly lower than those of gas molecules, typically ranging from tens to a few hundred metres per second, depending on the particle size and cometary activity level (Lara et al., 2007; Lin et al., 2009; Hsieh et al., 2010). Observations in the infrared have revealed spectral features consistent with water ice, confirming the presence of icy grains and aggregates in the coma (Kelley et al., 2013).

The morphology of the coma can exhibit a wide variety of features, including jets, fans, spirals, and arcs, which are manifestations of active regions on the nucleus. These features evolve with the rotation of the nucleus and can provide key information about its spin axis orientation, surface topography, and compositional inhomogeneities. For some comets, the periodic evolution of coma features has been used to infer rotation periods and constrain the geometry of active areas. Furthermore, compositional variations between different jets and the background coma can reveal local differences in the volatile content and degree of processing of the nucleus material. In practice, these features often require image enhancement techniques to be clearly identified, as their contrast relative to the background coma is usually low (Schleicher and Farnham, 2004). The study of the coma is particularly relevant for understanding the activity patterns and compositional diversity among different dynamical classes of comets.

1.3.3 The tails

When a comet approaches the Sun, the increasing solar radiation heats the surface of its nucleus, causing the sublimation of volatile ices and the subsequent release of gas and dust. The interaction of this escaping material with solar radiation and the solar wind produces one of the

most striking phenomena in the Solar System, the formation of the comet's tails. Typically, a comet develops two prominent tails: a broad, curved dust tail and a straight, narrow ion (plasma) tail. In some particularly bright comets, a third component known as the neutral sodium tail can also be detected.

1.3.3.1 Dust tail

The dust tail is composed of solid particles, ranging from sub-micron to millimeter sizes, that are released from the nucleus as gas drag overcomes the gravitational attraction of the comet. Once ejected, these grains are pushed away from the nucleus by the solar radiation pressure, while the Sun's gravity acts in the opposite direction. The resulting trajectory of the particles forms a broad, curved tail that generally trails behind the comet as it orbits. The scattering of sunlight by these dust grains gives the dust tail its characteristic yellow-white appearance. In very active comets, fine structures such as striations or filamentary arcs can often be observed, produced by temporal variations in dust emission or rotational modulation of active areas on the nucleus (Rotundi et al., 2015).

The relative strength of the solar radiation pressure F_{rad} and solar gravity F_{grav} acting on a grain of radius a and density ρ_a can be expressed by the ratio parameter $(1 - \mu)$, where:

$$(1 - \mu) = \frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{CQ_{\text{pr}}}{\rho_a a} \quad (1.2)$$

with Q_{pr} being the radiation pressure efficiency factor and $C = 1.2 \times 10^{-4}$, assuming the solar flux at 1 au. Variations in $(1 - \mu)$ lead to identifying the type of the tail curve: "*Syndyne*", which means that the nucleus emits particles of the same size, and "*Synchrone*" involves the distribution of particles emitted at any particular time, like the case of an outburst.

1.3.3.2 Ion (plasma) tail

The ion or plasma tail forms when neutral molecules in the coma are photoionized by solar ultraviolet photons. The resulting ions are subsequently swept away from the comet by the solar wind, a stream of charged particles carrying the interplanetary magnetic field. This interaction produces a narrow, straight tail that always points almost exactly in the anti-solar direction. The plasma tail is dominated by molecular ions such as CO^+ , H_2O^+ , OH^+ , and CO_2^+ , with CO^+ being responsible for the typical bluish color observed at wavelengths near 420 nm (Balsiger et al., 1986; Flynn, 1994).

Ion velocities typically range from 10 km s^{-1} near the nucleus up to 250 km s^{-1} farther from it. Because of its magnetic coupling to the solar wind, the ion tail can change shape rapidly and even undergo complete disconnection events when solar wind disturbances or magnetic sector boundaries pass over the comet. Such events have been observed in several comets, demonstrating the dynamic coupling between cometary plasmas and heliospheric conditions.

1.3.3.3 Neutral sodium tail

A third, rarer component of cometary activity is *the neutral sodium tail*. This feature was first detected in Comet C/1995 O1 (Hale-Bopp) during its 1997 apparition (Cremone and Fulle, 1997), and later confirmed in other very bright comets such as C/2020 F3 (NEOWISE). The sodium tail lies between the dust and ion tails and is formed by neutral sodium atoms resonantly scattering sunlight at the D-line (589 nm).

The origin of the sodium atoms remains debated: one hypothesis suggests that Na atoms are released from the nucleus or dust grains within the coma and subsequently accelerated by radiation pressure; another proposes that sodium is produced *in situ* in the tail by sputtering of dust grains by ultraviolet photons or by collisions between grains (Cremonese et al., 2002; Rietmeijer, 1999). Observations show that sodium tails are extremely long (up to tens of millions of kilometers), narrow, and point directly away from the Sun. These rare features highlight complex physical and chemical processes occurring in the near-nucleus environment of highly active comets.

The multiple tails of comets provide unique diagnostics of the different physical processes acting on cometary material. The dust tail reflects the mechanical response of solid particles to solar radiation pressure. The ion tail reveals plasma interactions with the solar wind and magnetic field, and the sodium tail, although less common, traces surface or grain-sputtering chemistry under intense solar irradiation. Together, these components represent dynamic manifestations of the coupling between cometary volatiles, solar energy, and heliospheric plasma flow. Figure 1.6 shows an image of ion, dust, and sodium tails of comet C/2020 F3 (NEOWISE).

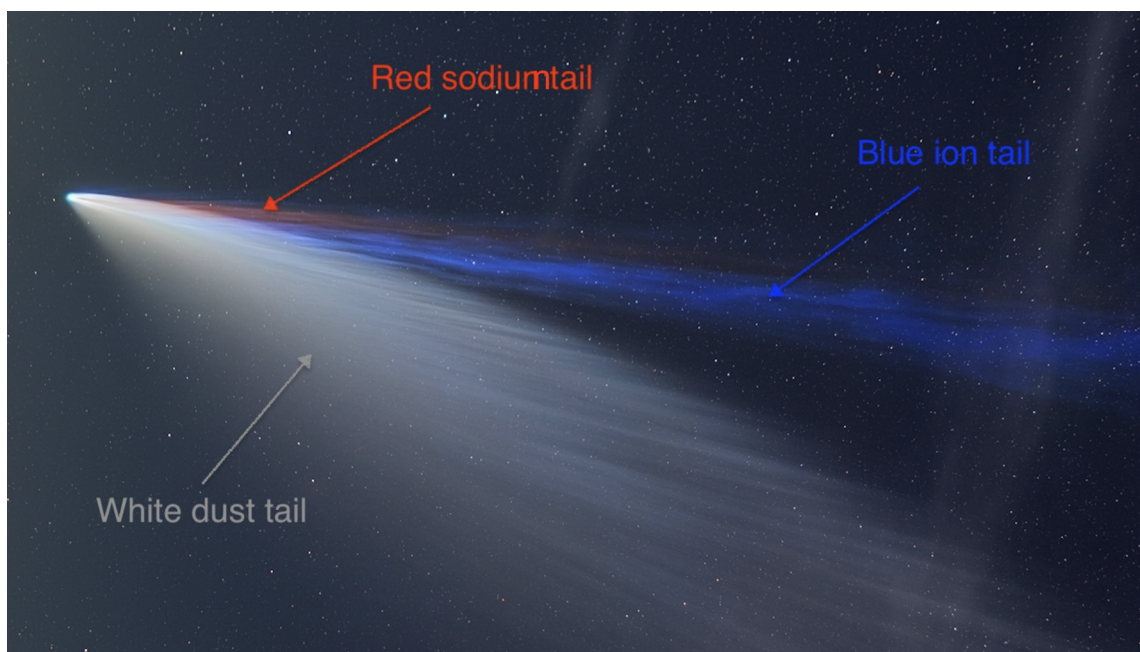


Figure 1.6: Ion, dust, and sodium tails of comet C/2020 F3 (NEOWISE). Credit: Nicolas Lefaudeux, adapted and modified by the author.

1.3.4 Sources and production mechanisms of cometary coma species

The chemical inventory observed in cometary comae is the end product of a cascade of physical and chemical processes that begin with the sublimation of nucleus volatiles and the release (or production) of refractory organic carriers. Species detected in the optical domain, radicals such as CN, C₂, C₃, NH₂, OH, and others, are commonly classed as *daughter* or *granddaughter* species because they are typically produced by photodissociation, electron-impact dissociation, or chemical transformation of more complex *parent* molecules emitted directly from the nucleus (e.g., H₂O, CO, CO₂, CH₃OH, HCN). This parent→daughter linkage underpins many interpretations of remote-sensing data, but in practice, the mapping from daughter abundances to nucleus composition is non-unique. Multiple progenitors, extended sources (grains or halos),

and in-coma chemistry all conspire to complicate the inversion problem; as a result, robust inferences about nucleus ice abundances require multi-wavelength, spatially resolved observations combined with physically motivated chemical–transport modeling (Fray et al., 2005; Combi and Fink, 1997; Cordiner et al., 2014).

A classic example that highlights these difficulties is CN. Hydrogen cyanide (HCN) is a plausible, and often measured, parent for CN; in many comets, the measured HCN production is sufficient to account for the observed CN flux. However, there is a substantial subset of comets for which CN production rates exceed those predictable from HCN measurements, sometimes by large factors (Fray et al., 2005; Dello Russo et al., 2009; Opitom et al., 2015b).

This discrepancy implies that either additional, less-easily-detected nitrogen-bearing parents contribute (e.g. HC_3N , C_2N_2 , C_4N_2), or CN forms, at least in part, from the breakdown of organic-rich grains (so-called CHON particles) or macromolecular refractory organics released into the coma. Spatial observations provide strong evidence for an extended source, as indicated by the CN jets and their distinct radial profiles observed in comets Halley and Hale–Bopp are better matched by a combination of nucleus and extended grain sources than by nucleus-only HCN photodissociation (A’Hearn et al., 1986; Lederer et al., 1997; Klavetter and A’Hearn, 1994). Electron-impact and gas-phase chemistry may also contribute to CN production under certain coma conditions, although quantitative assessments of these channels remain model-dependent and require accurate electron flux and cross-section data (Irvine et al., 1998; Rodgers and Charnley, 1998).

Carbon-chain radicals (C_2 , C_3) present a similar, and in many respects more severe, identification problem. Early proposals that simple hydrocarbons such as acetylene (C_2H_2) or ethane (C_2H_6) are the primary parents of C_2 were partially vindicated when IR and radio spectroscopy eventually detected these molecules in comae, but abundance arguments and radial profile shapes demonstrate that single-step photodissociation scenarios are often insufficient (Jackson, 1976; Crovisier, 1997). In numerous comets, the inner-coma radial profiles of C_2 are flatter than predicted for a pure parent→daughter pathway; this behaviour is naturally reproduced if C_2 is in significant part a granddaughter species (i.e. produced by the photodissociation of an intermediate daughter rather than directly from the nucleus) or if a spatially extended halo of carbonaceous grains injects C_2 -bearing fragments into the coma (O’Dell et al., 1988a; Combi and Fink, 1997; Helbert et al., 2005; Weiler, 2012). Detailed chemical-network modelling shows that plausible multi-step chains (e.g. $\text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_4 \rightarrow \text{C}_2$, or $\text{C}_2\text{H}_2 \rightarrow \text{C}_2\text{H} \rightarrow \text{C}_2$) can contribute to observed C_2 profiles, but efficiencies and branching ratios frequently fall short of explaining observed production rates without invoking additional sources or heterogeneous grain populations (Helbert et al., 2005; Weiler, 2012).

The ammonia family (NH_3 , NH_2 , NH) illustrates the role of observational limitations and photophysical uncertainties. NH_3 is widely regarded as the primary parent of NH_2 (and thence NH), but NH_3 is intrinsically difficult to detect in many comets, and fluorescence efficiencies and dissociation branching ratios remain imperfectly constrained. Consequently, even when NH_2 and NH are robustly observed, quantitative back-calculation to an NH_3 abundance is hampered by uncertainties in excitation rates and competing production pathways (Palmer et al., 1996; Dello Russo et al., 2014; Kawakita and Mumma, 2011). These limitations are not unique to ammonia; for many candidate parents, laboratory photodissociation cross-sections, product-branching ratios, and electron-impact rates are insufficiently characterized at comet-relevant photon and electron energies, which propagates into large uncertainties in chemical models.

A common analytical framework used in observational studies is the Haser-style parametric model, which links nucleus production rates to radial number-density profiles through simple assumptions about outflow geometry and parent/daughter lifetimes. In its standard form, the

parent number density is written:

$$n_p(r) = \frac{Q_p}{4\pi v r^2} \exp\left(-\frac{r}{\ell_p}\right),$$

and the daughter number density can be expressed as:

$$n_d(r) = \frac{Q_p}{4\pi v r^2} \frac{\ell_d}{\ell_d - \ell_p} \left[\exp\left(-\frac{r}{\ell_d}\right) - \exp\left(-\frac{r}{\ell_p}\right) \right],$$

where Q_p is the parent production rate, v is the radial expansion speed, and ℓ_p , ℓ_d are the scale-lengths (or lifetimes times v) of the parent and daughter, respectively. While useful for first-order interpretation and for converting narrow-band fluxes to production rates, Haser models are intrinsically limited: they assume isotropic outflow, single-step chemistry, and fixed scale-lengths, and thus cannot capture extended grain sources, anisotropic jets, or time-dependent photochemical behaviour. Consequently, Haser-model results should be regarded as effective parameters rather than unique, physically exhaustive solutions; more realistic chemical-transport models (and direct mapping using integral field spectrographs or radio interferometers) are required to disentangle the many contributing processes (Combi and Fink, 1997; Cordiner et al., 2014).

Given the observational and theoretical ambiguities, sound strategies for constraining species parentage rely on combining multiple, complementary measurements. Important approaches include: (1) simultaneous optical daughter and infrared/radio parent spectroscopy, which permits direct comparison of production rates for candidate parent–daughter pairs; (2) high signal-to-noise radial-profile mapping (ideally over large fields of view) to determine whether a species is nucleus-centered or arises from an extended source or halo; (3) correlation studies between dust production (e.g. $Af\rho$ or direct dust-mass-loss estimates) and daughter production rates to test grain-release hypotheses; (4) spatially resolved chemical-transport modelling that includes photolysis, electron-impact dissociation, and grain sublimation/sputtering; and (5) in-situ mass-spectrometric measurements when available, which provide unambiguous detection of parent molecules and refractory organics (Fray et al., 2005; A’Hearn et al., 1986; Cordiner et al., 2014). Modern facilities are particularly well suited to these tasks: ALMA and other mm/sub-mm arrays deliver high-sensitivity parent detections and spatial maps; wide-field optical integral field units (IFUs) permit mapping of daughter distributions with spectral discrimination; and long-term photometric monitoring from telescopes such as TRAPPIST telescopes provides the temporal context required to link activity changes to compositional diagnostics.

For long-period comets (LPCs) and dynamically new comets (DNCs), the issue of species origin assumes special significance. DNCs frequently display strong activity at large heliocentric distances driven by supervolatile species (CO, CO₂), and their comae can contain abundant, fresh, less-processed material that has not been thermally altered by repeated perihelion passages. Consequently, DNCs often present extended comae, bright dust halos, and pronounced jet activity, all conditions that favour the detection of extended sources and grain-derived fragments. Comparing parent/daughter ratios, radial scalelengths, and dust–gas correlations between DNCs and more evolved LPCs therefore provides direct tests of evolutionary processing: differences in the prevalence of grain-derived daughters, in parent abundances, or in photochemical pathways can be translated into constraints on thermal history, mantle formation, and primordial volatile inventory (Dello Russo et al., 2009; Opitom et al., 2015b).

Looking forward, progress in resolving parent–daughter relationships depends on three complementary advances. First, improved laboratory measurements of photodissociation cross sections, branching ratios, and electron-impact rates for candidate cometary molecules are essential input for reliable chemical models. Second, coordinated observational campaigns that combine

high-sensitivity IR/radio parent measurements with spatially resolved optical mapping and dust diagnostics (polarimetry, mid-IR spectroscopy, and mass-loss estimates) are required to tie molecular and particulate inventories together. Third, advances in modelling from multi-dimensional gas–dust dynamical simulations that include grain fragmentation and devolatilization to coupled chemical networks with time-dependent illumination and solar-wind effects will enable more realistic forward-modelling of observed comae. Together, these developments will reduce the ambiguity in parentage assignments and will sharpen the use of coma compositions as probes of the primordial Solar Nebula.

1.4 Cometary Populations Beyond the Solar System

The processes that gave rise to comets in our Solar System, ice condensation in a protoplanetary disk, scattering and ejection of planetesimals by migrating giant planets, are by no means unique to our planetary neighbourhood. Indeed, the widespread detection of hot Jupiters and tightly packed exoplanetary systems (Gillon et al., 2017) suggests that giant-planet migration and consequent dynamical upheaval are common in extrasolar systems. Accordingly, one would expect that many stellar systems host their own reservoirs of comets (so-called *exocomets*), and that a large population of comets may have been ejected into interstellar space, wandering between the stars. In the subsections that follow, we summarise the theoretical background and current observational evidence for both exocomet populations and interstellar comets.

1.4.1 Exocomets

Comets are pristine leftovers from planet-formation, recording the earliest conditions of their parent systems. In our Solar System, models of giant-planet migration and planetesimal wear-down show how massive dynamical instabilities can scatter or eject vast numbers of small bodies from their birth region. By analogy, extrasolar systems that host giant planets in close orbits should likewise have experienced disc disruption and small-body scattering, suggesting the existence of significant comet populations bound to other stars. Early theoretical work by Lecavelier Des Etangs et al. (1999) simulated the transit light curves of dust-laden exocomets, identifying two characteristic shapes (rounded triangular and symmetric ingress) and proposing that the dust tails of exocomets could produce observable stellar dimming events. Since then, high-precision time-series photometry and high-resolution spectroscopy have confirmed exocomet activity in numerous systems (e.g., Kiefer et al., 2017; Rappaport et al., 2018; Zieba et al., 2019; Rebollido et al., 2020; Pavlenko et al., 2021). These detections open a new window on the formation and evolution of planetary systems by extending the cometary record beyond the boundaries of the Solar System.

1.4.2 Interstellar Comets

Interstellar comets are bodies that formed around other stars, were subsequently ejected into interstellar space, and eventually traverse the Solar System on a hyperbolic trajectory, unbound to the Sun. While theoretical work long predicted their existence, only in recent years have we obtained direct observational evidence of such objects. These rare visitors provide a unique opportunity to sample material from extrasolar protoplanetary disks and to compare planetary-system formation processes beyond our own.

The ejection of cometary bodies into interstellar space is a natural consequence of the dy-

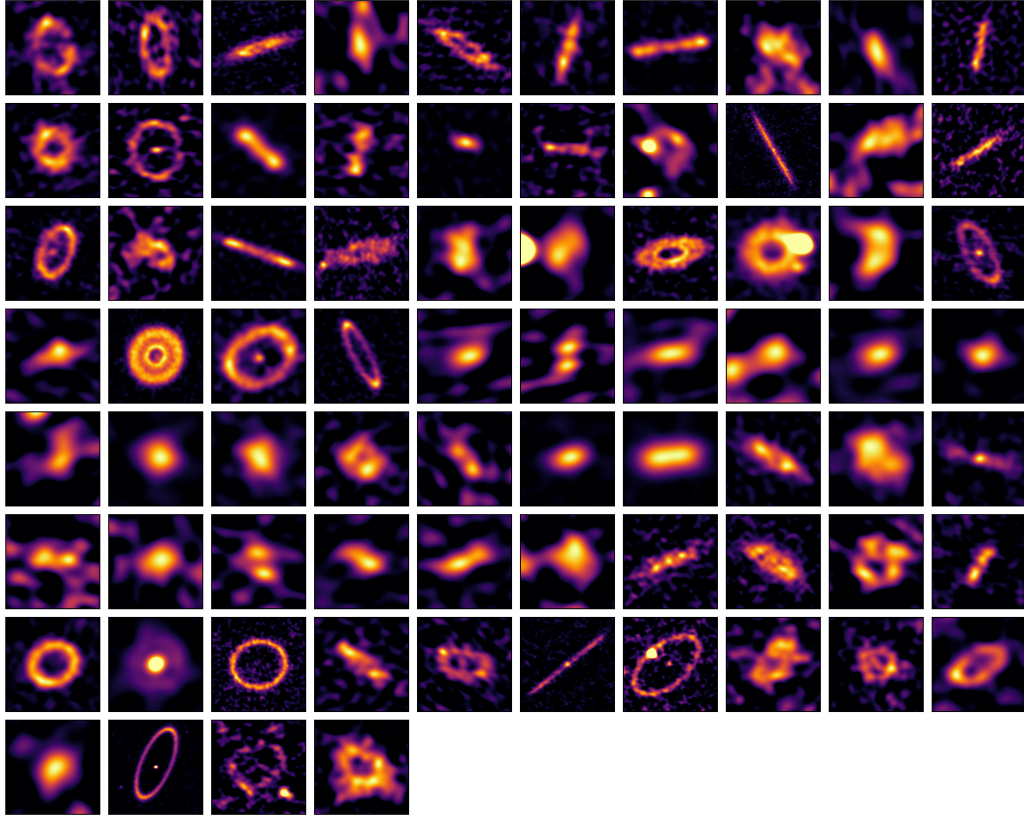


Figure 1.7: The 74 exocomet belts imaged by ALMA’s REASONS survey, showing belts of all shapes, sizes, and ages. Credit: [Matrà et al. \(2025\)](#)

namical evolution of planetary systems. In the formation and early migration of giant planets, planetesimals are scattered, some onto stable reservoirs (analogous to our Oort cloud) and others onto hyperbolic escape trajectories. Analytical and numerical studies of the outer Solar System’s Oort cloud under the influence of galactic tides and stellar perturbations show that a small fraction of comets can be ejected entirely, becoming interstellar objects ([Torres et al., 2019](#)). Extrapolating this process to the vast number of planetary systems in the Galaxy suggests an enormous population of interstellar comets (ISCs). For example, [Jewitt and Seligman \(2023\)](#) estimates a galactic number density corresponding to $\sim 10^{25} - 10^{26}$ such objects in the Milky Way, assuming a uniform distribution in the galactic disk.

Detecting interstellar comets is challenging because their residence time in the inner Solar System is brief, and their brightness is often faint. To qualify as interstellar, an object typically displays a hyperbolic orbit with eccentricity $e > 1$ and a significant hyperbolic excess velocity. The first such object, 1I/‘Oumuamua, discovered in 2017, exhibited no obvious cometary tail yet displayed non-gravitational acceleration consistent with outgassing or radiation pressure ([Meech et al., 2017](#); [Seligman and Moro-Martín, 2022](#)). The second, 2I/Borisov in 2019, displayed a clear coma and tail and was the first confirmed interstellar comet in the classical sense ([Guzik et al., 2019](#)). More recently, 3I/ATLAS has been identified as a third interstellar interloper ([Denneau et al., 2025](#)), with active outgassing and an elevated CO₂ content ([Cordiner et al., 2025](#)).

2I/Borisov revealed a remarkably high abundance of carbon monoxide (CO), measured at up to 35–100% relative to water vapor, far exceeding typical Solar System comets at similar heliocentric distances ([Cordiner et al., 2020](#)). This suggests that 2I/Borisov may have formed beyond the CO ice line in a cold, distant region of its natal system, preserving volatiles that are less common in Solar System comets. Polarimetric measurements show the coma dust to

Table 1.1: Key parameters of confirmed interstellar objects

Name	Discovery Year	Type	Eccentricity e	Excess Velocity ^a	Notable Composition	References
1I/Oumuamua	2017	Asteroid-like	~ 1.2	30 km s^{-1}	No clear coma	(Meech et al., 2017; Micheli et al., 2018)
2I/Borisov	2019	Comet	~ 3.3	32 km s^{-1}	$\text{CO}/\text{H}_2\text{O} \gtrsim 1.7$, active coma	(Bodewits et al., 2020; Cordiner et al., 2020)
3I/ATLAS	2025	Comet	Hyperbolic	60 km s^{-1}	$\text{CO}_2/\text{H}_2\text{O} \approx 8$, strong activity	(Cordiner et al., 2025; Opitom et al., 2025)

^a Approximate heliocentric excess velocity with respect to the Sun–planet frame.

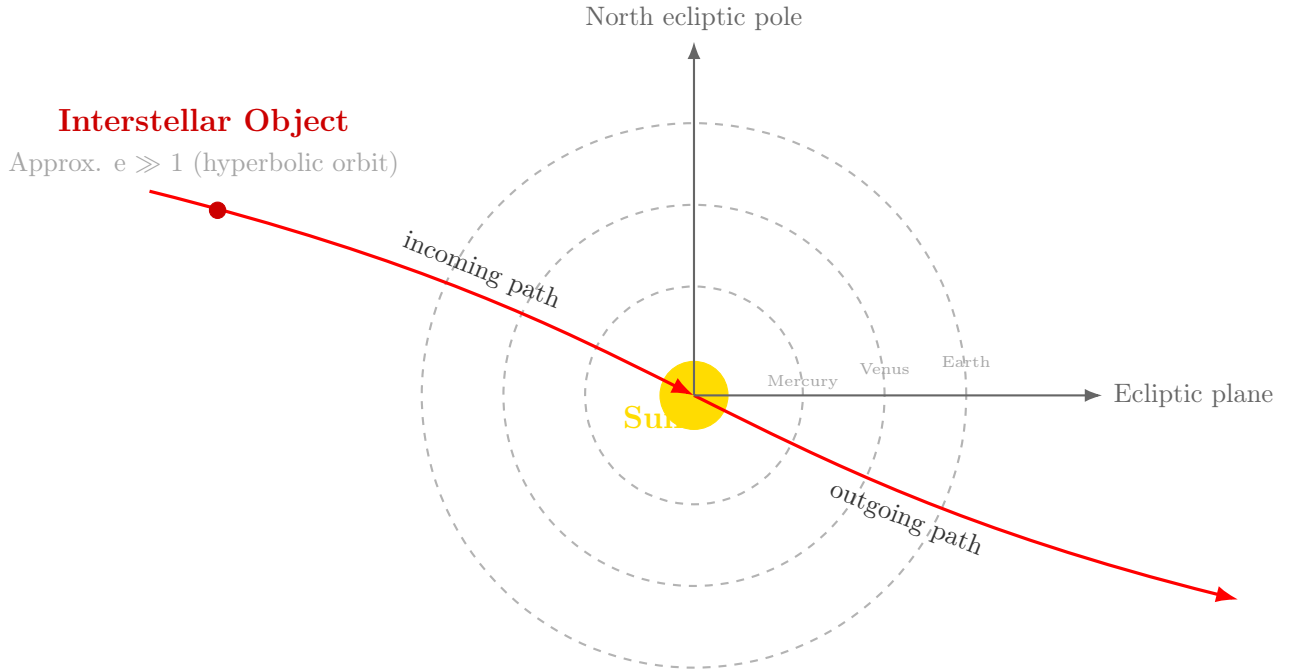


Figure 1.8: Schematic representation of an interstellar object entering and exiting the inner Solar System on a hyperbolic trajectory.

be unusually pristine, with high degrees of polarization implying minimal solar-system surface processing (Bagnulo et al., 2021). The more recent 3I/ATLAS displays an unusually high CO_2 to H_2O ratio at an inbound heliocentric distance of 3.32 au, raising questions about irradiation history and interstellar exposure over billions of years (Cordiner et al., 2025). These compositional peculiarities underscore the diversity of cometary building blocks across planetary systems.

Interstellar comets provide a direct, albeit fleeting, window into the chemical and dynamical conditions of other planetary systems. They complement studies of Solar System comets such as long-period and dynamically new comets by offering comparative baselines of primordial volatile inventories. Since ISCs likely avoided repeated passages near a central star, they may retain more pristine materials. By comparing nucleus activity, outgassing behavior, dust composition, and isotopic ratios across Solar and extrasolar comets, we can better constrain models of protoplanetary disk formation, planetesimal ejection, and interstellar transport of volatiles.

Improving detection rates and characterization of interstellar comets is now a key goal in small-body astronomy. Surveys such as the Vera C. Rubin Observatory (LSST) are expected to increase the number of detected hyperbolic objects by orders of magnitude. Moreover, mission concepts for rapid flyby intercepts of ISCs are under study, given the potential of direct sampling

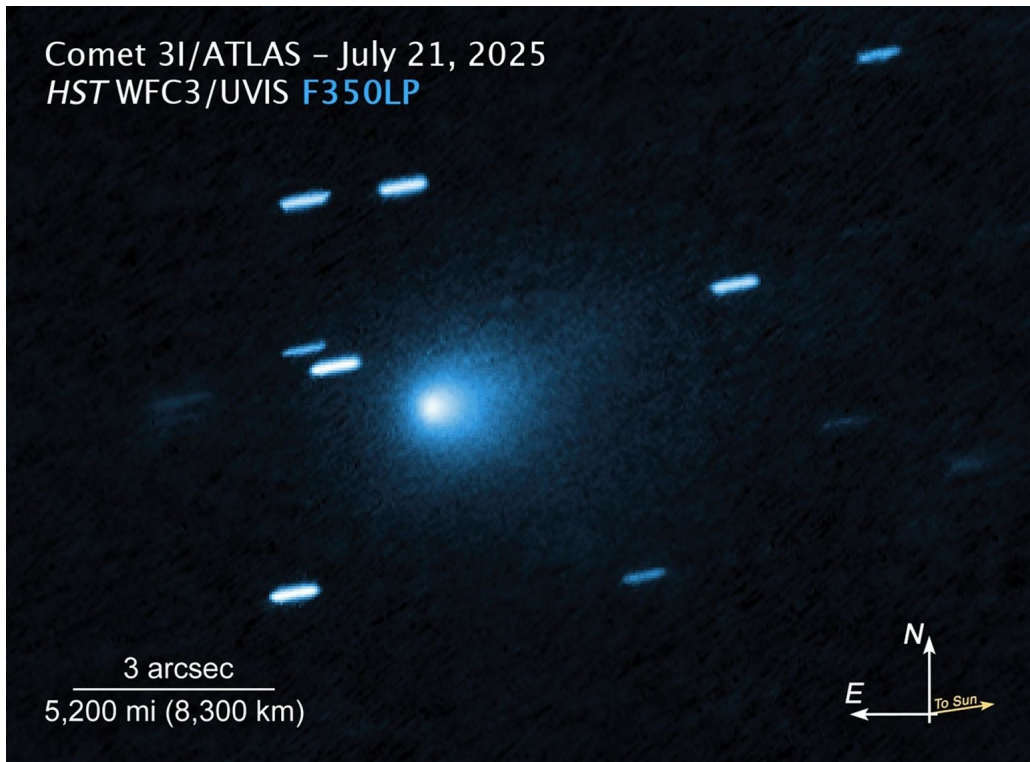


Figure 1.9: An HST image of the interstellar comet 3I/ATLAS, on July 21, 2025, when the comet was 2.98 au from Earth. Credit: NASA, ESA, D. Jewitt (UCLA).

of extrasolar materials ([Hoover et al., 2022](#)). Each new interstellar visitor promises to revise our understanding of cometary populations and the processes that scatter small bodies across the Galaxy.

Chapter 2

Observation and Data Reduction

This chapter presents a detailed description of the observational data, instrumentation, and analysis methods used in this work. Most of the data consist of broad- and narrowband photometric observations obtained with the TRAPPIST telescopes. In addition, spectroscopic observations of selected comets were conducted using both the high-resolution Ultraviolet-Visual Echelle Spectrograph (UVES), and the high-resolution infrared spectrograph (CRIRES⁺), mounted on the ESO/VLT, as well as data from the Long Slit Intermediate Resolution Spectrograph for Astronomy (LISA) mounted on the 1.2 m telescope of the Mount Abu Infrared Observatory (MIRO), and Low-resolution spectra with the Himalaya Faint Object Spectrograph and Camera (HFOSC) installed on the 2 m Himalayan Chandra Telescope (HCT).

The first part of this chapter outlines the technical characteristics of the instruments and the observational strategies adopted during our campaign. The subsequent sections describe the data reduction and calibration procedures applied to both photometric and spectroscopic datasets. Gas production rates were derived from the calibrated images by fitting a coma brightness profile based on the Haser model (Haser, 1957; Haser et al., 2020), which is discussed later in this section. Dust activity was quantified using the $Af\rho$ parameter.

2.1 TRAPPIST telescopes

The TRAPPIST project (“**TR**Ansiting **P**lanets and **P**lanetes**I**mals **S**mall **T**elescope”) is a project led by researchers at the University of Liège, which comprises two fully robotic 60 cm telescopes dedicated to exoplanet transit searches and to the photometric monitoring of small Solar System bodies (Jehin et al., 2011). TRAPPIST–South (TS) was commissioned at ESO’s La Silla Observatory in 2010 (top Fig. 2.4), while TRAPPIST–North (TN, bottom Fig. 2.4) began regular operations in May 2016 at the Oukaimeden Observatory (Atlas Mountains, Morocco) in collaboration with Cadi Ayyad University (Benkhaldoun, 2018). The deployment of the northern unit substantially increased sky access and, together, the two telescopes enable near-continuous monitoring of targets visible from both hemispheres. The TRAPPIST facilities are also notable for the discovery of the seven Earth-sized planets orbiting TRAPPIST-1 (Gillon et al., 2017).

Both telescopes are Ritchey–Chrétien systems operating at $f/8$ and are mounted on ASTELCO NTM-500 German equatorial mounts. Each telescope is equipped with a high-sensitivity CCD camera and a multi-position filter wheel. TN uses a thermo-electrically cooled $2\text{ k} \times 2\text{ k}$ Andor IKON-L detector, providing a $20' \times 20'$ field of view; with 2×2 on-chip binning the plate scale is $1.2'' \text{ pix}^{-1}$. TS carries a $2\text{ k} \times 2\text{ k}$ FLI PL3041-BB detector with $15\text{ }\mu\text{m}$ pixels, yielding a

$22' \times 22'$ field of view and a plate scale of $1.3'' \text{ pix}^{-1}$ when binned 2×2 . Both cameras exhibit high quantum efficiency across the optical band and are fitted with double Apogee filter wheels (18 filters on TN, and 18 on TS). A concise summary of these instrumental parameters is given in Table 2.1.

The telescopes are housed in automated domes (a 4.2 m Gambato dome for TN and a 5 m Ash-Dome for TS), and each site is equipped with environmental monitoring systems (Diffraction Limited Boltwood cloud sensors and SBIG all-sky cameras¹) that integrate with the remote-control software to ensure safe, unattended operations. These design choices, dual hemispheric coverage, robust meteorological monitoring, and flexible filter sets make TRAPPIST well-suited for sustained, homogeneous time-series photometry of comets and other transient small-body targets.



Figure 2.1: TRAPPIST telescopes: (top) TRAPPIST-South located at La Silla Observatory, Chile (IAU code I40), and (bottom) TRAPPIST-North located at Oukaimeden Observatory, Morocco (IAU code Z53).

TRAPPIST telescopes are equipped with a set of narrow-band filters originally developed for the Hale–Bopp campaign at the Lowell Observatory (Farnham et al., 2000). These filters isolate the principal emission bands of the major cometary daughter species, OH (3090 Å), NH (3362 Å), CN (3870 Å), C₃ (4062 Å), and C₂ (5141 Å), as well as four continuum regions in the ultraviolet, blue, green, and red (UC at 3448 Å, BC at 4450 Å, GC at 5260 Å, and RC at 7128 Å). Their design maximizes transmission within the targeted molecular bands while

¹<https://www2.cometa.uliege.be/TRAPPIST/Camera/CamerasTRAPPIST.php>

Table 2.1: Main technical specifications of the TRAPPIST-North and TRAPPIST-South telescopes and their instrumentation.

Parameter	TRAPPIST-North	TRAPPIST-South
Telescope and Mount		
Optical design	Ritchey-Chrétien	Ritchey-Chrétien
Aperture	0.6 m	0.6 m
Focal ratio	f/8	f/8
Mount type	German equatorial (Astelco NTM-500)	German equatorial (Astelco NTM-500)
Slewing speed	50° s^{-1}	50° s^{-1}
Tracking accuracy	~ 1 per 5 min	~ 1 per 5 min
Detector System		
Camera model	Andor IKON-L BEX2 DD	FLI ProLine PL3041-BB
Array size	2048×2048 pixels	2048×2048 pixels
Pixel size	$13.5 \mu\text{m}$	$15 \mu\text{m}$
Pixel scale	1.20 pix^{-1}	1.30 pix^{-1}
Field of view	20×20	22×22
Full well capacity	$100,000 \text{ e}^-$	$100,000 \text{ e}^-$
Readout modes	1, 3, 5 MHz	$1 \times 1 \text{ MHz}$, $1 \times 2 \text{ MHz}$, $2 \times 2 \text{ MHz}$
Readout noise	$7\text{--}32 \text{ e}^-$	$9.5\text{--}14 \text{ e}^-$
Readout time	$1.8\text{--}5 \text{ s}$	$2\text{--}6 \text{ s}$
Dark current	$0.15 \text{ e}^-/\text{s/pix}$ @ -65°C	$0.10 \text{ e}^-/\text{s/pix}$ @ -55°C
Cooling system	Thermoelectric, -100°C	Thermoelectric, -55°C
Temperature stability	0.1°C	0.1°C
Gain	$1.1 \text{ e}^-/\text{ADU}$	$1.1 \text{ e}^-/\text{ADU}$
Peak quantum efficiency	90%	96%
Filter System		
Filter wheel 1	B, V, R_c , I_c , I+z, z, Exo	B, V, R_c , I_c , I+z, z, Exo, H_2O^+ , NaI
Filter wheel 2	OH, NH, CN, C_3 , BC, C_2 , GC, RC	OH, NH, CN, CO^+ , C_3 , BC, C_2 , GC, RC, UC
Enclosures and Auxiliary Systems		
Dome type	4.2 m Gambato Dome	5.0 m Ash-Dome REB
Weather monitoring	Boltwood Cloud Sensor + SBIG AllSky	Boltwood Cloud Sensor + SBIG AllSky

minimizing dust-continuum contamination, with most gas filters reaching peak transmissions above 60%. The OH filter isolates the (0–0) band at $3090 \text{ \AA}$ while excluding the (1–1) band at $3126 \text{ \AA}$. The NH filter covers the entire (0–0) band, and the CN filter includes both the (0–0) and overlapping (1–1) bands of the B–X system. The homonuclear species C_2 and C_3 exhibit broad, blended rotational–vibrational features; the C_3 filter covers part of the $3400\text{--}4400 \text{ \AA}$ band complex while avoiding the CO^+ (3–0) band near $4000 \text{ \AA}$, whereas the C_2 filter isolates the $\Delta v = 0$ system near $5141 \text{ \AA}$.

TRAPPIST-South is additionally equipped with three filters dedicated to ionic and atomic emissions: CO^+ ($4270 \text{ \AA}$), H_2O^+ ($7050 \text{ \AA}$), and NaI ($5890 \text{ \AA}$). The CO^+ filter targets the 2–0 band at $4260 \text{ \AA}$, chosen to avoid the stronger but more blended $4010 \text{ \AA}$ band, while minimizing contamination from CN and CH. The H_2O^+ filter isolates the (0,6,0) band centered near $7010 \text{ \AA}$. A detailed summary of all filter characteristics is provided in Table 2.2, and their transmission curves are shown in Figure 2.3.

The continuum filters are designed to maximize dust signal while avoiding gas emissions. The UV continuum (UC) filter at $3448 \text{ \AA}$ suffers from contamination by OH, CO_2^+ , and especially C_3 , and is therefore not used for dust analysis in this work. The blue continuum (BC) filter at $4450 \text{ \AA}$, located between the CO^+ and C_2 bands, is the least contaminated and is used for continuum subtraction in the derivation of gas production rates. The green continuum (GC) filter at $5260 \text{ \AA}$ lies just redward of the C_2 $\Delta v = 0$ system and avoids most NH_2 emission, while the red continuum (RC) filter at $7128 \text{ \AA}$ was designed to avoid both H_2O^+ emission and telluric H_2O absorption. TRAPPIST is also equipped with Johnson–Cousins broad-band filters (B, V, R_c , I_c) (Bessell, 1990). While the B and V passbands include significant gas contributions, R_c

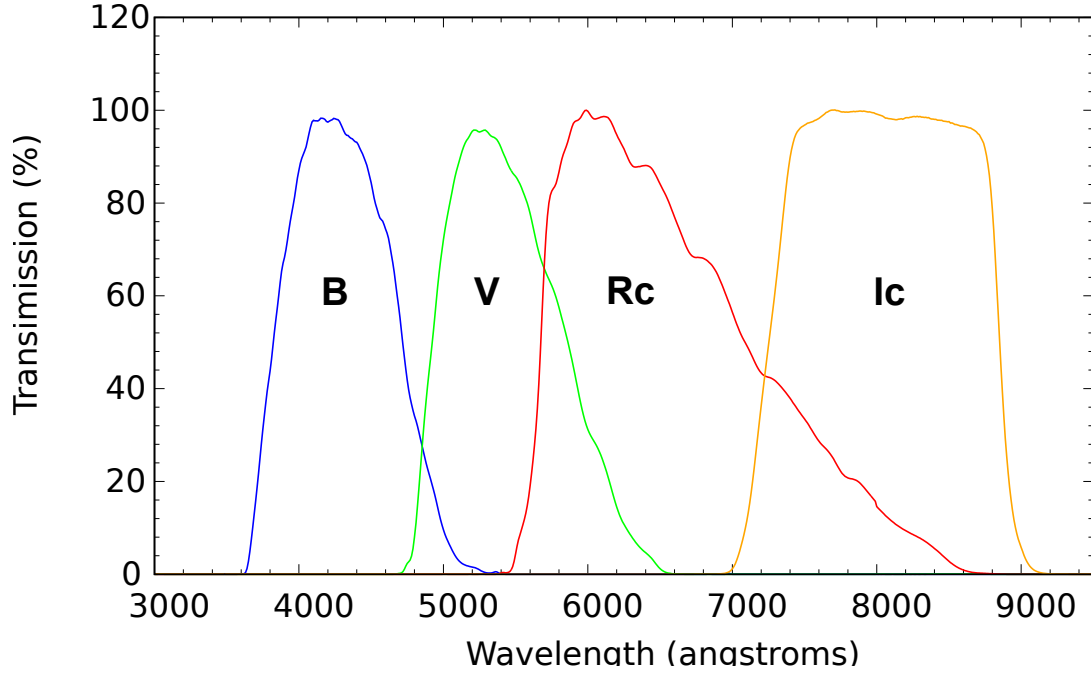


Figure 2.2: Transmission profiles for the Johnson/Cousins B, V, Rc, and Ic filters.

and I_c are relatively free of contamination and are therefore used to derive the $Af\rho$ dust proxy. Additional I+z, z, and Exo filters are available for the exoplanet monitoring program of the TRAPPIST project.

Table 2.2: Summary of the Hale–Bopp (HB) narrow-band comet filters and their principal characteristics.

Filter	Species ^(a)	$\lambda_c^{(b)}$ (Å)	FWHM ^(c) (Å)	Peak Trans. ^(d) (%)
OH	OH (0–0)	3090	62	56
NH	NH (0–0)	3362	58	63
UC	UV Continuum	3448	84	67
CN	CN ($\Delta v = 0$)	3870	62	67
C ₃	C ₃ (Swings system)	4062	62	62
CO ⁺	CO ⁺ (2–0)	4266	64	77
BC	Blue Continuum	4450	67	65
C ₂	C ₂ ($\Delta v = 0$)	5141	118	85
GC	Green Continuum	5260	56	78
NaI	Sodium D lines	5890	30	70
H ₂ O ⁺	H ₂ O ⁺ (0,6,0)	7020	170	75
RC	Red Continuum	7128	58	80

^(a)Emission band or designation. ^(b)Measured central wavelength. ^(c)Full width at half maximum. ^(d)Mean peak transmission.

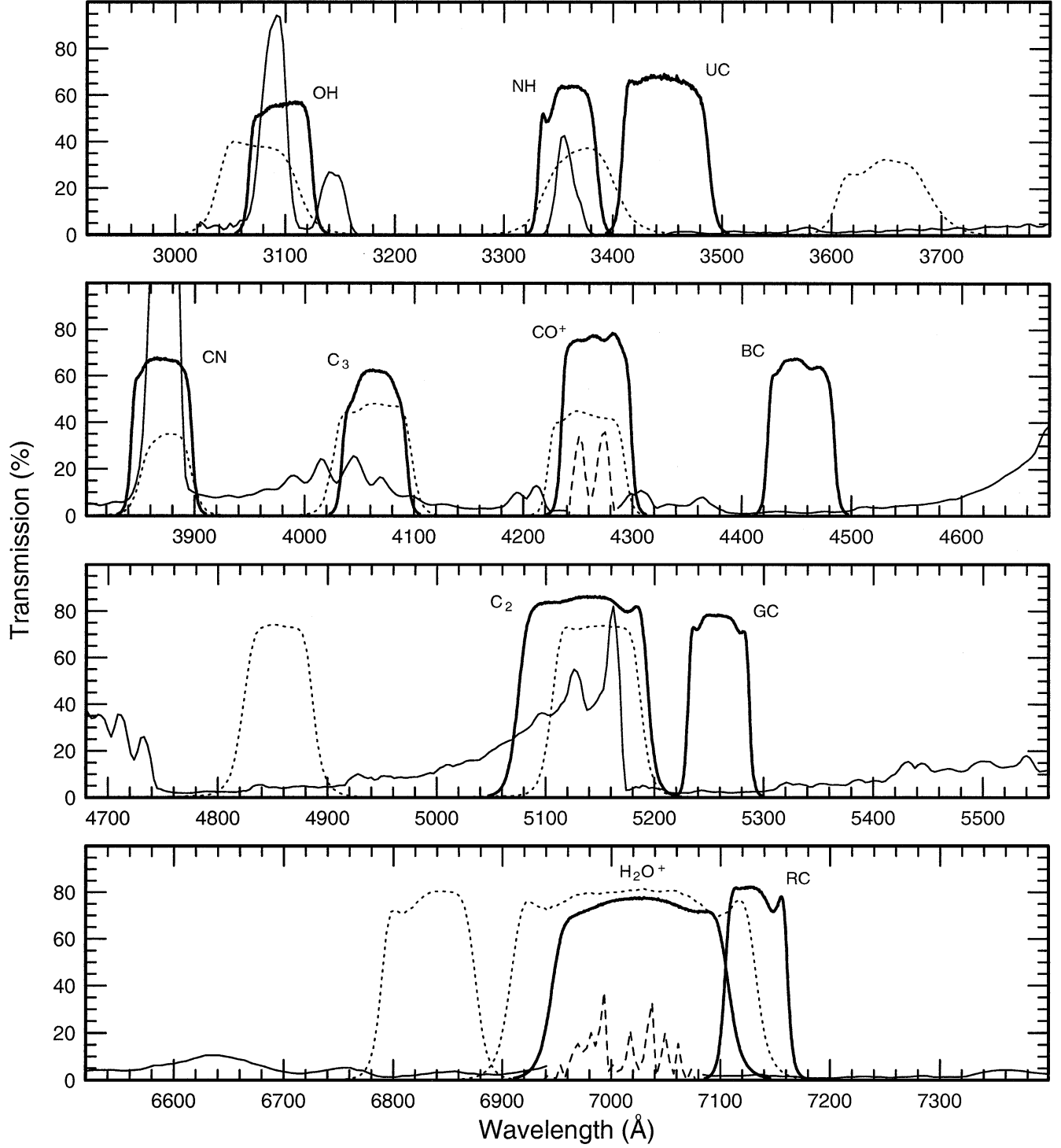


Figure 2.3: Transmission curves of the HB filters (thick lines) compared with the International Halley Watch (IHW) set from 1982 (dotted lines). Measured comet spectra are overplotted to indicate the positions of key emission features. The upper three panels show a spectrum of comet 122P/de Vico (resolution ~ 12 Å), while the lower panel displays a spectrum of comet 8P/Tuttle (resolution ~ 40 Å) (Farnham et al., 2000).

2.2 UVES and CRIRES⁺/ESO VLT

Among the comets presented in this work, C/2017 K2 was also observed with the Very Large Telescope (VLT) at Paranal Observatory. Located in the Chilean desert, Paranal is regarded as one of the world’s finest astronomical sites, offering extremely dry conditions and roughly 330 clear nights per year. The observatory hosts four 8.2 m Unit Telescopes (UTs), Antu, Kueyen, Melipal, and Yepun, together with four movable 1.8 m Auxiliary Telescopes.

In parallel with the long-term monitoring of C/2017 K2 carried out with the TRAPPIST telescopes, we also conducted complementary high-resolution spectroscopic observations using two instruments at the ESO VLT. To investigate the comet’s optical composition and its evolution on the approach to perihelion, we obtained a dedicated series of observations with UVES mounted on the Unit 2 telescope (UT2). In addition, near-infrared measurements were acquired with CRIRES⁺ on Unit 3 (UT3) over three nights, obtained simultaneously with the UVES campaign. Together, these datasets provide a detailed and multiwavelength view of the activity and compositional evolution of C/2017 K2.

2.2.1 UVES

UVES² (the Ultraviolet–Visual Echelle Spectrograph) is the high-resolution optical spectrograph installed on the UT2 Kueyen telescope of the ESO VLT at Paranal (Dekker et al., 2000). This cross-dispersed echelle instrument delivers high efficiency across a broad spectral range, from the atmospheric cutoff near 3000 Å up to the long-wavelength limit of the CCD detectors at about 11000 Å. UVES achieves two-pixel resolving powers of up to 80 000 in the Blue arm and 110 000 in the Red arm. The system is engineered for high mechanical stability, ensuring precise and repeatable wavelength calibration. The Blue arm uses a 2048×4096 pixel CCD (typically windowed to 2048×3000), while the Red arm employs a mosaic of two 4096×2048 CCDs separated by approximately 1 mm. A set of standard instrument configurations is available to support efficient preparation and calibration of observations. The specific UVES settings adopted for the observations presented in this work are detailed in Chapter 3. Comprehensive information on all standard UVES configurations is provided in the instrument user manual, accessible on the ESO website³.

2.2.2 CRIRES⁺

The CRIogenic InfraRed Echelle Spectrograph (CRIRES) was a highly successful, high-resolution near-infrared (NIR) spectrograph that operated on the Very Large Telescope Unit Telescope 1 (UT1) from 2006 to 2014 (Kaeufl et al., 2004). Its primary limitation was a very narrow simultaneous wavelength coverage ($\sim 15 \mu\text{m}$), which significantly reduced observing efficiency for modern science programs demanding broad spectral sampling. This issue was comprehensively addressed through a major upgrade project, transforming it into the CRIRES⁺⁴ cross-dispersed spectrograph. Commissioned and offered to the community from October 2021, CRIRES⁺ is now installed on Unit Telescope 3 (UT3), covering the wavelength range from 0.95 to $5.3 \mu\text{m}$ and maintaining a high resolving power ($R \geq 100,000$) (Dorn et al., 2023). The core upgrade involved converting the instrument to a cross-dispersed system, which increased the instantaneous spectral coverage by up to a factor of ten, alongside the implementation of new

²<https://www.eso.org/public/teles-instr/paranal-observatory/vlt/vlt-instr/uves/>

³<https://www.eso.org/sci/facilities/paranal/instruments/uves/doc.html>

⁴<https://www.eso.org/public/teles-instr/paranal-observatory/vlt/vlt-instr/crires+/>

detectors and dedicated spectropolarimetric and calibration units. These improvements facilitate long-slit spectroscopy with efficient wavelength calibration, making CRIRES⁺ optimally suited for high-precision radial velocity measurements, exoplanet atmosphere studies, and detailed spectral characterization of faint sources.

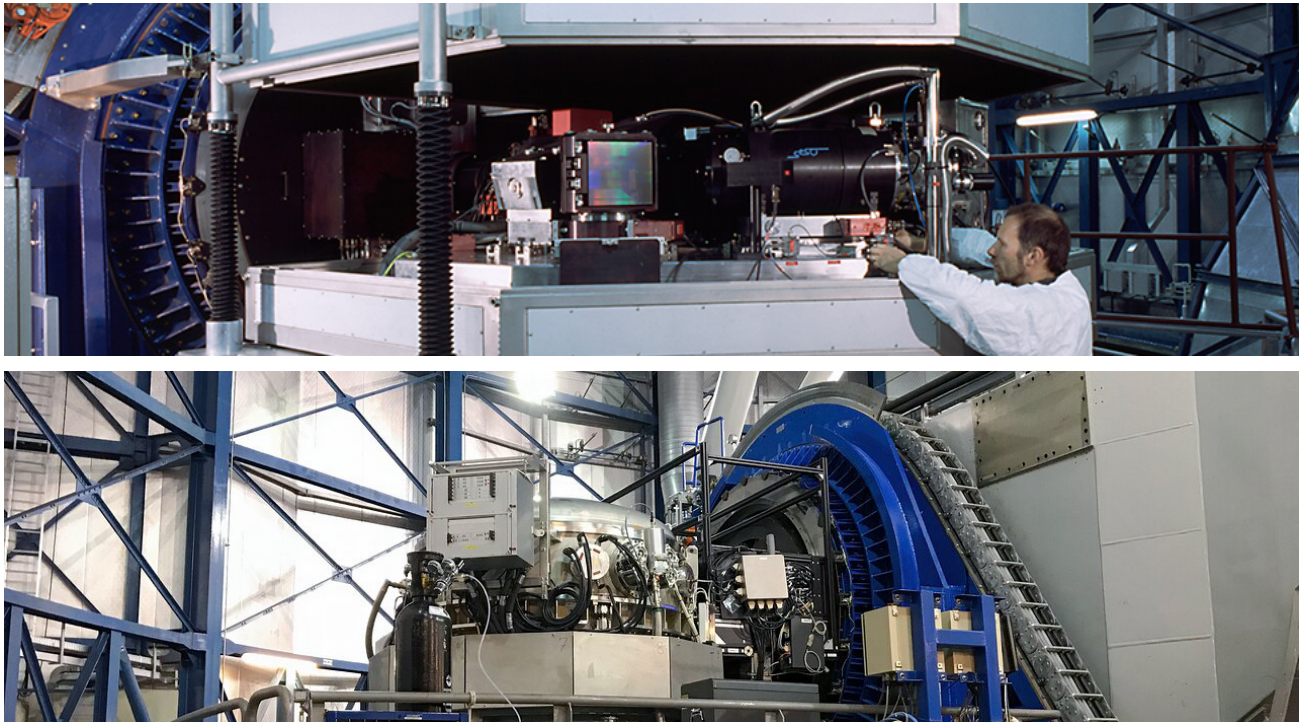


Figure 2.4: VLT High-Resolution Instrumentation. The figure shows (top) the UVES instrument on UT2 for high-resolution visible spectroscopy, and (bottom) the CRIRES⁺ instrument on UT3 for high-resolution near-infrared spectroscopy. Credit ESO.

2.3 TRAPPIST comet survey (2022–2026)

Between 2022 and 2026, the TRAPPIST telescopes enabled an extensive monitoring program encompassing over 40 long-period comets (LPCs), several dozen Jupiter-family comets (JFCs), and the third interstellar comet, 3I/ATLAS. Figure 2.5 summarizes the number of nights and images collected during my thesis period for LPCs, which constitute the primary focus of this thesis.

The substantial allocation of observing time with TRAPPIST allowed us to follow the temporal evolution of cometary activity and composition for bright comets over several months along their orbits. Observations were acquired using both narrow-band and broad-band filters, providing a homogeneous data set suitable for deriving light curves, gas production rates, and dust proxies. On average, approximately ten bright comets were monitored per year, yielding a well-characterized sample of LPCs and JFCs to study the evolution of their activity and composition as they traverse the inner Solar System. In addition, TRAPPIST telescopes also captured data for fainter comets, providing complementary support for observations with larger facilities and enabling rapid follow-up in the event of sudden outbursts or fragmentation events. Details of the data reduction procedures are presented in the following section, while later chapters focus on the activity and composition of selected comets.

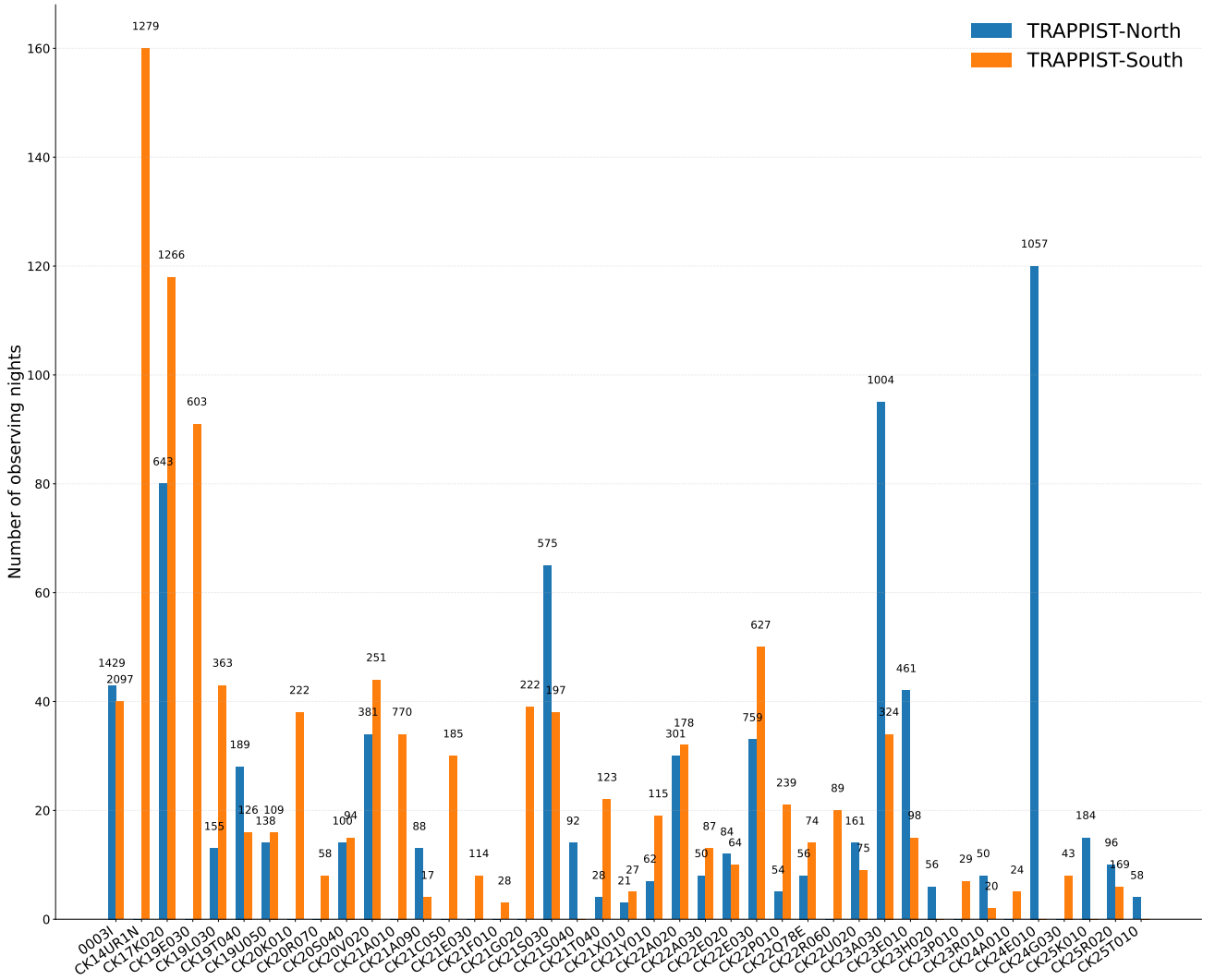


Figure 2.5: Number of Long-Period Comets Observed with the TRAPPIST Telescopes (2022–2026), with the Corresponding Numbers of Narrow-Band and Broad-Band Images per Comet. For more details, check Table B.1.

Over the four-year observing period, TRAPPIST-North accumulated 735 observing nights and acquired more than 8,332 images (broad- and narrow-band combined), whereas TRAPPIST-South reached 1,037 nights with over 10,406 images. This extensive coverage underscores the complementary monitoring capabilities and intensive effort of both telescopes in long-term cometary studies. The number of observations per comet varies considerably: for instance, C/2024 E1 was observed for 120 nights with TRAPPIST-North, resulting in more than 1,057 images, while C/2017 K2 was monitored across both telescopes for 202 nights during this period, yielding over 2,009 images. The interstellar comet 3I/ATLAS was observed on 80 nights, with more than 3,376 images acquired. Other comets, such as C/2021 X1 and C/2021 T4, were monitored for fewer than five nights due to limited visibility and brightness. Observations spanned a wide range of heliocentric distances, from 0.5 au for the closest active comets like C/2024 E1 to beyond 14 au for distant targets like C/2014 UN₂₇₁ and C/2017 K2. This diverse coverage highlights the complementary roles of TRAPPIST-North and TRAPPIST-South in enabling long-term, multi-aparition studies of cometary activity.

2.4 Photometric data reduction

2.4.1 TRAPPIST

We processed all TRAPPIST comet images following standard CCD reduction procedures, using custom routines built around the Image Reduction and Analysis Facility (IRAF; [Tody, 1986, 1993](#)). The reduction sequence includes correction for bias, dark current, and flat-field variations. The bias level represents the electronic offset added to each CCD pixel during readout; it is removed using zero-second bias frames that preserve pixel-to-pixel structure introduced by readout noise. Dark frames, obtained with the same exposure time and detector temperature as the science images, account for the thermally generated signal inherent to the CCD. Flat-field frames, taken on the evening or morning sky, are used to correct for non-uniformities in the optical path, most notably vignetting and the shadows of out-of-focus dust grains. To minimise noise and avoid frame-to-frame variations (e.g., the appearance of new dust specks), we combine calibration frames over 10 to 15 images (for each night) using the median to produce master bias, dark, and flat fields. Examples of TRAPPIST calibration frames are shown in [Figure 2.6](#).

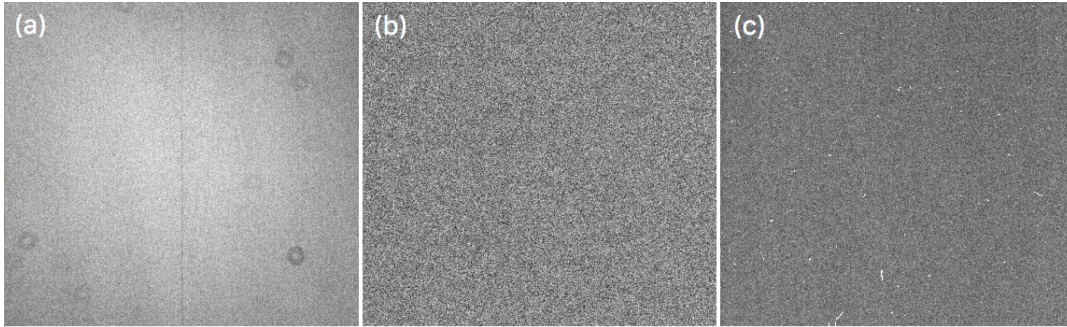


Figure 2.6: Examples of TRAPPIST calibration images: (a) Flatfield, (b) Bias, and (c) Dark.

The initial reduction step consists of subtracting the master bias and master dark from each raw comet frame, followed by division by the appropriately normalised master flat for the corresponding filter. This produces images corrected for instrumental signatures. [Figure 2.7](#) illustrates two Rc images of comet 398P/Boattini before and after basic reduction.

The subsequent step is the removal of the sky background, which primarily arises from atmospheric scattering and, depending on the lunar phase, moonlight. For extended sources such as comets, careful treatment of the sky is essential, particularly when the coma spans a large fraction of the field of view. Thanks to the wide field ($22' \times 22'$) of TRAPPIST, it was always possible to identify regions in each image free of cometary emission. After determining the photocentre of the comet, we select the nearest uncontaminated area, compute its median sky value, and subtract this constant level from the entire frame.

Radial brightness profiles are then extracted from both gas and dust filters. Whenever possible, continuum (dust) images were obtained during the same night as the gas images to ensure identical atmospheric and instrumental conditions. Among the available dust filters, the BC filter was preferred for dust subtraction due to its minimal contamination by gas emissions. The dust radial profile is scaled by a factor f_c , which depends on the degree of gas contamination in each filter, and subtracted from the gas profiles. The C_3 and C_2 filters are the most affected by dust contamination, whereas OH, NH, and CN are only weakly contaminated.

To convert pixel values (in ADU s^{-1}) into physical flux units ($\text{erg cm}^{-2} \text{s}^{-1}$), we followed the calibration procedure described by [Farnham et al. \(2000\)](#), based on observations of standard



Figure 2.7: Rc image of comet 3I/ATLAS before (left) and after (right) the basic reduction.

stars with well-characterised magnitudes and fluxes in the cometary filter bandpasses. These observations provide the coefficients required to transform measured count rates into absolute fluxes per square arcsecond. The calibrated flux F_c is computed as:

$$F_c = F_0 F 10^{0.4(K \cdot am - 25 + ZP)} \quad (2.1)$$

where am is the airmass, K the extinction coefficient, ZP the zero point for a star of magnitude zero in the corresponding filter, and F_0 the reference flux of a zero-magnitude star in units of $\text{erg cm}^{-2} \text{s}^{-1}$. The quantity F denotes the measured flux in $\text{ADU arcsec}^{-2} \text{s}^{-1}$, and F_c the resulting calibrated flux. Table 2.3 summarises the calibration parameters for each filter. Standard stars from Farnham et al. (2000) were observed regularly to update the zero points.

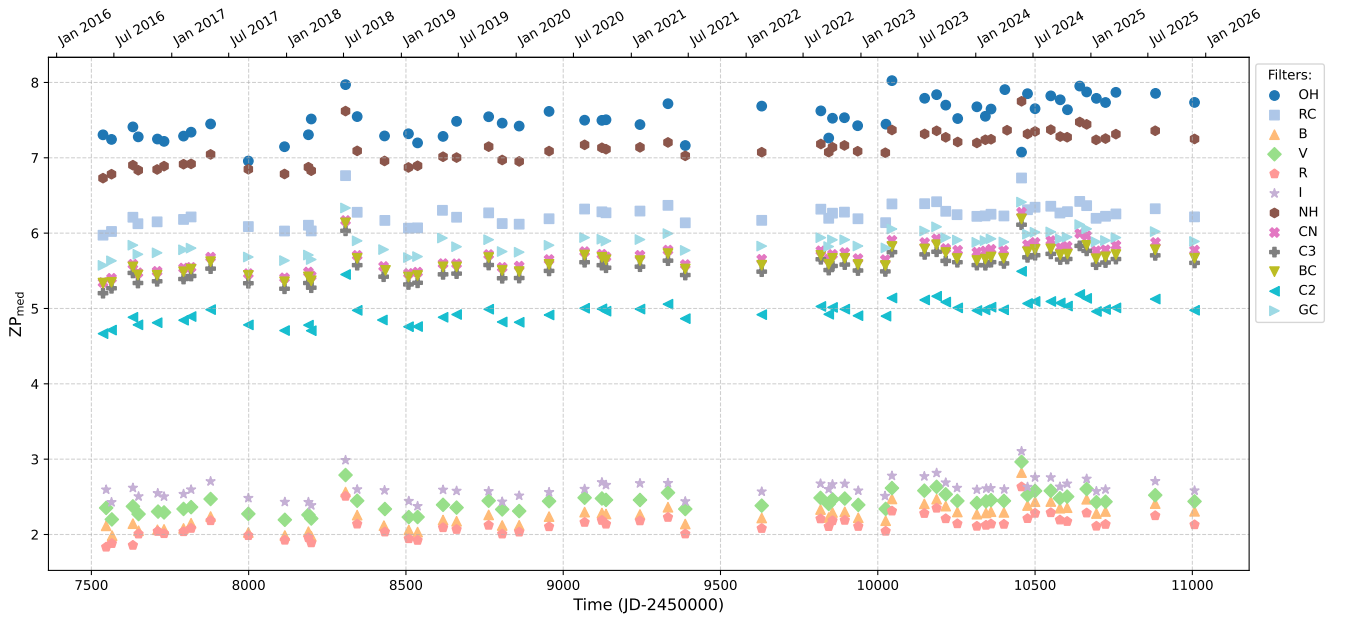


Figure 2.8: Evolution of zero points of broad- and narrow-band filters equipped with TN between 2016 and 2026.

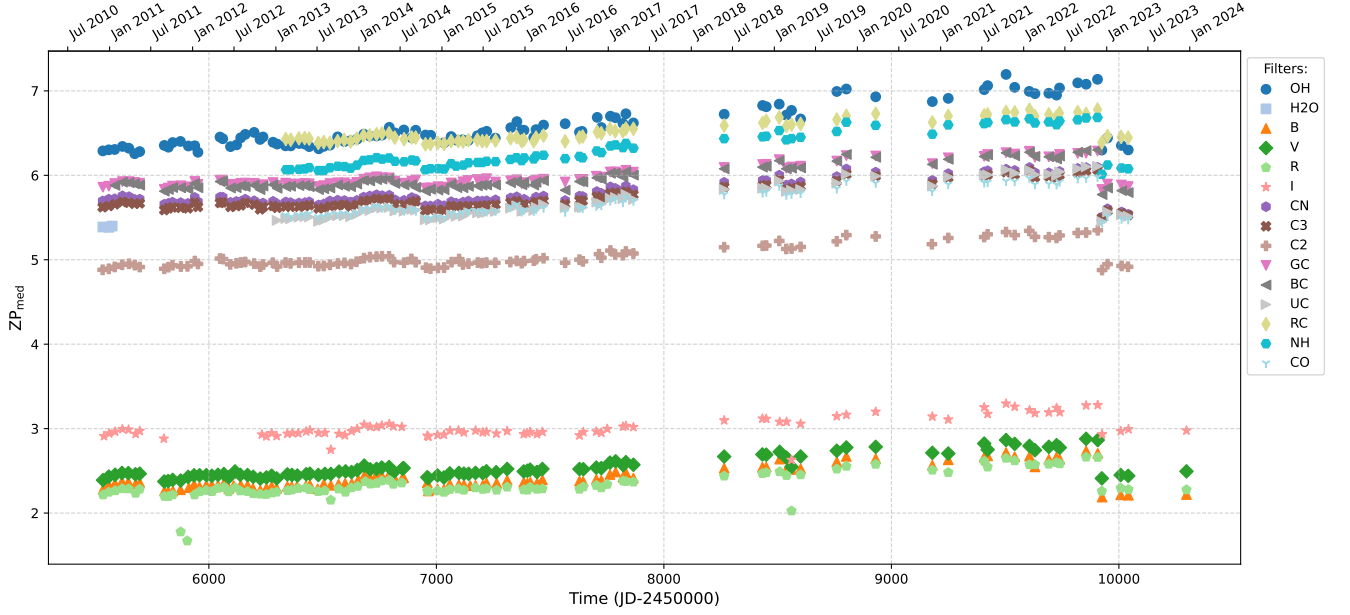


Figure 2.9: Evolution of zero points of broad- and narrow-band filters equipped with TS between 2011 and 2026.

Table 2.3: Calibration coefficients for the narrow-band comet filters from [Farnham et al. \(2000\)](#).

Species	$F_{0,XX}$ ($\times 10^{-9}$)	$m_{\odot,XX}$	$\gamma_{XX/XX}$	$\gamma'_{XX/XX}$	K
OH	10.56	1.791	1.698×10^{-2}	0.98	1.60
NH	8.42	1.188	1.907×10^{-2}	0.99	0.65
CN	8.60	1.031	1.812×10^{-2}	0.99	0.36
C ₃	8.16	0.497	3.352×10^{-3}	0.19	0.29
C ₂	3.88	-0.423	5.433×10^{-3}	0.90	0.15
BC	6.21	0.000	—	—	0.25
GC	3.61	-0.507	—	—	0.14
RC	1.31	-1.276	—	—	0.05
B	6.40	0.000	—	—	0.25
V	3.67	-0.649	—	—	0.14
Rc	1.92	-1.019	—	—	0.098
Ic	0.94	-1.375	—	—	0.043

$F_{0,XX}$ denotes the zero-magnitude stellar flux ($\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$), $m_{\odot,XX}$ is the corresponding solar color index, and $\gamma'_{XX/XX}$ is the fraction of the emission band transmitted through the filter. In contrast, $\gamma_{XX/XX}$ is the normalized value, accounting for filter width and throughput. K is the atmospheric extinction coefficient.

2.4.2 The Haser Model

A physical model of the coma is required to convert radial brightness profiles into gas production rates. Over the past century, various approaches have been developed to describe the spatial distribution of molecules in cometary atmospheres, ranging from simple analytical formulations to more sophisticated and physically motivated frameworks. The earliest description

was the fountain model (Eddington, 1910), in which the comet is treated as a point-like source emitting gas isotropically, leading to a density profile that decreases with the inverse square of the nucleocentric distance. This model was later found to be inadequate, as many of the species detected in the optical spectra of comets (e.g., NH, CN, C₂) are not primary volatiles but rather the products of photodissociation of more complex parent molecules.

Motivated by this understanding, (Haser, 1957; Haser et al., 2020) introduced a new formalism in which parent molecules released from the nucleus undergo direct photodissociation to produce daughter species in a spherically symmetric coma, with both populations expanding radially at constant velocity. Although highly simplified and not fully representative of the physical processes at play, the Haser model has remained the most widely used method for deriving cometary production rates because of its analytical tractability.

An improvement came later with the vectorial model proposed by Festou (1981), which accounts for the excess velocity imparted to daughter molecules during photodissociation and allows them to be ejected in any direction. While more realistic, neither the fountain, Haser, nor vectorial models could reproduce certain features observed in high-quality data, such as the pronounced flattening of C₂ radial profiles in the inner coma of comet 1P/Halley (O’Dell et al., 1988b; Fink et al., 1991). This led to the development of extended three-generation Haser-like models (e.g. O’Dell et al., 1988b), which introduce an additional production step and can better match such observations.

However, increasing model complexity inevitably introduces additional free parameters, many of which are poorly constrained. These uncertainties can significantly affect the reliability of the derived production rates. For this reason, despite its limitations, the classical Haser model continues to serve as a practical and consistent framework for the analysis of narrow-band cometary photometry.

In this work, we adopted the Haser model (Haser, 1957; Haser et al., 2020) to derive the gas production rates. Although it does not fully capture the physical complexity of cometary comae, it has been widely employed in comet studies for more than six decades, enabling straightforward comparison with results from other observations. In addition, the model involves only three free parameters, which makes it particularly convenient for consistent analysis. To determine the production rates of the various daughter species, we model the observed column-density profiles using the classical Haser formalism. This model, despite its simplicity, provides an effective first-order description of the cometary coma under a set of idealized assumptions. The nucleus is treated as a spherical body of radius r_n , with activity driven solely by solar irradiation. Gas molecules are released isotropically from the surface and expand radially at a constant velocity v_0 .

We derive the steady-state radial number density $n_p(r)$ of parent molecules for the classical Haser model under the usual simplifying assumptions:

- spherical symmetry (isotropic outflow from the nucleus),
- steady state (no explicit time dependence of the coma on the timescale considered),
- constant radial expansion speed v ,
- single-step photodissociation of parents with lifetime τ_p .

The easiest volume to consider in a spherically symmetric system is a thin spherical shell. Its volume is:

$$dV = 4\pi r^2 dr$$

The number of parent molecules contained in this shell is

$$dN = 4\pi r^2 n_p(r) dr.$$

In steady state, the amount of material inside the shell does not change: ($\frac{d(dN)}{dt} = 0$); the balance is between the net flux through the shell and the loss by photodissociation. If the gas is flowing radially outward with speed v , and there are $n_p(r)$ particles per unit volume at radius r , then every second a slice of thickness $v dt$ moves across any surface. In one second ($dt = 1$), the particles in a layer of thickness v cross the surface. Thus, the number of particles crossing per unit area per unit time (particles $\text{m}^{-2} \text{s}^{-1}$) is:

$$\Phi(r) = n_p(r) v.$$

A sphere of radius r has surface area:

$$A(r) = 4\pi r^2.$$

If $\Phi(r)$ particles cross each square meter of that sphere every second, then the total number crossing the whole sphere per second is

$$F(r) = \Phi(r) A(r) = \Phi(r) 4\pi r^2 = 4\pi r^2 n_p(r) v.$$

- $F(r)$: Inflow
- $F(r+dr)$: Outflow (outer boundary)

The net flow out of the spherical surface is $F(r+dr) - F(r) \approx \frac{d}{dr}(4\pi r^2 v n_p(r)) dr$. The loss of particles inside the shell due to photodissociation is:

$$\text{loss} = \frac{dN}{\tau_p} = 4\pi r^2 n_p(r) \frac{dr}{\tau_p},$$

because the destruction rate per particle is $1/\tau_p$. In steady state, the amount of material inside the shell does not change: ($\frac{d(dN)}{dt} = 0$), This immediately leads to:

$$(\text{net inflow}) + (\text{loss}) = 0,$$

Therefore, gives

$$\frac{d}{dr}(4\pi r^2 v n_p(r)) dr + 4\pi r^2 n_p(r) \frac{dr}{\tau_p} = 0.$$

Divide through by $4\pi dr$ and rearrange to obtain the continuity equation with a sink term:

$$\frac{1}{r^2} \frac{d}{dr}(r^2 v n_p(r)) = -\frac{n_p(r)}{\tau_p}. \quad (2.2)$$

Assuming v is constant allows simplification. Multiply Eq. (2.2) by r^2 and divide by v :

$$\frac{d}{dr}(r^2 n_p(r)) = -\frac{r^2}{v\tau_p} n_p(r).$$

Introduce the parent scale length.

$$L_p \equiv v \tau_p,$$

so that $1/(v\tau_p) = 1/L_p$. Defining $u(r) \equiv r^2 n_p(r)$, the previous expression becomes the simple first-order:

$$\frac{du}{u} = -\frac{dr}{L_p}.$$

Integrating gives

$$\ln(u) = -\frac{r}{L_p} + C,$$

$$u(r) = C' e^{-r/L_p},$$

or equivalently

$$n_p(r) = \frac{C'}{r^2} e^{-r/L_p}, \quad (2.3)$$

where C' is an integration constant to be determined from the total production rate.

The production rate Q (molecules s^{-1}) equals the total number of parent molecules crossing any spherical surface per unit time. Using $F(r) = 4\pi r^2 n_p(r) v$ and substituting Eq. (2.3) yields

$$Q = 4\pi r^2 \left(\frac{C'}{r^2} e^{-r/L_p} \right) v = 4\pi v C' e^{-r/L_p}, \quad (2.4)$$

The general solution of the continuity equation for a parent species in the classical Haser model is

$$n_p(r) = \frac{C'}{r^2} \exp\left(-\frac{r}{L_p}\right), \quad (2.5)$$

where C' is an integration constant that must be determined from the physical definition of the production rate Q .

To understand how this normalization is obtained, we consider the radial flux of parent molecules. If the gas expands radially at constant speed v , the flux crossing a spherical surface of radius r is

$$F(r) = 4\pi r^2 n_p(r) v. \quad (2.6)$$

Because Q is independent of r , the factor e^{-r/L_p} must be compensated by C' evaluated at the appropriate inner boundary. Taking the limit $r \rightarrow 0$ (or equivalently matching the definition of Q at the source) sets $e^{-r/L_p} \rightarrow 1$ and hence

$$C' = \frac{Q}{4\pi v},$$

Substituting back into Eq. (2.3) yields the standard Haser parent density:

$$\boxed{n_p(r) = \frac{Q}{4\pi v r^2} \exp(-r/L_p)} \quad (2.7)$$

Equation (2.7) expresses two intuitive effects: the $1/r^2$ geometric dilution of an isotropic outflow, and the exponential attenuation of parent number density due to photodissociation with e-folding length L_p . This result is the starting point for constructing the daughter density in the Haser formalism and for computing column densities by integrating $n_p(r)$ along the line of sight.

Parent molecules undergo single-step photodissociation to form daughter species, with each daughter associated with one parent. The photodestruction of a species follows the exponential decay law:

$$n = n_0 e^{-t/\tau_p},$$

where n_0 is the initial number of molecules at $t = 0$, and τ_p is the parent lifetime.

The total gas production rate Q_n must equal the molecular flux through a spherical surface surrounding the nucleus. For a spherically symmetric outflow, the flux at distance r is

$$\phi(r) = v_p n_p(r) 4\pi r^2, \quad (2.8)$$

But because of photodestruction, this flux is not conserved and decreases with distance according to

$$\phi(r) = \phi(0) e^{-r/L_p}. \quad (2.9)$$

Equating Eqs. (2.8) and (2.9) yields the parent-molecule density distribution:

$$n_p(r) = \frac{Q_n}{4\pi r^2 v_p} e^{-t/\tau_p} = \frac{Q_n}{4\pi r^2 v_p} e^{-r/L_p},$$

where $L_p = v_p \tau_p$ is the parent scale length, which varies as r_h^2 with heliocentric distance.

The number of parent molecules at distance ρ from the nucleus follows

$$4\pi \rho^2 N_p(\rho) = 4\pi r_n^2 N_p(r_n) e^{-(\rho-r_n)/L_p}. \quad (2.10)$$

Daughter molecules produced through parent photodissociation are themselves destroyed with scale length $L_d = v_d \tau_d$. Differentiating Eq. (2.10) with respect to ρ and accounting for daughter loss yields the flux in the interval $[\rho, \rho + d\rho]$:

$$d\phi_p(r) = 4\pi r_n^2 N_p(r_n) \frac{1}{L_p} e^{-(\rho-r_n)/L_p} e^{-(r-\rho)/L_d}. \quad (2.11)$$

Integrating over ρ and using

$$N_d(r) = v_d n_d(r), \quad Q_n = 4\pi r_n^2 N_p(r_n),$$

gives the daughter-molecule density:

$$n_d(r) = \frac{Q_n}{4\pi v_d r^2} \frac{L_d}{L_p - L_d} (e^{-r/L_p} - e^{-r/L_d}).$$

In general, the radial density profile in the Haser framework can be written as

$$n(r) = \frac{Q}{4\pi v r^2} \frac{\beta_0}{\beta_1 - \beta_0} (e^{-\beta_0 r} - e^{-\beta_1 r}), \quad (2.12)$$

with $\beta_0 = 1/L_p$ and $\beta_1 = 1/L_d$ for parent–daughter chains.

To compare with observations, Eq. (2.12) must be integrated along the line of sight to obtain the column density $N(r)$, which is directly related to the observed brightness profile. Two methods are commonly used:

Analytic integration : Following [Biver \(2011\)](#), the column density for parent molecules is

$$N(r) = \frac{2Q}{4\pi v} \frac{1}{r} \int_{\beta_1 r}^{\infty} K_0(x) dx,$$

and for daughters:

$$N(r) = \frac{2Q}{4\pi v} \frac{\beta_0}{\beta_1 - \beta_0} \frac{1}{r} \int_{\beta_1 r}^{\beta_0 r} K_0(x) dx,$$

where K_0 is the modified Bessel function of the second kind.

Numerical integration : Alternatively, $N(r)$ can be computed numerically as

$$N(r) = \frac{Q}{4\pi v} \int_{-z}^z e(r) dz,$$

with emissivity

$$e(r) = \frac{1}{r^2} \frac{\beta_0}{\beta_1 - \beta_0} (e^{-\beta_1 r} - e^{-\beta_0 r}).$$

The resulting column density is converted into observed flux through

$$N(r) = \frac{4\pi}{g} \frac{F}{\Omega},$$

where g is the fluorescence efficiency (g-factor), expressed as

$$g_\lambda = \lambda^2 f_\lambda F_\lambda \frac{\pi e^2}{m_e c^2} \frac{A_{ik}}{\sum_k A_{ik}}.$$

The solar flux per unit wavelength at 1 au is denoted by F_λ , and f_λ represents the oscillator strength. The Einstein coefficients A_{ik} quantify the transition probabilities between the upper level i and the lower level k . The ratio $\frac{A_{ik}}{\sum_k A_{ik}}$ expresses the branching fraction of photons emitted in the transition from level i to level k . The constants e and m_e correspond to the electron charge and mass, respectively.

The fluorescence efficiencies adopted in this work for the various gas filters are taken from Schleicher’s database⁵. For C₂, a single g-factor is used for the $\Delta v = 0$ band sequence near 5160 Å, scaled as r_h^{-2} ([A’Hearn et al., 1984](#)). The C₃ fluorescence efficiency, also scaled as r_h^{-2} , corresponds to the band complex peaking near 4030 Å and spanning 3300–4400 Å, following [A’Hearn \(1982\)](#). The CN and NH g-factors depend on heliocentric distance and velocity due to changes in the population of rotational levels and are taken from [Schleicher \(2010\)](#) and [Meier et al. \(1998\)](#), respectively. The OH (0–0) band g-factor at 3090 Å varies with heliocentric velocity and depends on the quenching of the lambda-doublet ground state; it is scaled as r_h^{-2} according to [Schleicher and A’Hearn \(1988a\)](#).

To ensure consistency with observational data, the photodissociation lifetimes of parent and daughter species are commonly replaced by *effective scale lengths*. These effective scale lengths are empirically adjusted to reproduce the observed radial brightness profiles as closely as possible. In principle, the most rigorous method would be to determine effective scale lengths for each observation and subsequently use them to compute the production rates. Such an approach was adopted by [Rauer et al. \(2003\)](#) in their study of comet Hale-Bopp. In practice, however, this

⁵Comet fluorescence efficiency: <http://asteroid.lowell.edu/comet/gfactor.html>

procedure is rarely achievable. Reliable derivation of effective scale lengths requires high signal-to-noise ratios and a well-sampled coma over a broad range of projected distances from the nucleus. This necessitates instruments with both adequate spatial resolution and a sufficiently large field of view. These requirements are challenging to fulfill for faint comets, for which the outer regions of the coma are often poorly constrained, making determining daughter scale lengths especially challenging. In addition, characterizing the dependence of scale lengths on heliocentric distance introduces further uncertainties. As a result, deriving scale lengths for every individual observation is generally impractical. Consequently, several authors have sought to determine representative Haser scale lengths and their empirical evolution with heliocentric distance, allowing for a consistent application across large observational datasets.

Table 2.4 summarizes the scale lengths, lifetimes, and fluorescence efficiencies adopted at 1 au from Schleicher’s database, all scaled by r_h^{-2} . Because we assume a constant radial outflow velocity of 1 km s^{-1} , the scale lengths correspond directly to molecular lifetimes. We follow the parameter set of A’Hearn et al. (1995b) to ensure consistency with previous TRAPPIST analyses and to facilitate comparison with their large-sample production-rate ratios. Figure 2.10 shows an example of images with NB filters of comet 3I/ATLAS and its radial profile after dust removal, together with the Haser-model fit.

Table 2.4: Scale lengths (scaled by r_h^2), lifetimes, and fluorescence efficiencies (g-factor, scaled by r_h^{-2}) of the main molecules at 1 au.

Molecule	Parent (km)	Daughter (km)	Lifetime (s)	g-factor ($\text{erg s}^{-1} \text{ mol}^{-1}$)
OH (0,0)	2.4×10^4	1.6×10^5	1.6×10^5	1.49×10^{-15}
NH (0,0)	5.0×10^4	1.5×10^5	1.3×10^4	6.27×10^{-14}
CN ($\Delta v = 0$)	1.3×10^4	2.1×10^5	2.1×10^5	2.62×10^{-13}
C ₃ (4050 Å)	2.8×10^3	2.7×10^5	2.7×10^5	1.00×10^{-12}
C ₂ ($\Delta v = 0$)	2.2×10^4	6.6×10^4	6.6×10^4	4.50×10^{-13}

The Haser model was subsequently fitted to the observational data. As the comets analyzed in this work were observed over a wide range of heliocentric and geocentric distances, the model adjustment was performed at a fixed physical distance of approximately 10 000 km from the nucleus. At this nucleocentric distance, the signal-to-noise ratio generally remains high, while the effects of atmospheric seeing, mainly confined to the innermost pixels, and dust contamination are significantly reduced.

Rather than deriving production rates from flux measurements within a single aperture, the model was adjusted directly to the radial brightness profiles. This approach minimizes aperture-dependent effects, such as the systematic variation of derived production rates with aperture size, which are commonly encountered when applying the Haser model. In practice, a synthetic brightness profile was generated using the Haser model and an initial estimate of the production rate. The mean flux was then measured over a radial range between 5 000 and 15 000 km from the nucleus. The same radial interval was applied to the observed brightness profiles, and the comparison between the modeled and observed mean fluxes was used to determine the final production rate.

Fig. 2.10 shows that the agreement between the observed radial profile and the Haser model is satisfactory. Nevertheless, such an agreement is not always achieved, depending on the comet and its heliocentric distance. This highlights the importance of adopting more realistic, effective Haser scale lengths when modeling cometary comae.

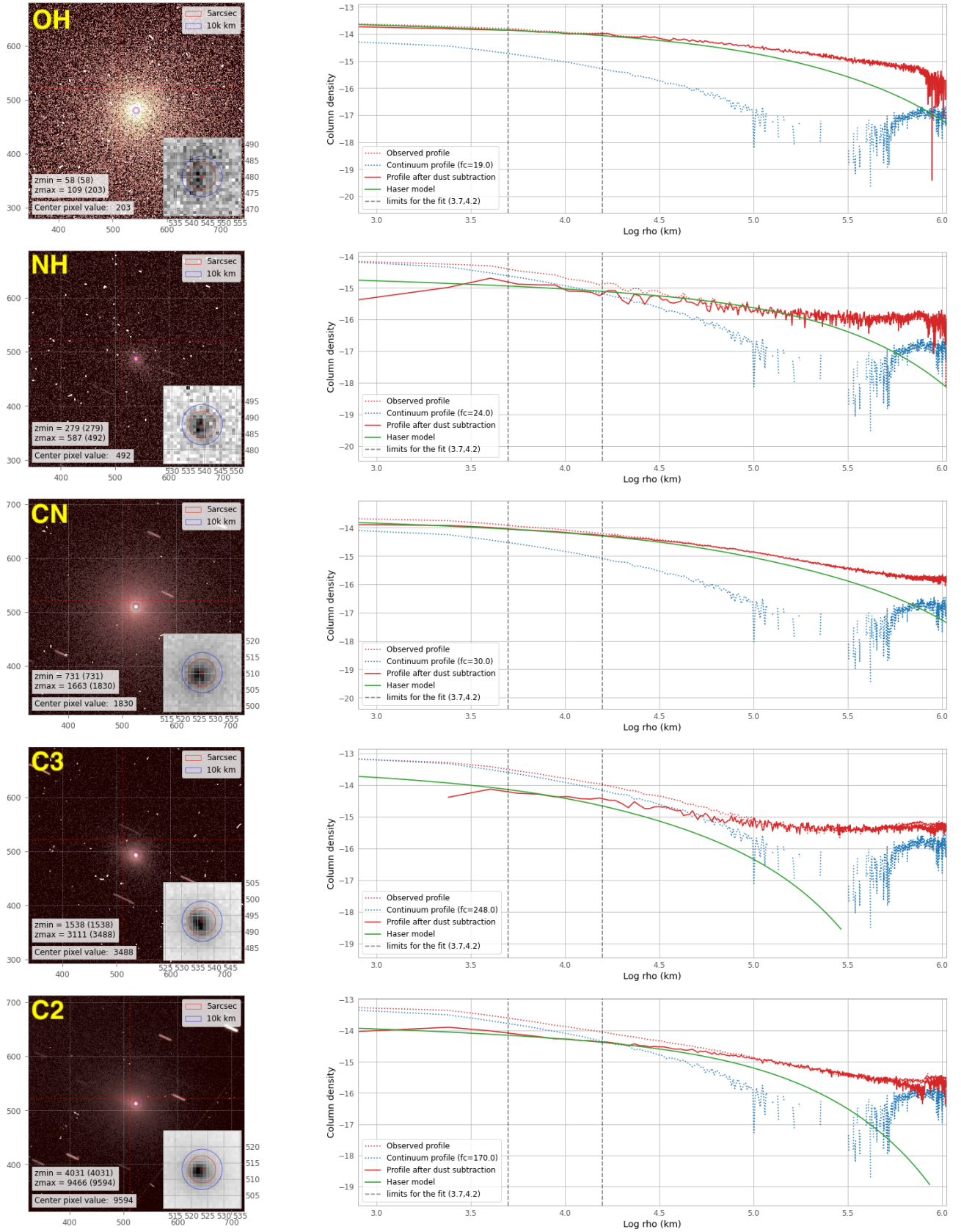


Figure 2.10: Reduced images of comet 3I/ATLAS and the corresponding column density for OH, NH, CN, C_3 , and C_2 . These images were taken on December 7, 2025, while the comet was 1.98 au from the Sun. We plotted the original radial profile (red dashed line), the continuum profile (blue dashed line), the radial profile obtained after dust subtraction (red line), and the fitted Haser model (green line).

2.4.3 The $Af\rho$ parameter, and dust color

To quantify the dust activity of the comets analysed in this work, we use the $A(\theta)f\rho$ parameter, first introduced by A'Hearn et al. (1984). This quantity is widely adopted as a proxy for the dust production and allows a direct comparison of dust activity among comets observed with different instruments and observing techniques. Under the assumptions of a steady-state isotropic coma, constant grain expansion velocity, and negligible grain fading, the dust surface brightness follows a $1/\rho$ radial dependence, making $A(\theta)f\rho$ theoretically independent of the aperture size.

The parameter $A(\theta)f\rho$ is defined as the product of three physical quantities: (i) the Bond albedo $A(\theta)$ at the solar phase angle θ , which represents the ratio between the reflected and incident solar flux; (ii) the filling factor f (illustrated with a gray color in Fig. 2.11), defined as the total geometric cross section of dust grains within the field of view divided by the surface of the aperture; and (iii) the radius ρ of the circular aperture projected at the comet. It can be expressed as

$$A(\theta)f\rho = \frac{(2\Delta r_h)^2}{\rho} \frac{F_{\text{com}}}{F_{\odot}}, \quad (2.13)$$

where r_h and Δ are the heliocentric and geocentric distances of the comet, respectively, F_{com} is the solar flux reflected by the dust grains within the aperture in a given filter bandpass, and $F_{\odot}$ is the solar flux at 1 au in the same spectral range⁶. The $A(\theta)f\rho$ parameter is expressed in centimeters.

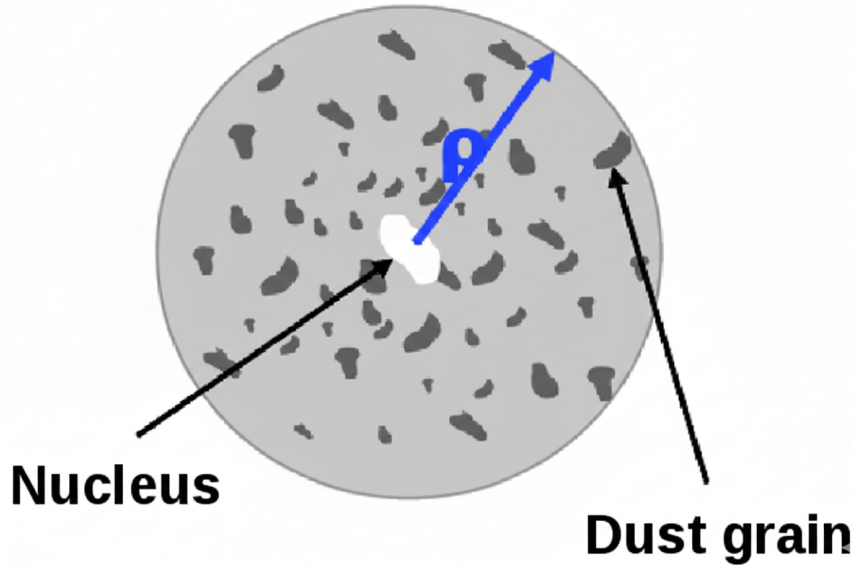


Figure 2.11: Illustration of the dust grains in the coma and the nucleus of a comet. The red features represent the grains in the coma with a radius ρ . Credit: Jorda (2010), adapted and modified by the author.

In this work, $A(\theta)f\rho$ values were derived from radial brightness profiles obtained in the dust continuum narrow-band filters (BC, GC, and RC), as well as in the broad-band R_c and I_c filters. As for the gas production rates, the dust activity was evaluated at a projected nucleocentric distance of approximately 10 000 km. Although $A(\theta)f\rho$ is expected to be independent of the nucleocentric distance in the ideal case, our observations indicate that the dust bright-

⁶The solar irradiance values corresponding to each bandpass used in this work are taken from : https://www.nlr.gov/grid/solar-resource/spectra-am1.5?utm_source=chatgpt.com

ness profiles often deviate from the canonical $1/\rho$ behavior, highlighting the limitations of the underlying assumptions.

The measured dust brightness is also affected by the dependence of the scattering efficiency on the solar phase angle. Cometary dust exhibits a strong enhancement in forward-scattering geometries and a weaker peak at small backscattering angles, leading to variations in $A(\theta)f\rho$ by up to a factor of a few over typical phase-angle ranges (Schleicher et al., 1998). To allow consistent comparisons between observations obtained at different phase angles, and between different comets, we correct the measured $A(\theta)f\rho$ values for phase-angle effects. Several phase functions have been proposed in the literature (e.g., Divine, 1981; Hanner and Newburn, 1989; Schleicher et al., 1998; Marcus, 2007). In this work, we adopt the composite dust phase function normalized at $\theta = 0^\circ$ (Figure 2.12), described by Schleicher (2010), which provides a good representation of cometary dust scattering over a wide range of phase angles.

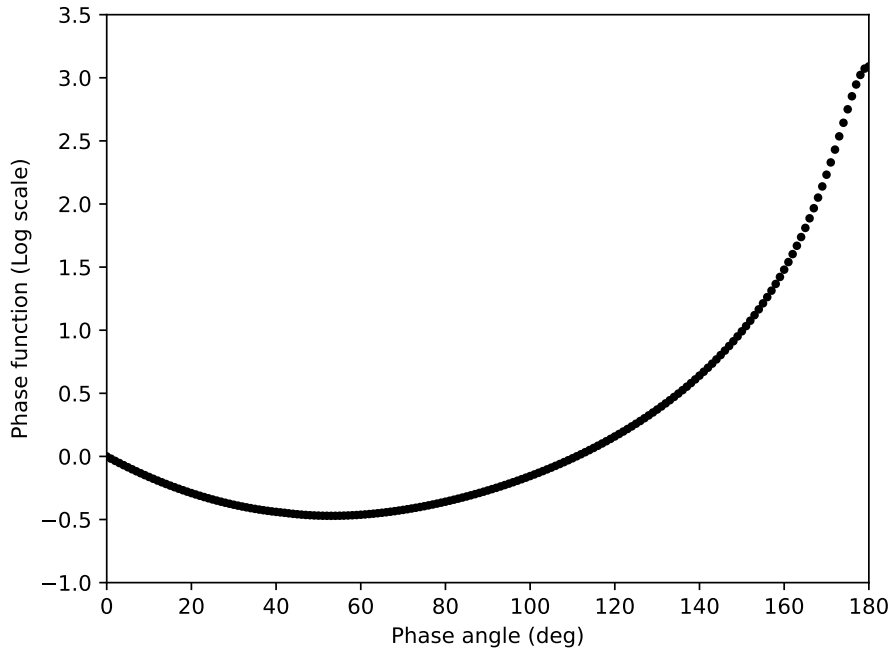


Figure 2.12: Phase function used to correct $A(\theta)f\rho$ for the phase-angle effect⁷

We derived the dust colors using the $A(0)f\rho$ values measured with narrow-band filters that are free from gas emission contamination. The normalized reflectivity gradient between two wavelengths, λ_1 and λ_2 , is defined as (A’Hearn et al., 1984; Jewitt and Meech, 1986):

$$S_v(\%/1000) = \frac{Af\rho_1 - Af\rho_2}{Af\rho_1 + Af\rho_2} \times \frac{2000}{\lambda_1 - \lambda_2} \quad (2.14)$$

where λ_1 and λ_2 correspond to the effective wavelengths of the filters: BC [4450 Å], GC [5260 Å], and RC [7128 Å].

The normalized reflectivity gradient is defined as the percentage increase in reflectance per 1000 Å. In this work, the dust color is primarily derived using the RC and BC continuum filters, as these bandpasses are minimally affected by gaseous emission features and therefore provide a reliable estimate of the dust spectral slope. In contrast, for comets exhibiting strong gas activity, the UC filter is significantly contaminated by molecular emissions, in particular by C_3 , and is thus not suitable for dust color determination (Farnham et al., 2000).

2.4.4 Coma image enhancement techniques

The brightness distribution of a cometary coma is generally dominated by a strong radial gradient, which can mask subtle morphological structures and make their identification challenging. As a result, valuable information related to the spatial organization of the coma is often concealed both in the innermost regions and in the faint outer parts. The analysis of coma morphology provides important insights into the physical properties of cometary nuclei, including rotation periods, the presence of localized active regions, and the degree of surface heterogeneity. Commonly observed morphological features include jets, fans, arcs, spirals, and global asymmetries.

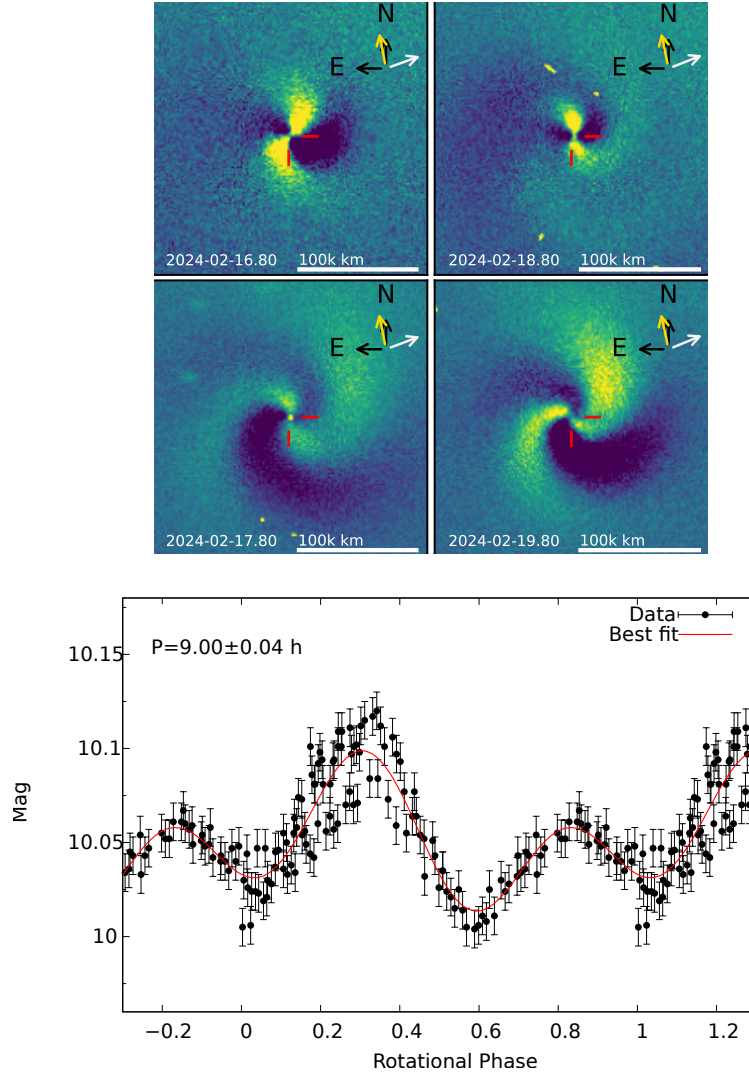


Figure 2.13: On the top, an example of comet 12P in the CN filter after subtraction of an azimuthal median profile. The yellow and white arrows are the anti-sunward and the negative of the target heliocentric velocity vector directions, respectively (Vander Donckt et al., 2025). On the bottom, an example of phased CN light curves for the nucleus rotation period of comet 46P (Moulane et al., 2023).

Although a detailed morphological analysis is not the primary objective of this thesis, TRAPPIST observations are well suited for such studies, thanks to their regular monitoring cadence, large field of view, and dedicated comet filters. As an illustration of the capabilities of TRAPPIST data, Fig.2.13 presents an enhanced CN image of comet 12P and a

phased CN light curve for the nucleus rotation period of comet 46P using TRAPPIST data. This example demonstrates how cometary activity patterns can be revealed using appropriate image-processing techniques.

Several methods exist to enhance low-contrast structures in comet images. In particular, rotational gradient filters implemented in the MaximDL software⁸ are effective in emphasizing near-nucleus features such as jets and inner-coma structures. Two main approaches are commonly used. The simple rotational subtraction method computes the difference between two copies of the image rotated by equal angles in opposite directions. The Larson–Sekanina filter (Schleicher and Farnham, 2004) combines rotated images and subtracts them from the original image, thereby enhancing azimuthal variations. In both cases, a constant offset is applied to ensure non-negative pixel values.

These techniques require accurate centering of the nucleus, which can be achieved either through centroid determination or manual adjustment. A variety of additional enhancement tools have been developed by the cometary science community. Martin et al. (2015) provides a web-based platform⁹ implementing several enhancement techniques, whose performance and limitations are discussed in detail by Samarasinha and Larson (2014). While these methods were tested on several TRAPPIST comet images (Opitom et al., 2015; Opatom et al., 2016; Moulane et al., 2018, 2023), the simple rotational filter was found to be the most suitable and was therefore retained for illustrative purposes.

⁸<https://diffractionlimited.com/product/maxim-dl/>

⁹<https://www.psi.edu/research/cometimen>

Chapter 3

A Detailed Study of the Activity and Composition of the Dynamically New Comet C/2017 K2 (PanSTARRS)

3.1 Scientific context and motivation

The sublimation of volatile species controls the onset and evolution of cometary activity. In the inner Solar System, water ice is the dominant driver of activity, becoming efficient only within approximately 3 au of the Sun. At larger heliocentric distances, activity must be sustained by more super-volatile species such as CO and/or CO₂, or by alternative mechanisms such as crystallization of amorphous ice or non-thermal processes (Jewitt et al., 2019). Studying comets over a wide range of heliocentric distances, therefore, provides a powerful means to disentangle the relative roles of different volatiles and to investigate the transition between various regimes of activity. Dynamically new comets (DNCs), originating from the Oort cloud and entering the inner Solar System for the first time, are particularly valuable targets because they are expected to retain relatively unprocessed surface material. Photometric and spectroscopic studies have shown that DNCs often display unusual activity patterns, including asymmetric light curves and strong activity at large heliocentric distances. These characteristics may reflect their pristine nature and the presence of abundant hypervolatile ices near the surface.

Comet C/2017 K2 (PanSTARRS), hereafter K2, is a dynamically new Oort cloud comet that represents an exceptional case of distant activity. It was discovered at a heliocentric distance of about 16.1 au (Wainscoat et al., 2017) and was later found to have been active as far as 23.8 au from the Sun (Jewitt et al., 2017; Meech et al., 2017). Sub-millimeter observations revealed a CO-rich coma (Yang et al., 2021), and the comet attracted significant interest as it brightened toward perihelion. Its extreme activity at large distances and its dynamical freshness make K2 the second-most distant discovery of an active comet, and an ideal laboratory for studying volatile-driven activity over an unprecedented heliocentric range.

The primary objective of this chapter is to present a comprehensive analysis of the long-term activity evolution and chemical composition of comet K2, based on photometric observations spanning nearly eight years, from 15.2 au pre-perihelion to 8.5 au post-perihelion (Table 3.2), and spectroscopic observations using two instruments at the ESO/VLT (Table 3.1). The results provide insight into the competition between different volatile species, the dust properties of the coma, and the compositional classification of this dynamically new comet (Hmiddouch et al., 2025).

Table 3.1: TRAPPIST observational circumstances and orbital elements of comet C/2017 K2. All orbital elements are taken from the NASA JPL/Horizons database.

Comet	i	T_j	Peri	T_p	r_h -range	Dates Start/End	Number of nights		Number of images	
	(°)		(au)	(UTC)	Pre/Post (au)		TN	TS	TN	TS
C/2017 K2 (PanSTARRS)	87.55	0.17	1.79	2022 Dec. 19	15.18 - 1.79 - 8.46	25.10.2017 - 20.04.2025	151	120	1323	881

Note: i: Inclination, T_j : Jupiter-Tisserand invariant, Peri: Perihelion distance, T_p : Time of perihelion passage. The format of the date is Day.Month.Year

3.2 Observations and data reduction

3.2.1 Long-term photometric monitoring with TRAPPIST

The long-term photometric monitoring of comet K2 was carried out using the TRAPPIST-North (TN) and TRAPPIST-South (TS) telescopes over an exceptionally extended time span. The first observations were obtained with TRAPPIST-North on October 25, 2017, when the comet was still at a heliocentric distance of 15.18 au and exhibited a faint visual magnitude of $V \sim 19.7$. At this early stage, only broad-band observations were feasible due to the low activity level of the comet. These early data provided a valuable baseline for characterising the onset of activity at large heliocentric distances.

As the comet approached the inner Solar System and became accessible from the southern hemisphere, the monitoring was extended using TRAPPIST-South. Observations with TS began on September 9, 2021, when the comet reached a heliocentric distance of $r_h = 5.4$ au and was sufficiently bright to allow the use of Hale-Bopp (HB) narrow-band cometary filters. From that point onward, the comet was observed on average three times per week, enabling a detailed temporal follow-up of its dust and gas activity. This intensive monitoring continued until October 24, 2022, when the comet became unobservable due to its proximity to the Sun in the sky. Following perihelion passage on December 19, 2022 ($r_h = 1.79$ au), the comet was successfully recovered on January 27, 2023, and subsequently monitored until May 3, 2023 ($r_h = 2.46$ au), as long as it remained sufficiently bright and well-positioned for observations. After this period, monitoring continued using broad-band filters only, extending until April 2025, when the comet had receded to a heliocentric distance of $r_h = 8.46$ au.

In total, the TRAPPIST monitoring campaign comprises approximately 2204 broad-band images and 174 narrow-band images obtained over 271 observing nights, spanning nearly eight years (see Table 3.1). The exposure times were adapted to the changing brightness of the comet, ranging from 30 to 240 s for the broad-band filters and from 300 to 1500 s for the narrow-band filters. This extensive and homogeneous data set constitutes one of the most complete long-term optical monitoring programs of a dynamically new comet at large heliocentric distances.

All images were reduced following standard procedures, including bias subtraction, dark current correction, and flat-fielding (see 2.4). The contribution of the sky background was carefully removed, and the images were flux-calibrated using observations of standard stars acquired regularly during the same observing periods. The calibration procedure follows the methodology described in previous TRAPPIST studies (e.g., [Opitom et al., 2015a](#); [Moulane et al., 2018](#)), ensuring consistency with earlier analyses. After determining the photocenter of the comet, median radial brightness profiles were extracted from both gas and dust images.

To correct for dust contamination in the gas emission profiles, images obtained with the BC continuum filter were used, as this filter is minimally affected by gas emissions compared to

other dust filters (Farnham et al., 2000). The fluxes measured in the OH, NH, CN, C₃, and C₂ filters were converted into column densities, and gas production rates were derived by fitting a Haser model to the observed radial profiles. Although the Haser model relies on simplifying assumptions, notably a spherically symmetric coma and a one-step photodissociation of parent molecules into daughter species, it remains widely used in optical cometary studies (sec. 2.4.2). Its main advantage lies in facilitating direct comparisons between different data sets and between different comets.

The model fitting was performed at a characteristic nucleocentric distance of approximately 10 000 km, where the influence of the seeing and point-spread-function effects near the optocenter is reduced, while the signal-to-noise ratio remains sufficiently high. At larger nucleocentric distances, the signal generally decreases, particularly for the OH filter, which is intrinsically faint. Fluorescence efficiencies (g-factors) used to convert column densities into production rates were adopted from the compilation provided by D. Schleicher. The C₂ and C₃ g-factors were taken from A’Hearn (1982), while those for CN and NH, which depend on heliocentric distance and radial velocity, were adopted from Schleicher (2010) and Meier et al. (1998), respectively. For the OH (0–0) band near 3090 Å, the g-factor variation with heliocentric distance and velocity was taken into account following Schleicher and A’Hearn (1988b). Parent and daughter scale lengths were adopted from A’Hearn et al. (1995b) and scaled with r_h^2 , in order to maintain consistency with previous TRAPPIST analyses and to facilitate comparisons with the large cometary survey presented in that work.

The evolution of the dust activity was investigated using broad-band observations acquired with the *B*, *V*, *R_c*, and *I_c* filters (Bessell, 1990), which allowed us to track the cometary light curve in different wavelength ranges over nearly eight years. Dust production was quantified using observations obtained in the BC, GC, and RC narrow-band continuum filters, as well as in the broad-band *R_c* filter. From the dust radial profiles, the *Af ρ* parameter was derived following the definition introduced by A’Hearn et al. (1984). To enable meaningful comparisons between observations obtained at different phase angles, all *Af ρ* measurements were corrected for the phase-angle dependence of dust scattering, yielding *A(0)f ρ* values. Several phase functions have been proposed in the literature (e.g., Divine, 1981; Hanner and Newburn, 1989; Schleicher et al., 1998; Marcus, 2007); in this work, we adopted the composite phase function described by Schleicher (sec 2.4.3), which combines the prescriptions of Schleicher et al. (1998) and Marcus (2007).

3.2.2 Optical spectroscopy with UVES

To investigate in detail the volatile composition of comet K2 in the optical domain and to follow its evolution as the comet approached and receded from perihelion, we carried out a dedicated spectroscopic observing program using the Ultraviolet–Visual Echelle Spectrograph (UVES) mounted on Unit Telescope 2 (UT2, *Kueyen*) of the ESO Very Large Telescope (VLT) at the Paranal Observatory. High-resolution optical spectra were acquired at three distinct epochs (Table 3.2), sampling heliocentric distances both beyond and within the water sublimation region (~ 3 au). This observational strategy was designed to capture potential changes in the relative abundances of gaseous species associated with the transition from hypervolatile-driven to water-driven activity.

Two complementary UVES standard dichroic settings were employed in order to achieve an almost continuous spectral coverage over the full optical wavelength range from 303 to 1060 nm. The first configuration used the dichroic #1 setting (346+580), providing spectral coverage from 303 to 388 nm in the blue arm and from 476 to 684 nm in the red arm. The second configuration

used the dichroic #2 setting (437+860), covering wavelengths from 373 to 499 nm in the blue arm and from 660 to 1060 nm in the red arm. Together, these settings ensured access to the main emission bands of several key cometary species, as well as a robust characterization of the dust-reflected continuum. A summary of the UVES observations, including observing dates, heliocentric and geocentric distances, and instrumental configurations, is provided in Table 3.3.

Table 3.2: The simultaneous UVES and CRIRES⁺ observational circumstances of comet C/2017 K2, with the UT2 and UT3 telescopes of the ESO VLT.

Date 2022	r_h (au)	r_Δ (au)	r'_Δ (km/s)
May 9	3.23	2.66	-37.7
July 5	2.73	1.82	-6.65
Sept 21	2.12	2.32	15.98
Sept 22	2.11	2.35	15.6

The observations were performed using a slit width of $0.45''$ in both spectrograph arms. In the blue arm, a slit length of $10''$ was used, yielding a resolving power of approximately $R \sim 70\,000$, while in the red arm a $0.45'' \times 12''$ slit provided a resolving power of $R \sim 90\,000$. The slit was centered on the inner coma of the comet and oriented along the Sun–comet direction in order to optimise the detection of gaseous emissions while minimizing systematic effects related to coma asymmetries.

The UVES data were reduced using the standard ESO UVES pipeline (Ballester et al., 2000), which performs bias subtraction, flat-field correction, order extraction, wavelength calibration, and merging of the echelle orders. This pipeline processing was complemented by custom routines developed to improve cosmic-ray rejection and to optimise the extraction of the cometary signal. Following the initial reduction, the spectra were corrected for the Doppler shift induced by the relative velocity between the comet and Earth at the time of observation.

Table 3.3: CRIRES⁺ and UVES observation log

Date	Instrument	Setting	Airmass	Exposure time [s]
9 May. 2022	CRIRES ⁺	L3377	1.130	2280
	CRIRES ⁺	M4318	1.115	1400
	UVES	346+580	1.24	3000
	UVES	437+860	1.28	3000
5 July 2022	CRIRES ⁺	L3377	1.130	3600
	CRIRES ⁺	M4318	1.115	2880
	UVES (a)	437+860	1.28	3000
	UVES (a)	346+580	1.15	3000
	UVES (b)	346+580	1.11	3600
	UVES (b)	437+860	1.13	3600
21 Sep. 2022	CRIRES ⁺	L3377	1.375	2400
	CRIRES ⁺	M4318	1.720	1600
	UVES	346+580	1.34	3000
	UVES	437+860	1.71	3000
22 Sep. 2022	CRIRES ⁺	L3377	1.595	2640
	CRIRES ⁺	L3302	1.288	2880
	UVES	346+580	1.29	3600
	UVES	437+860	1.66	3600

Absolute flux calibration was achieved using either the archived UVES master response curves or, when available, response functions derived from spectrophotometric standard stars observed close in time to the comet observations. In order to isolate the gaseous emission component, the underlying continuum dominated by sunlight reflected by cometary dust grains was removed. This was accomplished by dividing the spectra by a high-resolution solar reference spectrum obtained from the BASS2000 database¹, which was adjusted to match the spectral slope of the cometary continuum. The resulting spectra therefore contain only the emission lines of gaseous species present in the coma.

Additional details regarding the UVES data reduction procedures and calibration strategy can be found in [Manfroid et al. \(2021\)](#) and references therein. The high spectral resolution and broad wavelength coverage provided by UVES make these data particularly well suited for identifying faint emission features and for constraining the relative abundances of parent and daughter species in the coma of comet K2.

3.2.3 Near-Infrared spectroscopy with CRIRES⁺

To complement the optical spectroscopic observations and to directly probe the primary volatile inventory of comet K2, we obtained, with our colleague Manuela Lippi, high-resolution near-infrared (NIR) spectra using the CRIRES⁺ instrument mounted on Unit Telescope 3 (UT3, *Melipal*) of the ESO Very Large Telescope (VLT) at the Paranal Observatory. CRIRES⁺ is the upgraded version of the original CRIRES spectrograph ([Kaeufl et al., 2004](#); [Dorn et al., 2014](#)) and operates over a wavelength range of approximately 0.95–5.3 μm . Following its upgrade, CRIRES⁺ is now a cross-dispersed echelle spectrometer, providing a wavelength coverage nearly an order of magnitude larger than that of its predecessor while preserving a high spectral resolving power of $R \sim 40\,000$ for a slit width of 0.4".

The upgraded instrument is equipped with three state-of-the-art infrared detectors, which significantly enhance its performance by increasing the instantaneous spectral coverage, reducing read-out noise and dark current, and improving the overall quantum efficiency. In addition, CRIRES⁺ benefits from the Multi-Application Curvature Adaptive Optics (MACAO) system ([Paufigue et al., 2004](#)), which improves the spatial concentration of the signal at the slit and thus enhances the sensitivity to faint molecular emission lines in cometary comae.

Near-infrared spectroscopic observations of comet K2 were conducted over three nights, contemporaneously with the UVES observing campaign, thereby enabling a coordinated multiwavelength characterization of the comet's activity. The observing log, including instrumental configurations and observing circumstances, is summarized in Tables 3.2 and 3.3. The CRIRES⁺ spectral settings were carefully selected to cover emission bands of the main primary volatiles expected in cometary comae, including H₂O, CO, C₂H₆, CH₄, HCN, NH₃, and related species, and to track their evolution as the comet approached the Sun ([Lippi et al., 2023](#)). Observations were obtained using a slit width of 0.4", aligned along the extended Sun–comet radius vector in order to maximize sensitivity to radial compositional gradients and outflow patterns.

The CRIRES⁺ data were processed by Manuela Lippi using dedicated semi-automated reduction pipelines developed for high-resolution infrared cometary spectroscopy (see, e.g., [Villanueva et al., 2011, 2022](#); [Bonev, 2005](#)). These procedures include correction for detector artifacts, background subtraction, spectral extraction, and wavelength calibration. The removal of telluric absorption features and the absolute spectral calibration were performed by comparison with highly accurate atmospheric radiance and transmittance models generated

¹https://bass2000.obspm.fr/solar_spect.php

using the Planetary Spectrum Generator (PSG) framework and its associated PUMAS module (Villanueva et al., 2018). This approach enables a precise modeling of the terrestrial atmosphere at the time of observation, which is essential for the accurate retrieval of weak cometary emission lines in the near-infrared.

Flux calibration was achieved using spectra of standard stars observed close in time to the comet observations and processed using the same reduction and calibration procedures. The production rates and relative abundances (expressed as mixing ratios with respect to water) of the detected primary volatile species were derived following the methodology described in Lippi et al. (2020) and references therein. This analysis relies on advanced fluorescence excitation models that account for solar pumping, radiative transfer effects, and molecular rotational populations (e.g., Villanueva et al., 2012; Radeva et al., 2011).

3.3 Data analysis and results

3.3.1 Photometric analysis with TRAPPIST

This section presents the photometric analysis of comet K2 based on the extensive dataset obtained with the TRAPPIST telescopes. The long temporal coverage allows us to investigate the evolution of the cometary activity over nearly eight years, from the distant outer Solar System through perihelion and well into the post-perihelion phase. We first analyze the broadband light curves and the evolution of the coma dust colors, which provide constraints on the dust properties and their temporal stability. We then examine the production rates of the main optical radicals and the dust proxy $Af\rho$, together with their ratios, in order to characterize the activity regime of the comet and its compositional evolution.

3.3.1.1 Light curves and coma dust colors

Figure 3.1 shows the temporal evolution of the apparent magnitude of comet K2 measured within a 5 arcseconds aperture in the B, V, Rc, and Ic broadband filters, together with the predicted magnitude from the JPL ephemeris. The observed magnitudes were fitted using the standard formulation:

$$M = M_0 + 5 \log_{10}(r_\Delta) + 2.5 n \log_{10}(r_h), \quad (3.1)$$

where M_0 is the absolute magnitude, n is the heliocentric dependence coefficient, and r_Δ and r_h are the geocentric and heliocentric distances, respectively. Thanks to the long-term monitoring, the comet was observed continuously in the four broadband filters throughout its passage in the inner Solar System, except for the period around perihelion when it was unobservable due to solar conjunction. The comet reached a maximum brightness in the Rc band of 11.18 on 30 January 2023. While the light curve exhibits noticeable large-scale deviations from a simple power-law behavior, no clear outbursts were detected during the monitoring period.

The broadband color indices B–V, B–R, V–R, and R–I are presented in Figure 3.2 as a function of heliocentric distance. Remarkably, the colors remain nearly constant over a wide range of heliocentric distances, indicating that the dust properties in the inner coma did not undergo significant changes during most of the apparition. Deviations are only observed close to perihelion ($r_h \lesssim 2$ au), where the B and V filters become contaminated by gas emissions, primarily CN and C₂, respectively. Outside this region, the stability of the colors suggests

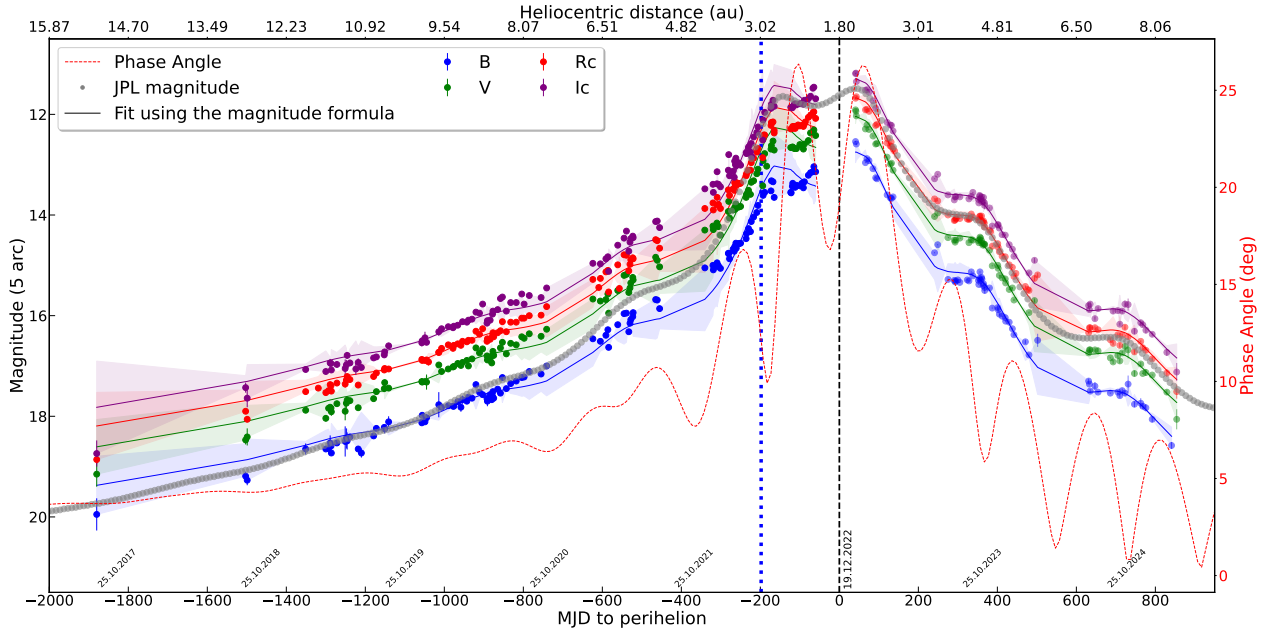


Figure 3.1: Broadband light curve of comet C/2017 K2 obtained with TRAPPIST, measured within a 5 arcseconds radius aperture as a function of time and heliocentric distance relative to perihelion. The vertical dashed line marks the perihelion passage at 1.79 au on 19 December 2022, while the vertical blue dotted line indicates the approximate water-ice sublimation boundary at ~ 3 au.

that the grain size distribution and composition in the near-nucleus coma remained largely unchanged.

The measured colors are in excellent agreement with those reported for a sample of 25 active long-period comets by [Jewitt \(2015\)](#) (Table 3.4; Figure 3.3). To further investigate potential differences related to dynamical origin, the sample of [Jewitt \(2015\)](#) was divided into dynamically new comets and returning comets. No statistically significant differences were found between these two populations, nor between them and K2. This result is consistent with the findings of [Holt et al. \(2024\)](#) and supports the conclusion that broadband dust colors alone do not provide a reliable diagnostic of cometary dynamical class. We note, however, that K2 lies toward the bluer end of the overall color distribution.

3.3.1.2 Temporal evolution of photometric activity

To quantify the long-term evolution of the photometric activity, the Rc-band light curve was divided into four distinct temporal intervals relative to perihelion, each corresponding to a different activity regime (Figure 3.4, Table 3.5).

At large heliocentric distances, from 15.18 to 5.3 au (-1880 to -500 days to perihelion), the comet exhibited a slow and steady brightening. This phase likely corresponds to the early onset of activity driven by the sublimation of highly volatile species such as CO and CO₂, resulting in a weak but measurable increase in brightness. As the comet moved closer to the Sun, between 4.29 and 2.71 au (-360 to -160 days), a much steeper brightening trend was observed, indicating a rapid intensification of activity. This phase is consistent with enhanced dust release and the progressive contribution of less volatile ices.

Closer to perihelion, between 2.37 and 1.96 au (-130 to -50 days), the light curve entered a plateau phase characterized by an almost flat slope. This unexpected stagnation in brightness,

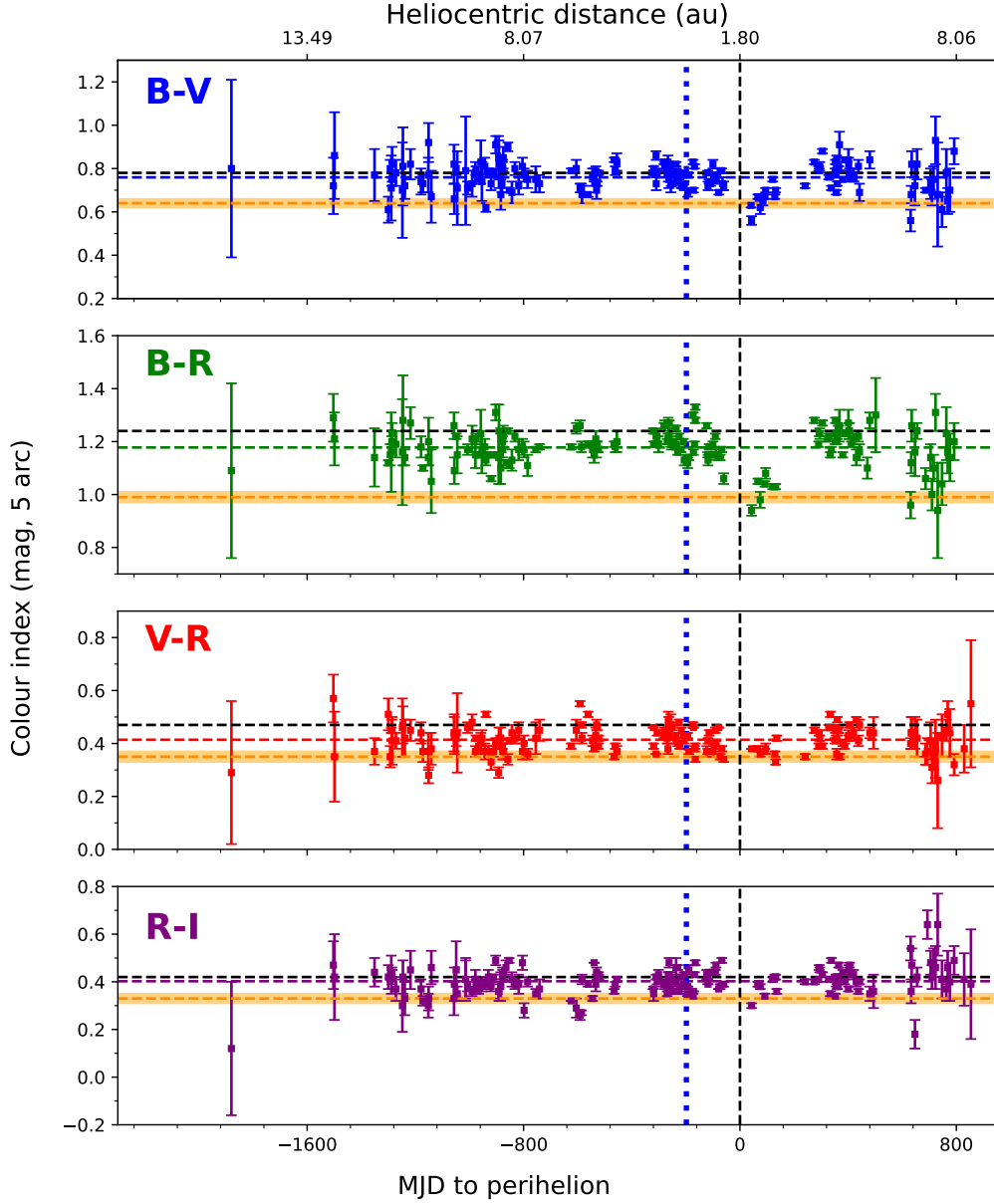


Figure 3.2: Broadband color indices (B-V, B-R, V-R, and R-I) of comet C/2017 K2 as a function of time relative to perihelion and heliocentric distance. The mean colors derived in this work (Table 3.4) are compared with the average values for 25 active long-period comets from Jewitt (2015) (horizontal dashed black lines) and with the solar colors from Holmberg et al. (2006) (horizontal dashed orange lines). The vertical dashed line marks the perihelion passage, while the vertical dotted blue line indicates the approximate location of the water-ice sublimation boundary (~ 3 au).

despite increasing solar insolation, suggests a temporary balance between energy input and mass loss, or a depletion of near-surface volatiles. After perihelion, from 1.87 to 8.46 au (+40 to +460 days), the comet faded rapidly as the heliocentric distance increased and solar heating diminished, following a well-defined declining trend typical of long-period comets.

Table 3.4: Comparison of the C/2017 K2 colors with those of active LPCs

Object	B - V	V - R	R - I	B - R
C/2017 K2	0.76±0.06	0.42±0.04	0.40±0.05	1.18±0.06
DNCs	0.76±0.05	0.49±0.05	0.42±0.02	1.26±0.07
RLPCs	0.80±0.05	0.48±0.05	0.37±0.09	1.28±0.05
Active LPCs	0.78±0.02	0.47±0.02	0.42±0.03	1.24±0.02
Sun	0.64±0.02	0.35±0.01	0.33±0.01	0.99±0.02

Note: The mean colors of C/2017 K2 are compared to the mean colors of DNC and to those of returning comets from the sample of 25 LPC from [Jewitt \(2015\)](#). The Sun color is from [Holmberg et al. \(2006\)](#).

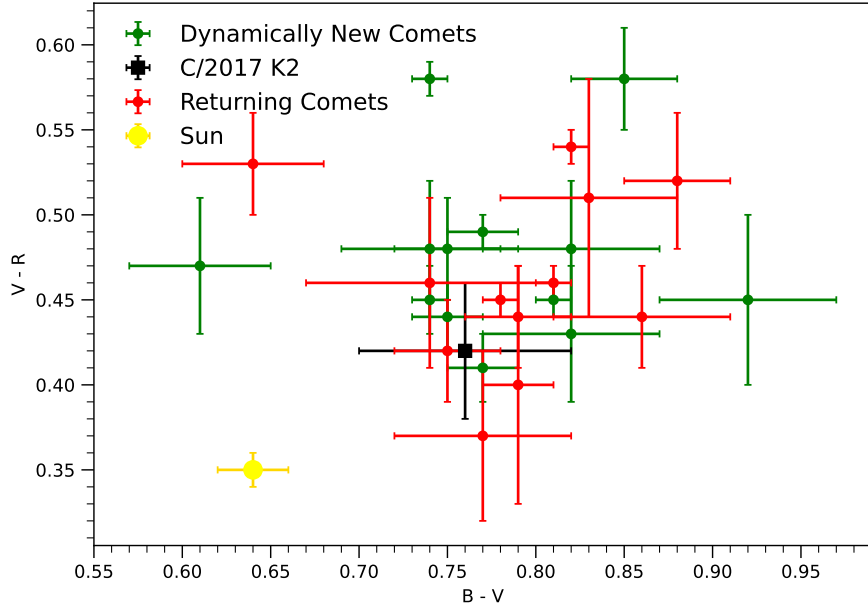


Figure 3.3: Color-color plot comparing C/2017 K2 (black square) with dynamically new comets (green) and returning comets (red) from [Jewitt \(2015\)](#). The color of the Sun is marked by a yellow circle.

Table 3.5: Slope fitting results in the light-curve evolution of comet C/2017 K2.

Days to perihelion r_h -range (au)		Best Slope	Intercept	R-squared
-1880, -500	15.18 - 5.3	$-3.16 \pm 0.068 \times 10^{-3}$	13.43	0.97
-360, -160	4.29 - 2.71	$-1.06 \pm 0.046 \times 10^{-2}$	10.56	0.94
-130, -50	2.37 - 1.96	$-4.92 \pm 0.60 \times 10^{-3}$	11.71	0.82
40, 860	1.87 - 8.46	$6.75 \pm 0.13 \times 10^{-3}$	11.80	0.97

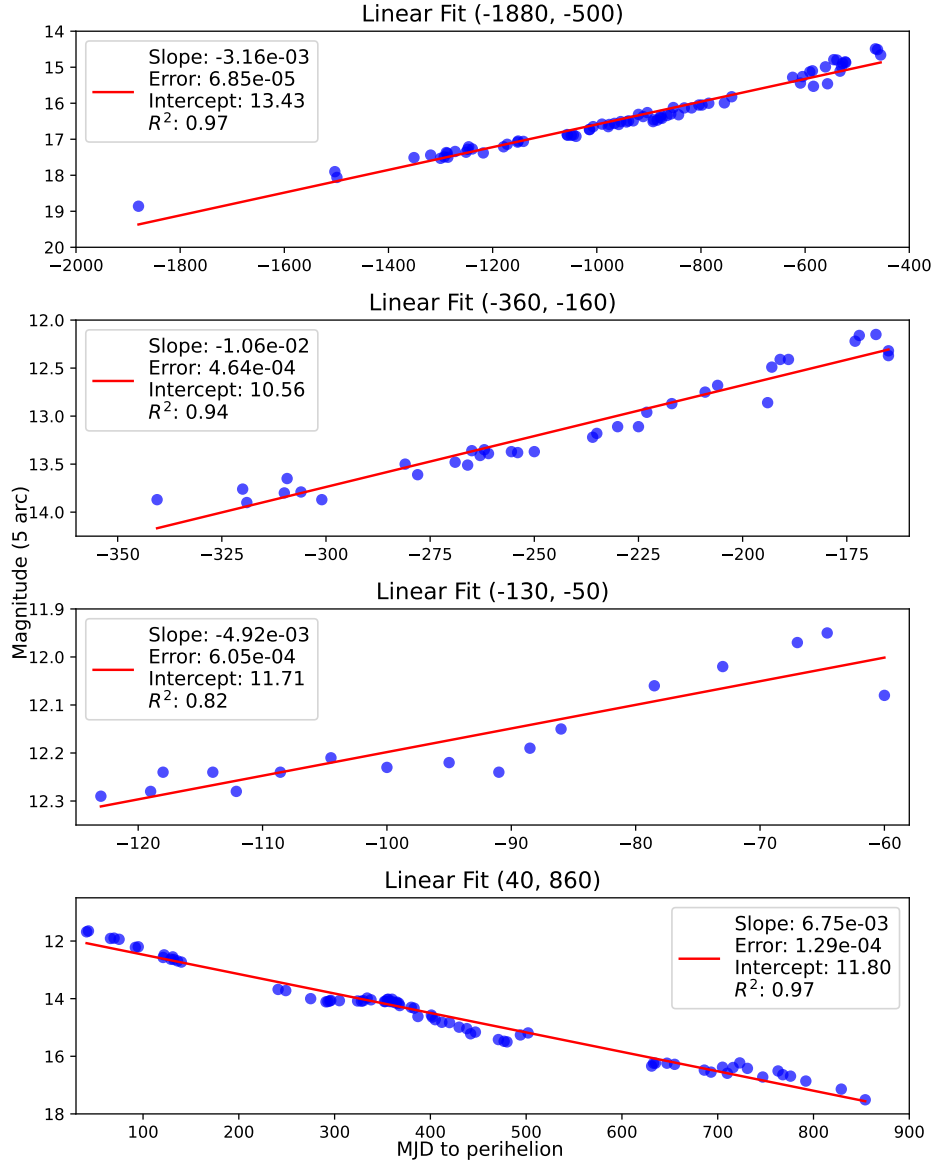


Figure 3.4: Four different slope regimes in the R_c light curve of comet C/2017 K2.

3.3.1.3 Gas production rates, $Af\rho$, and activity ratios

Figure 3.5 presents the evolution of the production rates of several volatile species (OH, NH, CN, C_2 , and C_3) in comet K2. For clarity, the OH production rates have been divided by a factor of ten. The use of a logarithmic scale allows a direct comparison between species with different absolute production levels and emphasizes the temporal variations in cometary activity as a function of heliocentric distance. The corresponding production rate values are listed in Table C.1.

The CN and C_2 radicals were first detected in late March 2022 at a heliocentric distance of 3.62 au, followed by the appearance of most other species approximately one month later. The NH radical was detected later, in mid-August 2022. As the comet approached the Sun from 3.62 to 2.71 au, the production rates of all detected species increased progressively. Unexpectedly, this increase was followed by a stabilization phase, characterized by a plateau-like behavior that persisted both before and after perihelion, in close agreement with the evolution observed in the optical light curve.

After perihelion, CN remained detectable until mid-October 2023 at 3.88 au, whereas C_2

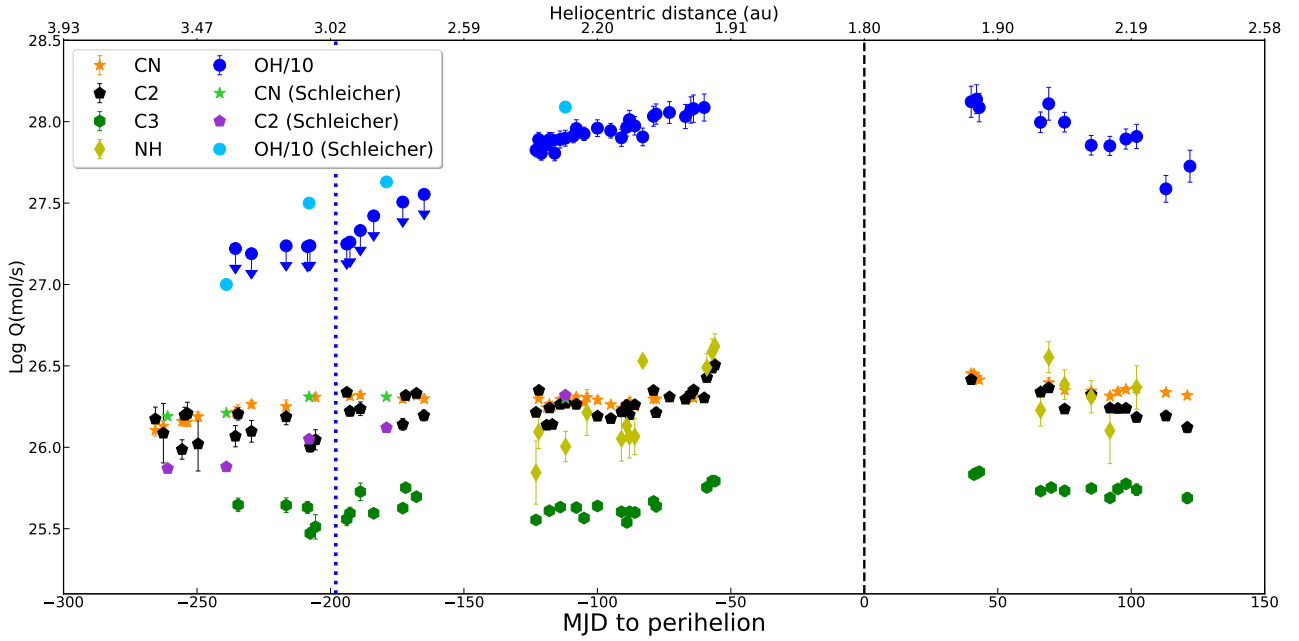


Figure 3.5: Logarithmic production rates of OH, NH, CN, C₂, and C₃ of comet C/2017 K2 from TRAPPIST photometry as a function of time and the heliocentric distance. The vertical dashed line indicates the perihelion at 1.79 au on December 19, 2022.

and C₃ were no longer detected beyond early October 2023 at 3.83 au. OH emission was observed until September 20, 2023 at 3.69 au, while NH was detected until the end of March 2023 at 2.20 au. The production rates derived for OH, CN, and C₂ are consistent with independent measurements obtained from SOHO observations of the Lyman- α hydrogen line (Combi et al., 2025), as well as with narrowband photometric data provided by Schleicher (private communication; see also Figure 3.5).

We derived production rate ratios relative to CN and OH, as well as the dust-to-gas ratio, in order to characterize the compositional properties of comet C/2017 K2. The value $\log [A(0)f\rho/Q(\text{OH})] = -24.75 \pm 0.43$ indicates that K2 belongs to the dust-rich class of comets when compared to typical cometary values reported by A’Hearn et al. (1995a) (see Table 3.6). Figure 3.6 shows the temporal evolution of the logarithmic C₂/CN ratio as a function of time relative to perihelion and heliocentric distance. According to the taxonomic classification scheme of A’Hearn et al. (1995a), K2 can be classified as a “typical” comet, characterized by standard relative abundances of C₂ and C₃ with respect to CN and OH. A comparison between the abundance ratios measured for K2 and those of the cometary database is presented in Table 3.6.

The observed apparent magnitude of a comet depends on its heliocentric distance, geocentric distance, and phase angle at the time of observation. In order to remove these geometric and illumination effects, we computed the absolute magnitude H , defined as the magnitude the comet would exhibit if observed at unit heliocentric and geocentric distances and at zero phase angle. The absolute magnitude is given by

$$H = m - 5 \log_{10}(r_h r_\Delta) - f(\alpha), \quad (3.2)$$

where m is the apparent magnitude in a given filter, r_h is the heliocentric distance, and r_Δ is the geocentric distance. The phase correction term $f(\alpha)$ is defined as $-2.5 \log_{10}[\phi(\alpha)]$, where $\phi(\alpha)$ represents the phase function corresponding to the observed phase angle, following Schleicher et al. (1998). The temporal evolution of the absolute magnitude of K2 is presented in Figure 3.7.

The absolute magnitude measured in the R_c band was subsequently used to estimate the effective scattering cross-section, C_e (Jewitt et al., 2019), which provides a quantitative measure

Table 3.6: Average logarithmic production rates and $A(0)f\rho$ ratios of comet C/2017 K2 in comparison with the A’Hearn et al. (1995a) taxonomic classes.

	C/2017 K2 (This work)	Typical comets (A’Hearn et al., 1995a)	Depleted comets
C_2/CN	-0.037 ± 0.005	0.06 ± 0.10	-0.61 ± 0.35
C_2/OH	-2.65 ± 0.07	-2.44 ± 0.20	-3.30 ± 0.35
CN/OH	-2.58 ± 0.34	-2.50 ± 0.18	-2.69 ± 0.14
C_3/OH	-3.29 ± 0.07	-3.59 ± 0.29	-4.18 ± 0.28
NH/OH	-2.83 ± 0.14	-2.37 ± 0.27	-2.48 ± 0.34
$A(0)f\rho/OH$	-24.75 ± 0.43	-25.82 ± 0.40	-25.30 ± 0.29

Note: The $A(0)f\rho$ values used were computed from the images taken with the RC narrowband filter.

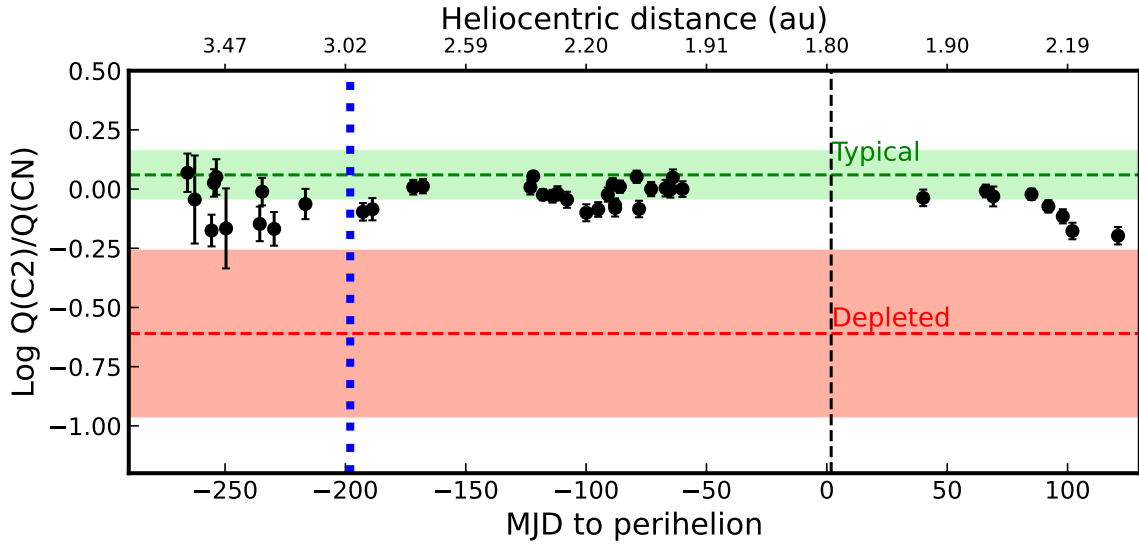


Figure 3.6: Logarithm of C_2/CN production rate ratios of comet C/2017 K2 as a function of time and heliocentric distance.

of the dust content and scattering efficiency within the coma. It is expressed as

$$C_e = \frac{\pi r_0^2}{p} 10^{0.4(m_{\odot,R} - H_R)}, \quad (3.3)$$

where r_0 is the mean Earth–Sun distance in kilometers, p is the geometric albedo of the dust grains, and $m_{\odot,R}$ is the apparent magnitude of the Sun in the R_c band. Adopting $r_0 = 1.5 \times 10^8$ km and $m_{\odot,R} = -26.97$ (Willmer, 2018), Eq. 3.3 reduces to $C_e = (1.5 \times 10^6/p) \times 10^{-0.4H_R}$. An albedo value of $p = 0.04$ was adopted based on previous estimates (Jewitt et al., 2019; Zhang et al., 2019).

The effective scattering cross-section was further used to estimate the average dust mass-loss rate according to

$$\frac{dM}{dt} = \frac{4}{3} \frac{\rho \bar{a} C_e}{\tau_r}, \quad (3.4)$$

where ρ denotes the bulk density of the dust particles, $\bar{a}$ is the mean particle radius, and $\tau_r = L/v_{ej}$ represents the residence time of dust particles within an aperture of projected

radius L , with v_{ej} being the dust ejection velocity. Following [Jewitt et al. \(2019\)](#), we adopted $\rho = 500 \text{ kg m}^{-3}$ and $\bar{a} = 100 \text{ }\mu\text{m}$. A projected aperture radius of $5''$ was used, corresponding to a physical scale that varies with the geocentric distance. Although dust velocities are expected to vary with heliocentric distance, a constant ejection velocity of 14 m s^{-1} was adopted for consistency, in agreement with the average velocity reported for $100 \text{ }\mu\text{m}$ grains by [Liu and Liu \(2024\)](#).

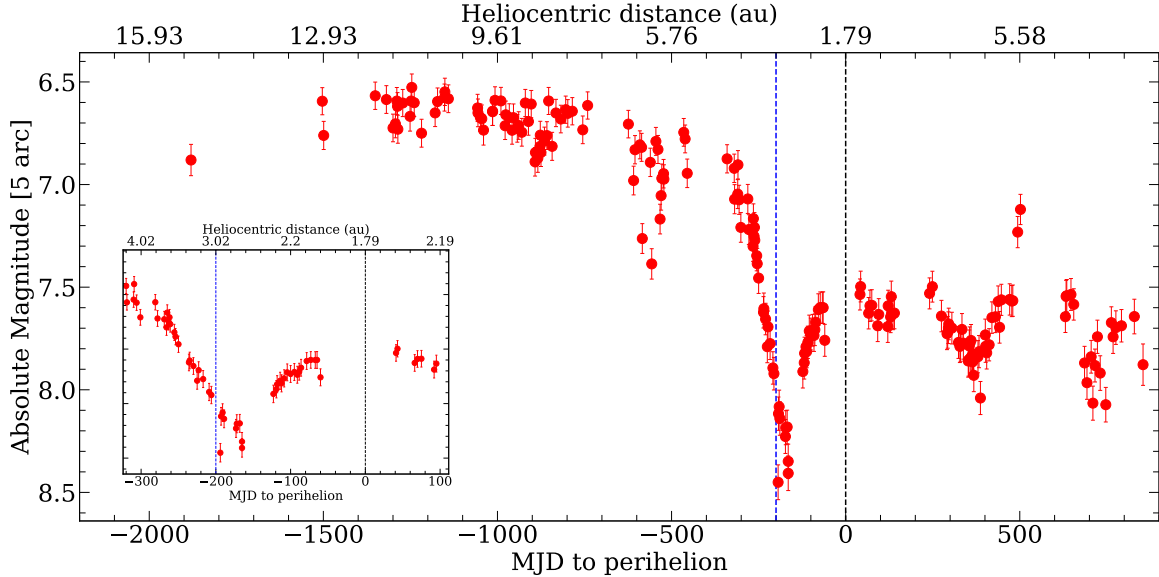


Figure 3.7: The absolute magnitude of comet C/2017 K2 as a function of days to perihelion. The dashed line represents the perihelion. The inset is a zoomed-in region of the light curve around 3 au.

As the comet migrated toward the inner Solar System, it exhibited an unusual and complex activity pattern. At large heliocentric distances (~ 15 au), K2 appeared exceptionally bright, corresponding to a low absolute magnitude and indicating substantial activity in the outer Solar System. This early activity phase is primarily attributed to CO sublimation ([Meech et al., 2017](#)), which is consistent with the pronounced brightening observed between 15 and 13 au. A similar trend was previously reported by [Jewitt et al. \(2019\)](#) at comparable heliocentric distances.

At distances smaller than ~ 12 au, the absolute magnitude began to increase, indicating a gradual fading of the comet and suggesting a decline in CO-driven activity. The most prominent feature in the light curve is a rapid increase in magnitude between 4 and 3 au (see the inset of Figure 3.7), corresponding to a marked decrease in activity. This behavior can be interpreted as the progressive depletion of near-surface CO and/or CO₂ ice, which had previously dominated the outgassing process. In support of this interpretation, no OH emission was detected in the TRAPPIST and UVES observations prior to the comet crossing 3 au, indicating that water-ice sublimation had not yet become efficient. Furthermore, CRIRES⁺ spectra obtained in May 2022 ($r_h = 3.23$ au) did not reveal strong CO or H₂O emission features, reinforcing the hypothesis of a temporary reduction in volatile-driven activity.

Once the comet reached heliocentric distances smaller than ~ 3 au, corresponding to the water-ice sublimation zone, the absolute magnitude began to decrease again, reflecting a renewed brightening phase associated with the onset of H₂O-driven activity. However, the increase in brightness remained moderate, as water sublimation alone was insufficient to fully compensate for the decline in CO- and CO₂-driven activity. This interpretation is further supported by the concurrent evolution of gas production rates and dust activity indicators.

The evolution of the dust proxy parameter $Af\rho$ is shown in Figure 3.8 (see also Table C.1). Measurements were obtained using the broadband R_c filter as well as the narrowband dust continuum filters (RC, GC, and BC), following the formalism introduced by A’Hearn et al. (1984). The vertical dashed line marks the time of perihelion at 1.79 au, when $Af\rho$ reached a maximum value of approximately 15 000 cm, placing K2 among the most active long-period comets. Prior to perihelion, $Af\rho$ exhibits a clear increasing trend, as commonly observed for comets approaching the Sun, reflecting enhanced dust release driven by progressively stronger ice sublimation.

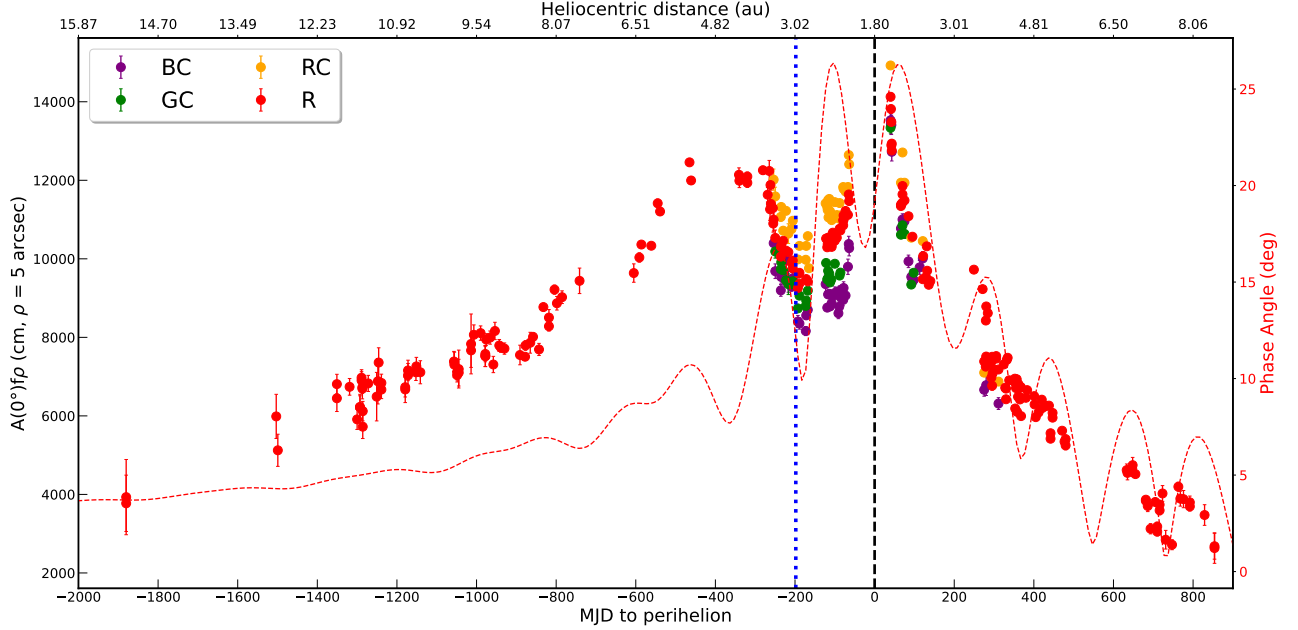


Figure 3.8: The $A(0)f\rho$ parameter of comet C/2017 K2 from the broad- and narrowband filters as a function of time and the heliocentric distance.

A distinctive and unexpected behavior in the dust activity of comet K2 was observed between approximately -260 and -170 days from perihelion, corresponding to heliocentric distances between 3.60 and 2.74 au. During this interval, $Af\rho$ exhibited a pronounced decrease followed by a rapid recovery, suggesting a possible correlation with variations in the phase angle. However, this anomalous trend remained evident even after applying phase-angle corrections, indicating that the observed variability is intrinsic to the comet rather than a purely geometrical effect. Concurrently, a sharp increase in the water production rate was detected near 3 au (see Figure 3.9), coinciding with a renewed rise in $Af\rho$ and dust emission. This transition likely reflects the progressive depletion of near-surface CO and/or CO₂ ice, which typically governs cometary activity at heliocentric distances between 3 and 6 au, and the subsequent activation of water-ice sublimation as the dominant driver of mass loss.

Overall, the activity of K2 during its passage across the water-ice snowline was characterized by a temporary decline, manifested by the flattening of the optical light curve and the stagnation of gas production rates. A similar evolutionary pattern was independently identified by Kwon et al. (2024) using photometric data from the ZTF IRSA archive² (Masci et al., 2019), covering heliocentric distances from approximately 14 to 2.3 au. Although the general trends are consistent, systematic differences in $Af\rho$ values are present, likely resulting from photometric calibration uncertainties, particularly related to zero-point determinations (personal communication).

²https://irsa.ipac.caltech.edu/applications/ztf/?__action=layout.showDropDown&

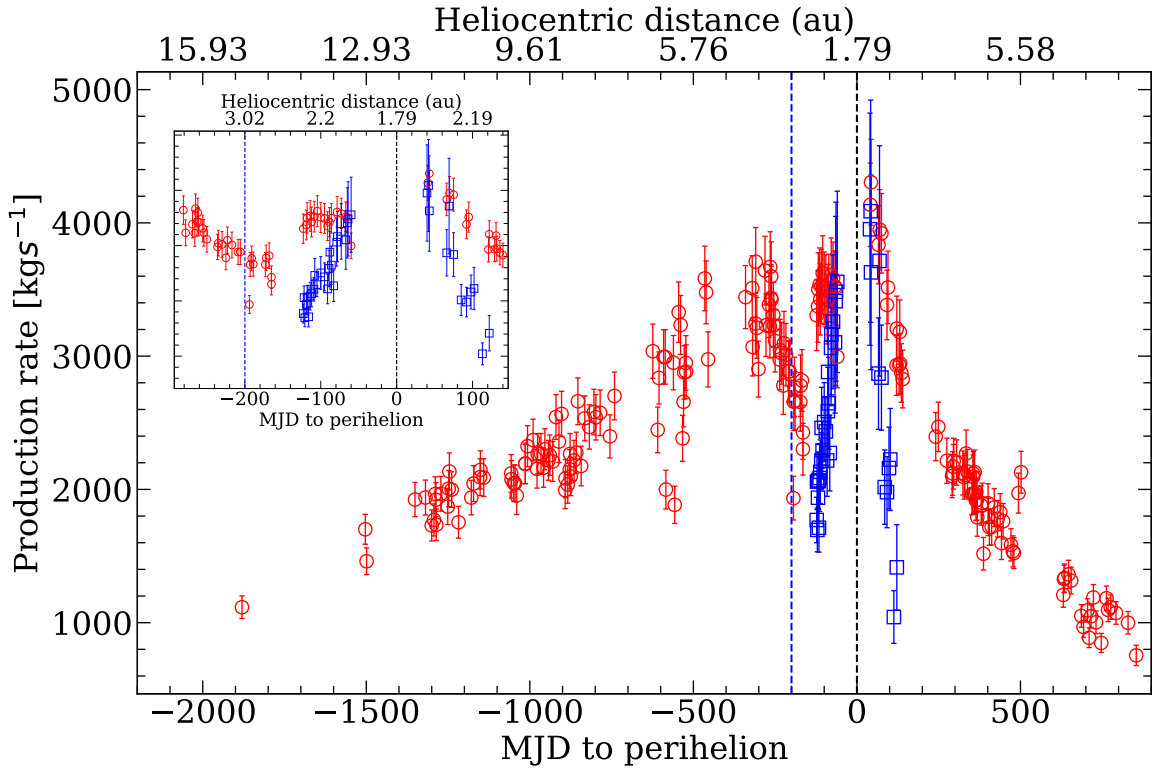


Figure 3.9: Comparison of dust-mass loss and water-mass production in comet C/2017 K2 as a function of time and the heliocentric distance. The dust-mass loss was computed using equation 3.4, and the water-mass production was computed from the OH production rate observed by TRAPPIST. The vertical dotted blue line represents the water-ice sublimation boundary (~ 3 au), within which the main driving source of comet outgassing changed from supervolatile ices to H_2O ice (Kwon et al., 2023).

Following perihelion, $A_f\rho$ decreases steeply and shows no significant correlation with the phase angle. This post-perihelion behavior is commonly observed among long-period comets and reflects the progressive decline of both gas and dust production as the nucleus recedes from the Sun.

3.3.2 High-resolution spectroscopy: Optical spectroscopy with UVES

3.3.2.1 The gas production rates

During the first observing epoch on May 9, 2022 ($r_h = 3.23$ au), only the CN, C_3 , and C_2 emission bands were clearly detected in the UVES spectra, in agreement with contemporaneous TRAPPIST imaging observations. At this stage, no significant emission from other common cometary radicals was observed.

During the second epoch on July 5, 2022 ($r_h = 2.73$ au), the onset of water-driven activity became apparent through the detection of OH, together with other typical daughter species such as NH, CH, and NH_2 . By the third epoch on September 20, 2022 ($r_h = 2.12$ au), the emission features had intensified substantially, reflecting a marked increase in overall cometary activity (see Figure 3.10).

CO_2^+ ions were detected at multiple epochs, whereas no CO^+ emission was identified in any of the UVES spectra. This indicates that K2 does not belong to the class of CO^+ -rich comets, in contrast to comet C/2016 R2, whose optical spectrum at similar heliocentric distances was

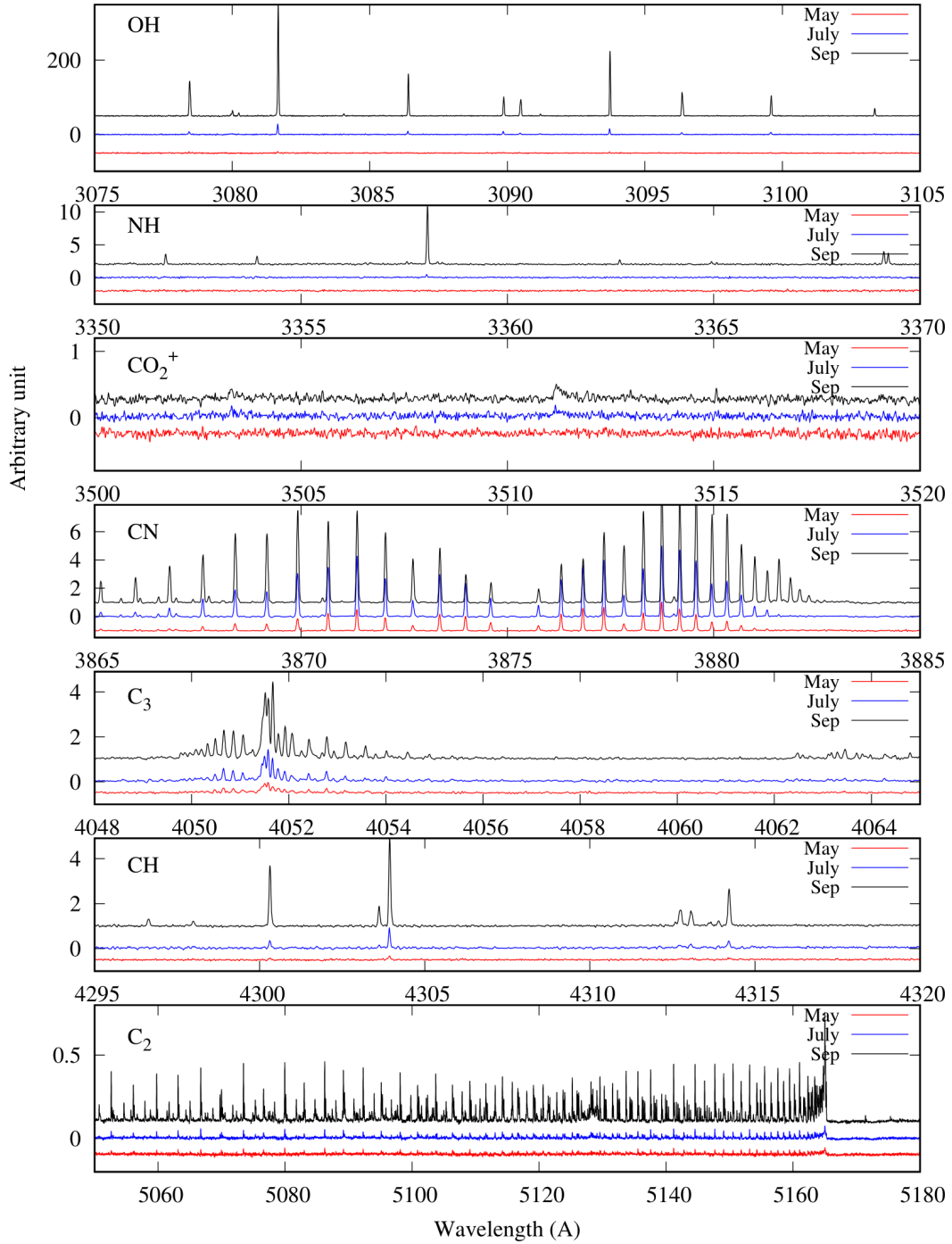


Figure 3.10: Spectral regions of interest of comet C/2017 K2 acquired with UVES, with detected daughter species in three different epochs: May ($r_h=3.23$ au), July ($r_h=2.73$ au), and September ($r_h=2.12$ au). The flux is reported in arbitrary units for clarity.

dominated by strong CO⁺ bands (Opitom et al., 2019). Nevertheless, a potential observational bias cannot be excluded. High-resolution UVES observations over the past two decades have rarely revealed CO⁺ features, primarily because the narrow slit is typically centered on the bright inner coma, where emissions from neutral species dominate and may obscure weaker ionic lines. In addition, the limited slit length ($\sim 10''$) reduces the likelihood of intercepting the narrow and often asymmetric ion tails, which are generally oriented in the anti-solar direction. Observations with slit offsets toward the tail are therefore more favorable for ion detection.

Production rates for the detected daughter species were derived using the Haser model (Haser, 1957), based on their principal emission bands (see Table 3.7). These measurements

were subsequently compared with the abundances of the corresponding parent species obtained from CRIRES⁺ observations. Owing to the relatively low signal-to-noise ratio in the CN emission lines, however, the available data do not allow reliable determinations of nitrogen and carbon isotopic ratios.

Table 3.7: Gas production rates of comet C/2017 K2 from UVES observations

Date (2022)	OH	CN	C ₂
May 09	$3.96 \pm 0.79 \times 10^{27}$	$7.57 \pm 1.51 \times 10^{25}$	$2.88 \pm 0.58 \times 10^{25}$
Jul 05 (a)	$1.23 \pm 0.12 \times 10^{28}$	$1.07 \pm 0.11 \times 10^{26}$	$7.03 \pm 1.41 \times 10^{25}$
Jul 05 (b)	$1.51 \pm 0.16 \times 10^{28}$	$1.15 \pm 0.12 \times 10^{26}$	$5.86 \pm 1.17 \times 10^{25}$
Sept 21	$5.23 \pm 0.51 \times 10^{28}$	$1.15 \pm 0.12 \times 10^{26}$	$1.01 \pm 0.20 \times 10^{26}$
Sept 22	$5.59 \pm 0.57 \times 10^{28}$	$1.18 \pm 0.11 \times 10^{26}$	$9.59 \pm 1.92 \times 10^{25}$

3.3.2.2 The forbidden oxygen lines [OI]

The high spectral resolution and sensitivity of UVES enabled the detection of the three forbidden atomic oxygen emission lines, [OI], during all three observing epochs. The green line was identified at 5577.31 Å, while the red doublet was detected at 6300.31 Å and 6363.78 Å. Owing to the Doppler shift induced by the relative motion of the comet with respect to the Earth, the cometary oxygen emissions are clearly separated from the strong telluric [OI] lines (see Figure 3.11). The integrated fluxes for each emission line, as well as the green-to-red intensity ratio (Cochran and Cochran, 2001);

$$G/R = \frac{I_{5577}}{I_{6300} + I_{6364}}$$

were measured for each epoch and are reported in Table 3.8. The G/R ratio exhibits a clear dependence on heliocentric distance, decreasing from a relatively high value of approximately 0.25 beyond the water-ice sublimation boundary at 3.0 au (Crovisier and Encrenaz, 2000) to values close to 0.1 at heliocentric distances near 2 au. This behavior is in excellent agreement with previous measurements reported by Decock et al. (2013) and references therein, as well as by Opitom et al. (2019), Cambianica et al. (2021), Kwon et al. (2023), and Aravind et al. (2024) for comets observed over a wide range of heliocentric distances (see Figure 3.12). A clear discrepancy is observed when comparing our results with those reported by Cambianica et al. (2023), as our measured values are significantly lower. This difference is supported by our reanalysis of the spectra, which yields reduced values consistent with those obtained from our UVES dataset. This agreement strengthens the reliability of our measurements and suggests that the previously reported values may have been overestimated.

The G/R ratio is commonly used as a diagnostic of the dominant parent molecules of atomic oxygen in cometary comae, in particular to assess the relative contributions of H₂O, CO₂, and CO, which are the primary sources of oxygen through photodissociation processes (Festou, 1981). Laboratory and theoretical studies have shown that this ratio depends strongly on the parent species, with typical values of ~0.1 for water and higher values for CO and CO₂ (see Table 2 in Festou 1981).

Submillimeter observations have confirmed the presence of carbon monoxide in the coma of K2 (Yang et al., 2021), while Cambianica et al. (2023) reported a high G/R ratio of 0.28 at

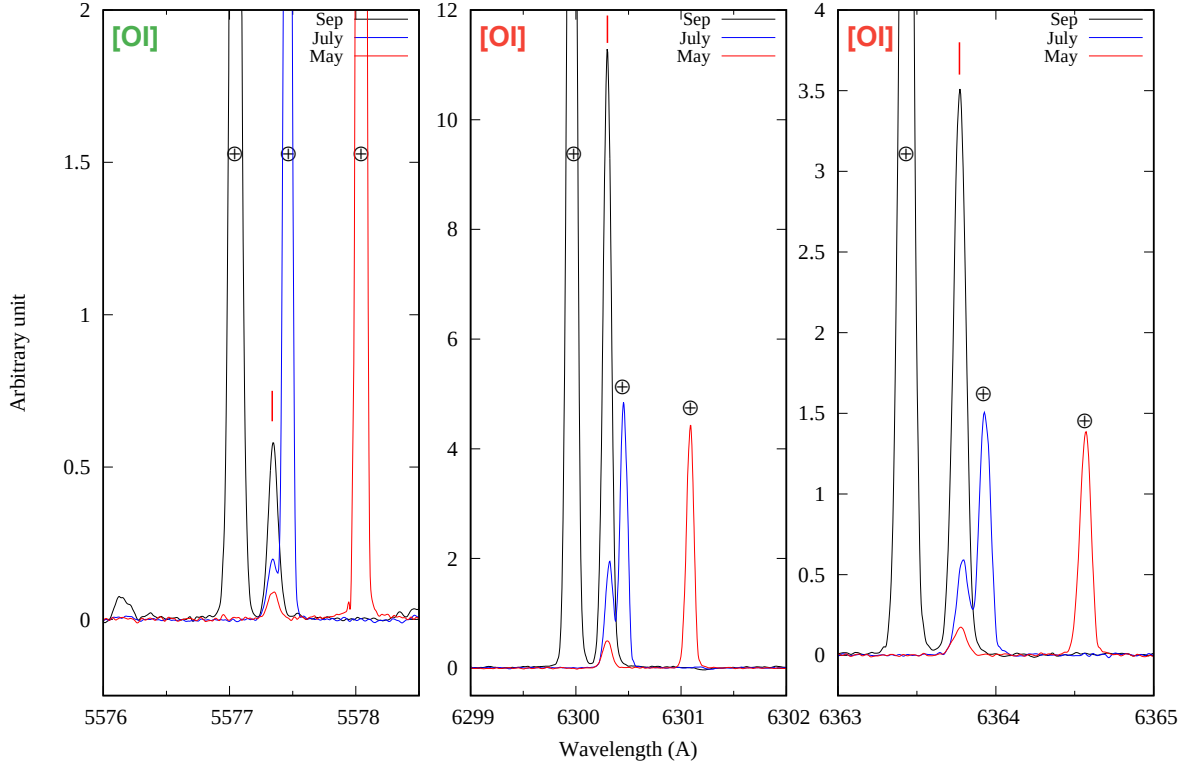


Figure 3.11: Forbidden green oxygen line [OI] and red doublet lines detected with UVES at the VLT in the three epochs May 9 ($r_h=3.23$ au), July 5 ($r_h=2.73$ au), and September 20 ($r_h=2.12$ au)

2.8 au. In our data, we measured a value of 0.25 at 3.2 au and 0.15 at 2.7 au, consistent with the average value of 0.15 at 2.53 au derived by [Kwon et al. \(2023\)](#) using MUSE at the VLT. At smaller heliocentric distances, the ratio decreases rapidly to 0.08 at 2.1 au, in agreement with the trend reported by [Decock et al. \(2013\)](#). This evolution reflects the progressive dominance of water sublimation inside 3.0 au.

Table 3.8: Flux measurements and G/R intensity ratios of the [OI] emission lines for comet C/2017 K2.

Date (2022)	Fluxes [erg/s/cm ² /Å/arcsec ²]			G/R
	(5577 Å)	(6300 Å)	(6363 Å)	
May 09	1.64×10^{-17}	5.76×10^{-17}	1.98×10^{-17}	0.25 ± 0.013
Jul 05a	2.42×10^{-17}	1.52×10^{-16}	4.65×10^{-17}	0.14 ± 0.007
Jul 05b	4.03×10^{-17}	2.43×10^{-16}	7.43×10^{-17}	0.15 ± 0.008
Sep 21	1.01×10^{-16}	1.18×10^{-15}	3.82×10^{-16}	0.08 ± 0.004
Sep 22	1.02×10^{-16}	1.17×10^{-15}	3.62×10^{-16}	0.08 ± 0.005

This interpretation is further supported by the UVES spectra, which do not show detectable OH emission prior to the second observing epoch. Since OH is a direct photodissociation product of H₂O, its absence at larger heliocentric distances confirms that water-driven activity was not yet significant at that stage. Similar trends in the G/R ratio have been observed in several comets at large heliocentric distances, including K2, indicating that the measured values

are not exceptional within the broader comet population. Consequently, the available data do not support the conclusion that K2 was unusually enriched in CO or CO₂, as even higher G/R values would be expected in such a case.

Nevertheless, the non-detection of CO in the UVES spectra combined with the detection of CO₂⁺ suggests that CO₂ may have been the dominant driver of activity at heliocentric distances larger than approximately 2.5 au. Additional measurements at distances beyond 4.0 au would be required to further test this hypothesis and to better constrain the relative contributions of the main volatile species.

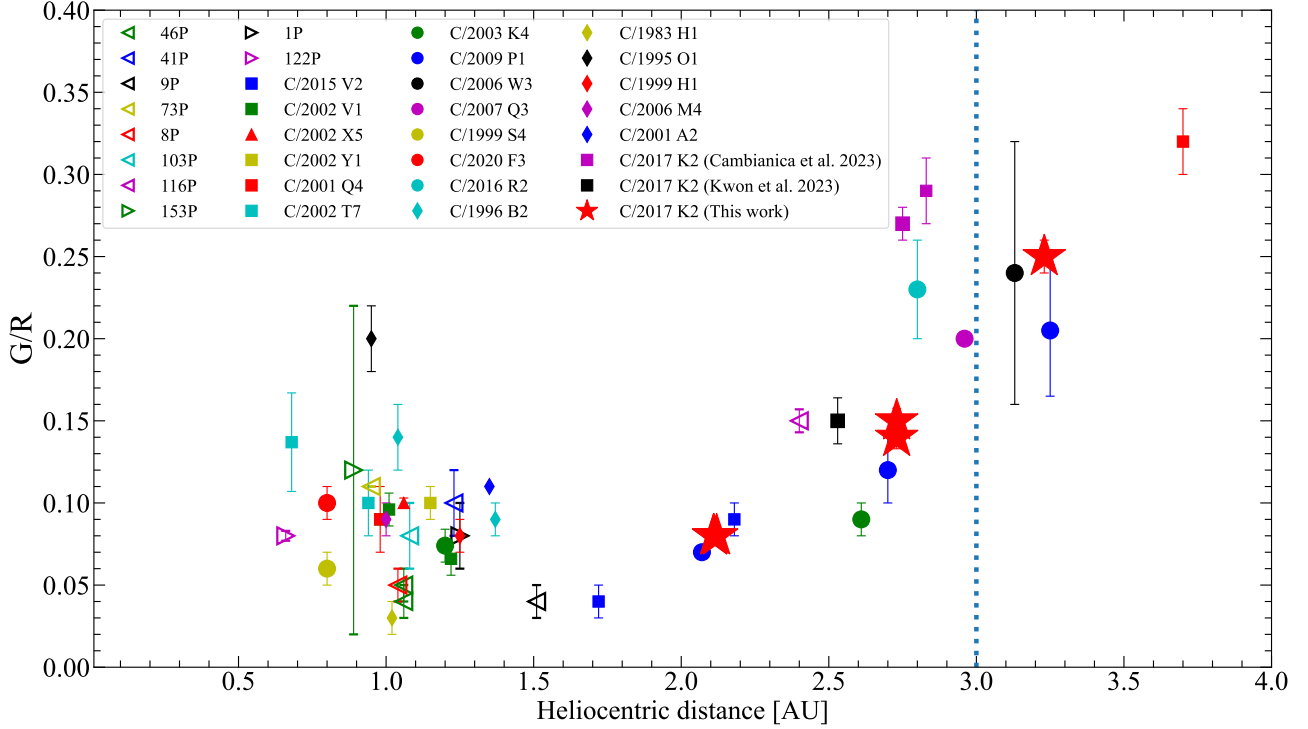


Figure 3.12: G/R intensity ratio plotted as a function of the heliocentric distance. The same symbol is used for multiple points of a given comet. Open markers represent short-period comets, and solid markers represent LPCs. The vertical dotted line indicates the distance beyond which water sublimation decreases significantly (Crovisier and Encrenaz, 2000).

3.3.2.3 Detection of FeI and NiI lines

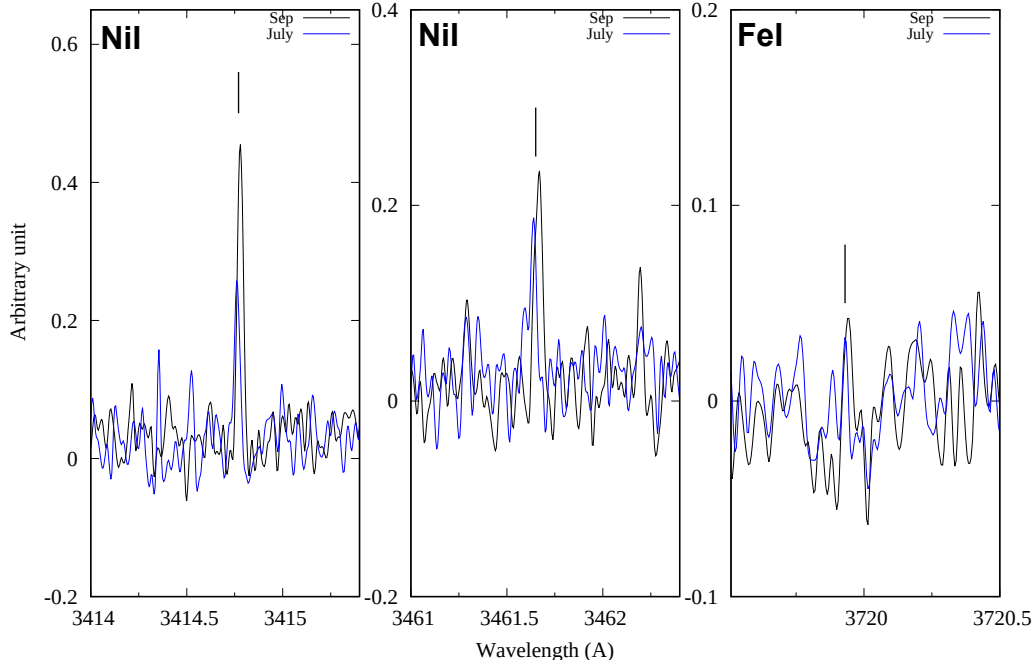
Recent high-resolution spectroscopic studies have revealed the presence of neutral metallic emission lines, in particular those of iron and nickel, in the comae of comets, even at large heliocentric distances (Manfroid et al., 2021). In the case of K2, we identified and measured the fluxes of eight Ni I lines and two Fe I lines in the blue spectra obtained during the last two observing epochs, although some measurements are affected by relatively large uncertainties (see Figure 3.13 and Table 3.9).

Using the excitation model developed by Manfroid et al. (2021) and Hutsemékers et al. (2021), the team derived the corresponding production rates for iron and nickel. For the July and September epochs, we obtained $\log_{10}(Q_{\text{Fe}}) = 22.01 \pm 0.21$ and 22.14 ± 0.21 , and $\log_{10}(Q_{\text{Ni}}) = 21.97 \pm 0.04$ and 22.23 ± 0.08 , respectively. The resulting abundance ratios are $\log_{10}(Q_{\text{Ni/Fe}}) = -0.04 \pm 0.22$ in July and 0.09 ± 0.23 in September.

These values are consistent, within the uncertainties, with the average ratio measured for a sample of 17 comets, $\log_{10}(Q_{\text{Ni/Fe}}) = -0.06 \pm 0.31$, but differ by nearly one order of magnitude

Table 3.9: Fluxes of NiI and FeI in C/2017 K2.

Line (Å)	Fluxes $\times 10^{-3}$ [erg/s/cm ² /Å/arcsec ²]			
	July 5 (a)	July 5 (b)	September 21	September 22
NiI 3414.764	8.0 ± 3.0	10.0 ± 3.0	10.0 ± 3.0	17.0 ± 3.0
NiI 3446.259	–	4.4 ± 2.0	3.0 ± 2.0	4.7 ± 3.0
NiI 3458.460	–	–	–	20.0 ± 10.0
NiI 3461.652	5.0 ± 2.0	5.0 ± 2.0	–	13.0 ± 3.0
NiI 3492.956	–	–	6.0 ± 3.0	–
NiI 3515.052	3.0 ± 2.0	5.0 ± 4.0	7.9 ± 3.0	11.0 ± 3.0
NiI 3524.536	6.0 ± 2.0	10.0 ± 3.0	13.7 ± 3.0	15.0 ± 3.0
NiI 3619.391	4.5 ± 2.0	3.4 ± 2.0	6.2 ± 3.0	2.9 ± 2.0
FeI 3719.935	–	3.9 ± 2.0	–	4.9 ± 2.0
FeI 3737.132	–	1.9 ± 2.0	–	3.1 ± 2.0

**Figure 3.13:** Example of the NiI and FeI lines detected in comet C/2017 K2.

from the ratios derived for the dust of 1P/Halley (Jessberger et al., 1988) and for the coma of the sungrazing comet Ikeya–Seki (Manfroid et al., 2021). Despite being classified as a dynamically new comet and exhibiting significant activity at large heliocentric distances, K2 therefore displays a NiI/FeI abundance ratio that is comparable to that of other comets.

As illustrated in Figure 3.14, K2 occupies an intermediate position within the correlation identified by Hutsemékers et al. (2021) between the degree of carbon-chain depletion, as measured by the C₂/CN ratio, and the NiI/FeI abundance ratio in long-period comets. This relationship suggests that the observed diversity in metallic abundance ratios among comets is primarily linked to their formation conditions in the early Solar System, rather than to evolutionary or chemical processes occurring in the coma.

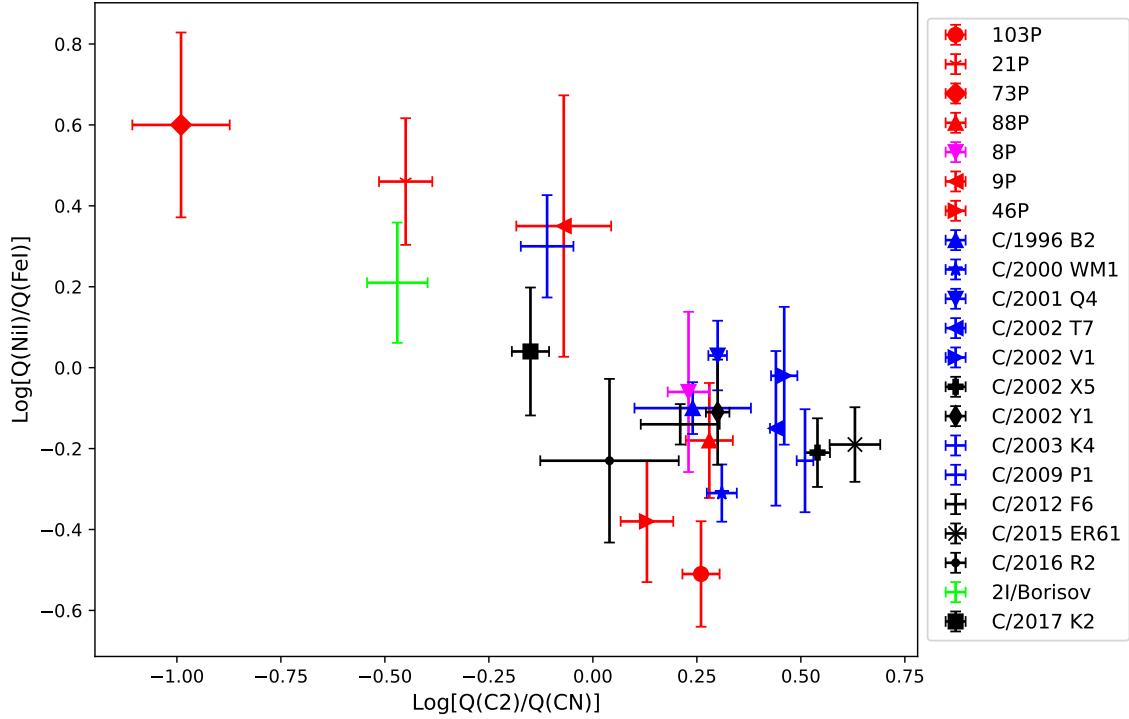


Figure 3.14: NiI/FeI abundance ratios against the C_2/CN adapted from [Hutsemékers et al. \(2021\)](#). The colors in the plot represent different dynamical classes: Jupiter-family comets (red), Halley-family comets (pink), long-period comets (blue), and dynamically new comets (black). The black square shows comet C/2017 K2.

3.3.3 High-resolution spectroscopy: NIR spectroscopy with CRİRES⁺

The CRİRES⁺ observations provide direct constraints on the native volatile composition of comet K2 and, when combined with the optical measurements obtained with UVES and the long-term photometric monitoring performed with TRAPPIST, offer a comprehensive multi-wavelength view of the physical and chemical processes governing the activity of this comet over a wide range of heliocentric distances. This part was prepared with our collaborator Manuela Lippi from the INAF institute. A representative selection of CRİRES⁺ spectra of comet K2 is shown in Fig. 3.15, illustrating the quality of the data and the richness of the detected molecular emission features.

The rotational temperatures, molecular production rates, and mixing ratios, as well as the corresponding upper limits derived from the CRİRES⁺ observations, are summarized in Table 3.10. Despite the pronounced activity of K2 at large heliocentric distances, our infrared observations reveal a markedly different picture, characterized by a weak dust continuum and faint emission features from most parent species. In the infrared domain, the dust signal results from the combined contributions of reflected solar radiation and thermal emission. The low dust continuum observed in our spectra may therefore be partly attributed to the low temperature of the dust grains, given the large heliocentric distance of the comet. In combination with the physical properties of the dust, such as grain size and composition, this effect may significantly reduce the infrared signal. Dedicated modeling is required to quantitatively assess the origin of the discrepancies between the optical and infrared observations.

Moreover, the infrared counterparts of several species detected in the optical, including H_2O , C_2H_2 , and HCN , were only marginally detected, even during periods of enhanced optical

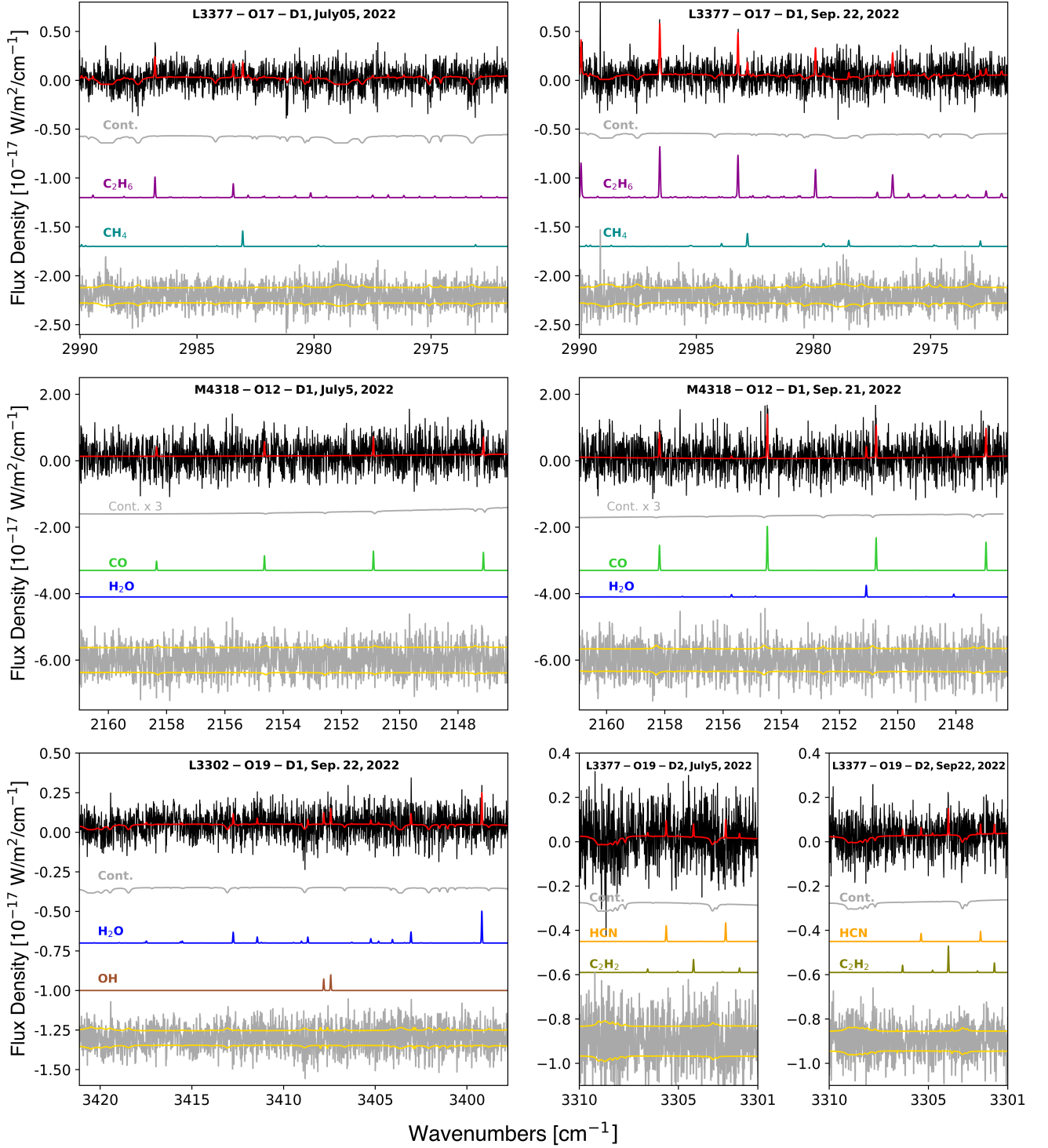


Figure 3.15: High-resolution NIR spectra of comet C/2017 K2 obtained with CRIRESE⁺. For each panel, the upper spectrum shows the observed data together with the best-fit total synthetic model (red), while the gray spectrum below represents the modeled atmospheric transmittance. Individual molecular fluorescence models used to derive production rates are overplotted in different colors and identified by labels. The residuals between the observations and the total model are shown at the bottom in gray, with the yellow lines indicating the $\pm 1\sigma$ uncertainty levels. The instrumental setting, detector number, and date of observation are indicated at the top of each panel.

activity. This is particularly evident in the spectra acquired on May 9, in which the CO emission lines are close to the noise level and too weak to allow a reliable determination of the corresponding production rate. Initially, based on the strong activity observed at optical wavelengths, we expected spectra dominated by hypervolatile species such as CO and CH₄. The absence of such features led us to consider that the comet might still have been too distant from both the Sun and the Earth to be efficiently probed in the infrared.

Subsequent analysis, combined with the TRAPPIST and UVES results, supports a more complex interpretation. In particular, our nondetections are most likely related to a depletion of near-surface CO before the comet enters the water-ice sublimation regime ($r_h \lesssim 2.8$ au), rather than to purely observational limitations.

Table 3.10: Production rates and mixing ratios (relative to water) retrieved for the CRIREs⁺ observations

Date	Molecule	Q_{NC} [10 ²⁶ mol/s]	$Q_{Tot}^{(a)}$ [10 ²⁶ mol/s]	MR [% wrw]
5 July 2022	H ₂ O	203 ± 53	335 ± 96	100
	HCN	< 0.8	< 1.3	< 0.4
	C ₂ H ₂	< 0.9	< 1.5	< 0.5
	C ₂ H ₆	1.57 ± 0.34	2.59 ± 0.64	0.77 ± 0.32
	CH ₄	7.8 ± 1.7	12.9 ± 3.2	3.8 ± 0.8
	CO	21.8 ± 5.5	36 ± 10	10.7 ± 2.7
21 Sep 2022	H ₂ O ^(b)	252 ± 29	446 ± 82	100
	CH ₃ OH	10.5 ± 3.5	19 ± 7	4.2 ± 1.4
	HCN	0.37 ± 0.12	0.66 ± 0.23	0.15 ± 0.05
	C ₂ H ₂	< 0.8	< 1.4	< 0.3
	C ₂ H ₆	3.36 ± 0.22	5.95 ± 0.92	1.33 ± 0.09
	CH ₄ ^(b)	6.5 ± 3	11 ± 5	2.6 ± 1.2
22 Sep 2022	CO	35 ± 3	60 ± 10	13.9 ± 1.2
	H ₂ O ^(b)	252 ± 29	446 ± 82	100
	CH ₃ OH	11.5 ± 3.5	20 ± 6	4.6 ± 1.2
	HCN	0.58 ± 0.24	1.02 ± 0.44	0.23 ± 0.10
	C ₂ H ₂	< 1.2	< 2.2	< 0.5
	C ₂ H ₆	3.64 ± 0.26	6.45 ± 1.02	1.44 ± 0.10
	CH ₄ ^(b)	6.5 ± 3	11 ± 5	2.6 ± 1.2

Note: (a) Calculated using a Q_{scale} value of (1.65 ± 0.20) and (1.77 ± 0.25) for the July and September observations, respectively; (b) Weighted average of the two observations in September.

Table 3.11 presents a comparison between our derived production rates and mixing ratios and those reported in recent studies. Our results are consistent within 2σ with the values obtained by Ejeta et al. (2025), with the notable exception of HCN, for which we derive a significantly lower abundance. Similarly, the production rates measured during the July observing campaign are in good agreement with those obtained using the James Webb Space Telescope when the comet was located at 2.35 au from the Sun (Woodward et al., 2025). Although the latter study reports a water production rate approximately twice as high as our estimate, their corresponding mixing ratios are consequently lower, remaining broadly compatible with our measurements.

In comparison with other comets, K2 appears to be enriched in most volatile species and exhibits compositional similarities with C/1999 T1, C/2009 P1, and C/2013 R1 (see Figure 3.16).

Table 3.11: Comparison of the total production rates and mixing ratios as retrieved in this work, Ejeta et al. (2025), and Woodward et al. (2025).

r_h [au]	CRIRES ⁺		iSHELL	JWST
	2.7	2.1	2.35	2.35
Total Production Rates [10^{26} mol/s]				
H ₂ O	335 ± 96	446 ± 82	365 ± 66	760 ± 15
CH ₃ OH		19 ± 7	17.1 ± 1.9	22.2 ± 0.7
HCN	< 1.3	0.7 ± 0.2	1.75 ± 0.16	1.7 ± 0.3
C ₂ H ₂	< 1.5	< 1.4	1.97 ± 0.34	
C ₂ H ₆	2.6 ± 0.6	6.3 ± 0.9	5.25 ± 0.67	2.3 ± 0.4
CH ₄	12.9 ± 3.2	11.0 ± 5.0	15.7 ± 2.3	14.8 ± 0.4
CO	36 ± 10	60 ± 10	63.7 ± 5.7	62 ± 1
Mixing Ratios [w.r.t. water]				
CH ₃ OH		4.4 ± 1.2	4.69 ± 1	2.93 ± 0.08
HCN	< 0.4	0.2 ± 0.1	0.48 ± 0.10	0.23 ± 0.05
C ₂ H ₂	< 0.5	< 0.5	0.54 ± 0.13	
C ₂ H ₆	0.77 ± 0.32	1.4 ± 0.1	1.44 ± 0.32	0.31 ± 0.04
CH ₄	3.8 ± 0.8	2.6 ± 1.2	4.29 ± 1.0	1.95 ± 0.05
CO	10.7 ± 2.7	13.9 ± 1.2	17.5 ± 3.5	8.2 ± 0.3

One possible interpretation is that the material composing K2 formed in a cold, organic-rich environment, characterized by a high CO abundance and efficient hydrogenation reactions on icy grains. These processes may have contributed significantly to the enhanced abundances of molecules such as methanol, ethane, and methane.

Furthermore, as a dynamically new comet, K2 has likely preserved much of its primordial composition throughout its residence in the Oort cloud. The retention of this pristine, hypervolatile-rich material is consistent with the strong activity observed at heliocentric distances exceeding 20 au.

To investigate the origin of the radicals detected in the coma of K2, we compared the abundances of daughter species derived from optical observations with those of their potential parent molecules measured in the infrared using CRIRES⁺. Table 3.12 summarizes the relative abundances of selected radicals observed in the optical domain and their corresponding parent species detected in the infrared over comparable observing periods.

Table 3.12: Abundance ratios derived from the optical and infrared data of comet C/2017 K2

UT Date	r_h	r_Δ	Abundances ratios (10^{-3})					Tel/Instrument
	(au)	(au)	CN/OH	HCN/H ₂ O	C ₂ /OH	C ₂ H ₂ /H ₂ O	C ₂ H ₆ /H ₂ O	
2022 Jul 05	2.73	1.82	—	<3.88	—	<4.78	7.73±2.93	CRIRES ⁺
2022 Jul 07	2.71	1.82	5.56±3.89	—	5.98±4.18	—	—	TRAPPIST
2022 Sep 21	2.12	2.34	1.68±0.22	1.48±0.58	1.76±0.23	<3.14	13.30±3.20	TRAPPIST & CRIRES ⁺
2022 Sep 22	2.11	2.35	2.03±0.29	2.29±1.07	1.69±0.24	<4.93	14.50±3.50	TRAPPIST & CRIRES ⁺

The derived CN/OH ratios are consistent with the HCN/H₂O ratios obtained from near-simultaneous infrared observations, particularly for the data acquired on September 21, 2022 (see Table 3.12). This agreement strongly supports HCN as the dominant parent molecule of CN in the coma of K2. In contrast, the relatively low abundance of C₂ compared to that of C₂H₆ suggests that C₂ is more likely produced through the photodissociation of C₂H₂ rather than C₂H₆. Previous studies have shown that C₂ can be associated with both parent species

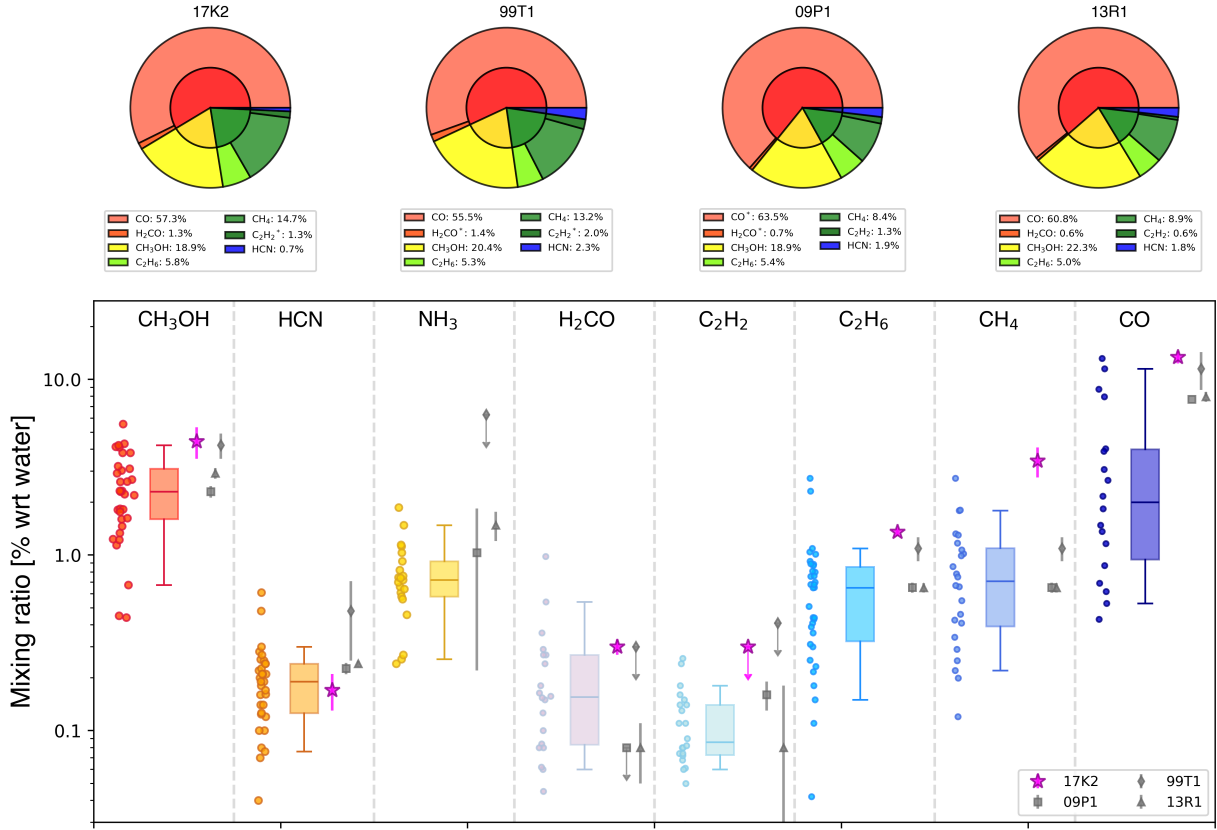


Figure 3.16: Comparison of C/2017 K2 with other comets. In the upper panel, the comet is compared with C/2009 P1, C/1999 T1, and C/2013 R1, which show the closest relative abundance proportions. In the bottom plot, we compare K2 (marked with a magenta star) for each species with the box plot statistic from other infrared results relative to comets observed within 2 au from the Sun (Lippi et al., 2021). For each box, the middle line corresponds to the median, the box is limited to the 25th and 75th percentiles, and the whiskers are limited to the 5th and 95th percentiles. C/2009 P1, C/1999 T1, and C/2013 R1 are also shown with a gray square, diamond, and triangle, respectively.

even at large heliocentric distances, as observed in comet Hale–Bopp (Helbert et al., 2005). Furthermore, no clear parent molecule for C₃ was identified in the infrared spectra of K2. This absence suggests that C₃ is likely produced through chemical reactions occurring within the coma rather than being directly released from a primary volatile.

3.4 Concluding remarks

We performed an extensive multiwavelength observational study of comet K2, a dynamically new Oort cloud comet that exhibited sustained activity at unusually large heliocentric distances. By combining long-term photometric observations obtained with the TRAPPIST telescopes and high-resolution spectroscopic data acquired with UVES and CRILES⁺ at the Very Large Telescope, we investigated the temporal evolution of the cometary activity and molecular composition as the comet approached and receded from perihelion.

The TRAPPIST monitoring program extended over nearly eight years and covered both the pre- and post-perihelion phases of the comet. During this period, more than 270 nights of observations were conducted, yielding over 2200 broadband and 170 narrowband images. This

unique dataset enabled a detailed analysis of the brightness evolution, coma morphology, and color behavior of K2. The resulting light curve revealed a smooth and progressive evolution of activity, with no evidence for major outbursts or abrupt variations. In addition, the measured optical colors remained remarkably stable over a wide range of heliocentric distances, indicating relatively uniform dust properties throughout the observed period.

The combined analysis of narrowband photometry, optical, and infrared spectroscopy provided detailed constraints on the gas production rates and chemical composition of the coma. The first clear detections of CN and C₂ radicals were obtained in March 2022, followed by the appearance of additional molecular species as the comet approached the Sun. The production rates exhibited a gradual increase prior to perihelion, followed by a phase of stabilization around and after perihelion. Based on the relative abundances of C₂, C₃, CN, and OH, K2 was classified as a typical comet within the taxonomic scheme of [A'Hearn et al. \(1995a\)](#). Moreover, the comparison between parent species detected in the infrared and daughter species observed in the optical confirmed that HCN is the primary source of CN in the coma, while C₂ is more likely produced from the photodissociation of C₂H₂ rather than C₂H₆.

Our analysis indicates that optical colors alone do not provide a reliable criterion for distinguishing between different dynamical classes of comets, in agreement with recent results reported by [Holt et al. \(2024\)](#). Within this broader distribution, comet K2 is located toward the bluer end of the color range. The temporal evolution of its activity reveals several distinct phases that can be directly associated with the sublimation, depletion, and subsequent activation of different volatile reservoirs at the nucleus surface.

The combined analysis of the absolute magnitude, $A(0)f\rho$, and dust production rates revealed an unusual decrease in brightness and dust activity between approximately -260 and -170 days from perihelion. This temporary decline is likely related to variations in the relative contributions of CO, CO₂, and H₂O-driven sublimation processes. In particular, our results suggest that this phase corresponds to a partial exhaustion of near-surface hypervolatile ices, leading to a transient reduction in activity. As the comet approached perihelion and water ice sublimation became increasingly efficient, the activity resumed and progressively intensified. This transition from a CO₂-dominated to an H₂O-dominated coma is further supported by the rapid decrease in the observed green-to-red ([OI]) emission line ratio as the comet crossed the water-ice sublimation boundary at approximately 3 au.

Overall, our findings provide new insights into the long-term physical and chemical evolution of comet K2. They emphasize the crucial role of CO and other supervolatile species in sustaining cometary activity at large heliocentric distances. In addition, the compositional properties of K2 contribute to a broader understanding of dynamically new comets and their evolutionary pathways within the Oort cloud population. Our results further suggest that progressive depletion of volatile-rich surface layers can lead to significant changes in activity patterns as comets evolve toward the inner Solar System.

The existence of a population of comets characterized by gradual erosion of their outermost supervolatile-rich layers, resulting in fading or intermittent activity, represents an important topic for future investigation. Continued multiwavelength monitoring of similar objects will be essential to refine our understanding of comet formation environments, thermal evolution, and dynamical histories, and to place comet C/2017 K2 (PanSTARRS) within the broader context of long-period comet evolution.

Chapter 4

Comparative Analysis of Light Curves, Dust–Gas Activity, and Dynamical Evolution of Dynamically New and Returning Long Period Comets

4.1 Introduction

Comets, which originated approximately 4.6 billion years ago within our evolving protoplanetary disk, are some of the most unaltered celestial entities within the solar system. Their virtually unchanged nature since their formation offers an unparalleled glimpse into the early solar system’s volatile evolution during the epoch of planet genesis (Brasser and Morbidelli, 2013). Encased within these celestial bodies lies a trove of information, from clues about the primordial conditions at the dawn of the solar system to hints about the processes during the accretion of planetesimals.

Table 4.1: TRAPPIST observational circumstances and orbital elements of the comets reported in this work. All the orbital elements are taken from the NASA JPL/Horizon database.

Comets	Type	1/a	Peri (au)	Tp (UTC)	r _h -range Pre/Post	Dates Start/End	Number of nights		Number of BB images		Number of NB images	
							TN	TS	TN	TS	TN	TS
C/2009 P1 (Garradd)	LPC - 0.00064515	1.55	2011 Dec. 23	4.70-1.79/2.32-5.81	08.12.2010 - 09.05.2013	-	86	-	413	-	860	-
C/2012 F6 (Lemmon)	LPC + 0.0020268	0.73	2013 Mar. 24	2.26-0.82/1.01-1.54	17 .11.2012 - 06.06.2013	-	63	-	421	-	1031	-
C/2013 R1 (Lovejoy)	LPC + 0.0019608	0.81	2013 Dec. 22	1.92-1.06/1.26-4.21	10.09.2013 - 14.10.2014	-	68	-	261	-	286	-
C/2020 M3 (ATLAS)	LPC + 0.0372895	1.26	2020 Oct. 25	1.43-1.27/1.27-2.53	10.09.2020 - 04.04.2021	25	3	133	18	117	21	-
C/2012 K1 (PanSTARRS)	DNC - 0.0001339	1.05	2014 Aug. 27	6.21-1.38/1.07-5.81	27.03.2013 - 13.12.2015	-	137	-	693	-	456	-
C/2017 T2 (PanSTARRS)	DNC + 0.0002857	1.61	2020 May. 05	3.70-1.61/1.64-2.11	03.08.2019 - 15.08.2020	61	13	385	106	386	-	-
C/2020 V2 (ZTF)	DNC - 0.0005280	2.22	2023 May. 08	3.10-2.30/2.30-5.26	26.10.2022 - 13.08.2024	34	44	234	251	147	-	-
C/2021 S3 (PanSTARRS)	DNC - 0.0002148	1.32	2024 Feb. 14	4.60-1.32/1.37-2.47	19.02.2023 - 13.07.2024	65	38	378	195	197	-	-

Note: i: Inclination, Peri: Perihelion distance, T_p: Time of perihelion passage. The format of the date is Day.Month.Year

Dynamical models have provided valuable insight into the cometary journey. For instance, studies by Gomes et al., 2005 and Walsh and Morbidelli, 2011 suggest that after their formation, the tumultuous migrations of giant planets played a pivotal role in scattering comets into their contemporary reservoirs, namely the Oort Cloud and the scattered disk of the Kuiper Belt. Within these reservoirs, especially the distant Oort Cloud, comets have been frozen

in time, preserving the chemical and mineralogical properties inherited from their nascent environment (Dones et al., 2004). Such preservation makes nearly-isotropic comets (NIC) particularly interesting. Conceived in the giant planets region and later propelled into the Oort Cloud through planetary disturbances, these comets have resided in an almost collision-free zone for billions of years, possibly making them the best-conserved objects in the solar system. Although dynamically new comets are, strictly speaking, a subset of the Long Period comet population, for clarity and to avoid confusion, we use dynamically new comet (DNC) to denote objects with no evidence for any previous return through the inner Solar System, and Long Period comet (LPC) to refer here to the returning comets in our sample.

While they serve as repositories of the solar system’s history, their elusive nature, characterized by their rapid movement, poses significant challenges to in-depth studies. Multi-wavelength surveys, spanning the radio domain (Crovisier et al., 2009), the infrared spectrum (Bockelée-Morvan et al., 2004), and the optical realm (A’Hearn et al., 1995b), have unveiled a rich chemical diversity among comets, hinting at diverse formation processes and possibly different regions of origin within the early solar system. Such observations provide a unique opportunity to unravel the intricate processes that sculpted the early Solar System and its subsequent evolution (Eisstrup et al., 2019).

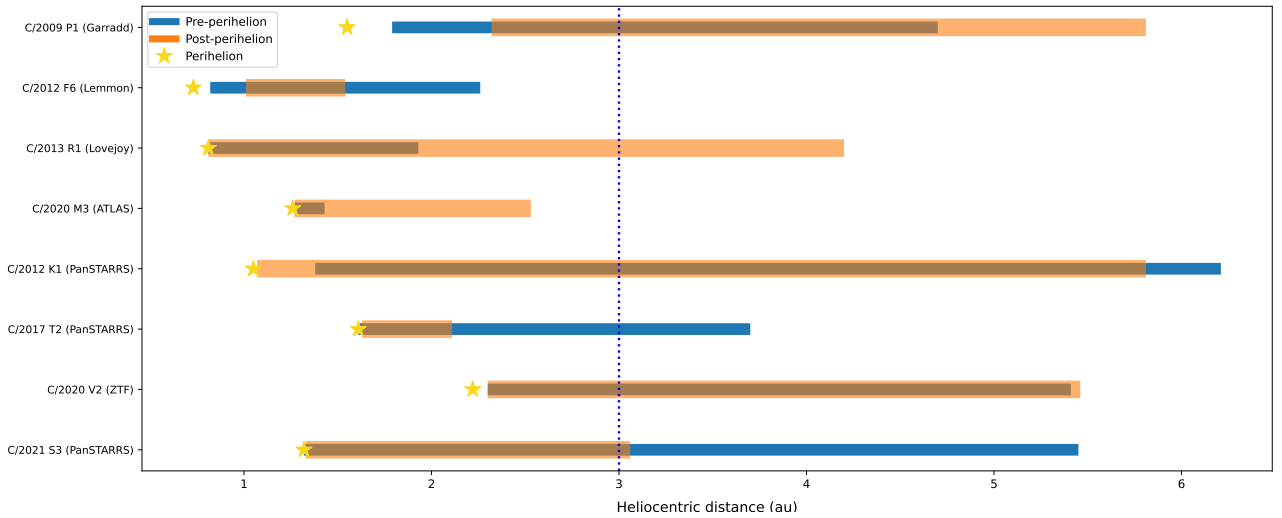


Figure 4.1: Heliocentric distance ranges for comets observed in this work. The vertical dotted blue line represents the water-ice sublimation boundary (~ 3 au).

In this work, we present results from dense and long photometric monitoring of four Long Period comets (LPC) and four dynamically new comets (DNC) obtained between 2010 and 2024 with both TRAPPIST telescopes. Although DNCs are, strictly speaking, a subset of the Long Period comet population, for clarity and to avoid confusion, we use DNC to denote objects with no evidence for any previous return through the inner Solar System, and LPC to refer here to the returning comets in our sample. Through the analysis of these comets, we can infer details about the activity and basic composition of objects coming from the Oort Cloud and look for differences among them. Furthermore, as these comets travel from the very distant regions towards the Sun, they undergo substantial physical changes. By observing these changes over time, we can gain valuable insight into the physical and chemical properties of the cometary nuclei.

The study of multiple comets bestows invaluable insights into the variability that exists among these bodies. By identifying differences in composition and activity level, we can get some information on the conditions present during their formation and subsequent thermal

processing history. Finally, studying a group of comets can enhance our predictive capabilities, which is of great use when trying to anticipate the behavior and characteristics of as-yet-unobserved comets. This knowledge can inform the planning of future observational campaigns and spacecraft missions to comets, such as the ESA Comet Interceptor mission (Snodgrass and Jones, 2019), which intends to target a dynamically new comet.

We followed the evolution of the production rates of the gas species, e.g., OH, NH, CN, C₃, and C₂, using the HB narrow band filters (Farnham et al., 2000). We also measure the magnitude and the $A(\theta)f\rho$ parameter, a proxy for dust production (A’Hearn and Millis, 1984), in the broad-band filters B, V, Rc, and Ic (Bessell, 1990) and in the narrow-band dust continuum filters BC, GC, and RC for blue, green, and red (Farnham et al., 2000). Data calibration followed standard procedures mentioned before (see 2.4). In order to compute the gas production rates from the HB narrow-band images, we derived the median radial brightness profiles for these images. The BC images are used to remove the dust contamination, because it is less contaminated by cometary gas emission than other dust filters (Farnham et al., 2000). The flux is converted to column density, and the profile is fitted with the Haser model (Haser, 1957; Haser et al., 2020) at 10,000 km from the nucleus. We use an outflow velocity of 1 km/s and the effective scale lengths from (A’Hearn et al., 1995b). For more details, we refer to previous works (Hmiddouch et al., 2025; Vander Donckt et al., 2026; Moulane et al., 2018; Opitom et al., 2015a). We compute the vectorial-equivalent water production rates using the empirical relationship $Q(H_2O) = 1.361r_h^{-0.5}Q(OH)$ based on a $r_h^{-0.5}$ dependence of the H₂O outflow velocity, a photodissociation branching ratio for water to OH of 90%, and the heliocentric distance (Schleicher et al., 1998). We compute the $Af\rho$ parameter within 10,000 km from the nucleus, and we correct it for the phase angle effect according to the phase function normalized at $\theta=0^\circ$ described by Schleicher¹, which is a composite of two different phase functions from Schleicher et al., 1998 and Marcus, 2007.

This chapter is structured as follows. Following the introduction in Section 4.1, Section 4.2 presents the dynamical histories and prior Solar-System context. Our observations and the associated data reduction techniques are described in Section 4.3. Section 4.3.1 presents the evolution of activity and composition, including production rates, dust proxies, and colors. Section 4.4 presents further results and discussion, and Section 4.5 closes the paper with a summary and conclusion.

4.2 Dynamical histories and prior Solar-System exposure

4.2.1 Numerical methods

To assess how strongly each comet may have been altered by previous passages through the inner Solar System, we reconstructed their past orbital evolution using N-body integrations of the nominal orbit and associated clone swarms. The integrations were carried out with MERCURY (Chambers, 1999, 2012) and performed with the Hybrid integrator. REBOUND was used as an independent verification of the broad dynamical behavior recovered with MERCURY. Depending on the dynamical behavior of the object, we either employed IAS15, the adaptive high-order integrator, or MERCURIUS, the hybrid integrator (Rein and Tamayo, 2015). In practice, IAS15 was preferred for the more chaotic or dynamically old cases, for which it generally produced the cleanest results, although at substantially higher computational cost. The integrations were initially carried backward to -1 Myr. For comets whose evolution indicated a possible previous

¹<https://asteroid.lowell.edu/comet/dustphase.html>

perihelion passage beyond this interval, the integrations were extended further backward in time to recover, where possible, the timing and orbital parameters of that preceding passage.

For both integrators, we independently generated 1000 massless clones of each comet in the sample based on its nominal orbital elements and the associated covariance matrix from the JPL *Small Body Database*, sampling from a multivariate normal distribution centered on the nominal orbit. The positions of the eight planets and each comet clone were computed at every timestep. Each clone acted as an independent test particle, without mutual gravitational interactions. When available in the orbital solution, non-gravitational forces were included. General relativity was neglected. We did not include galactic tides: This is an important caveat for clones reaching very large heliocentric distances, where external perturbations can affect the long-term evolution of Oort-cloud comets. The present integrations should therefore be viewed as a first-order estimate of the past dynamical histories rather than as a complete external-perturbation model. In practice, the omission of galactic tides is least problematic for clones that remain well inside the outermost scale of the Solar System’s gravitational sphere of influence, often taken to be of order 2×10^5 au (e.g. [Chebotarev, 1965](#)). Clones are removed from the simulation when their heliocentric distance surpasses 10^6 au.

Table 4.2: Summary of the dynamical classification results for the comet sample.

Object	$1/a$ (au^{-1})	t_{prev} (yr)	$1/a_{\text{prev}}$ (au^{-1})	q_{prev} (au)	Avg. no. orbits /1 Myr	New Type
C/2009 P1	-0.0006452	-1.1×10^5	$+0.0003971 \pm 0.0000043$	1.50 ± 0.03	4.66 ± 23.94	LPC
C/2012 F6	+0.0020268	9750	$+0.0020706 \pm 0.0000513$	0.58 ± 0.01	3.47 ± 5.78	LPC
C/2013 R1	+0.0019608	6902	$+0.0027820 \pm 0.0000197$	0.71 ± 0.003	21.93 ± 91.89	LPC
C/2020 M3	+0.0372895	139	$+0.0405200 \pm 0.0000002$	1.22 ± 0.00005	388.59 ± 814.62	LPC
C/2012 K1	-0.0001339	-4.2×10^6	$+0.0000335 \pm 0.0000001$	91.62 ± 32.76	0.00	DNC*
C/2017 T2	+0.0002857	-5.1×10^6	$+0.0000372 \pm 0.0000167$	48.35 ± 30.40	0.00	DNC*
C/2020 V2	-0.0005280	-4.6×10^6	$+0.0000312 \pm 0.0000001$	11.94 ± 17.38	0.00	DNC*
C/2021 S3	-0.0002148	–	–	–	0.00	DNC

Note. Objects marked DNC* are nominally classified here as dynamically new comets, but may in fact be returning objects whose previous perihelion passage occurred several Myr ago. Their previous orbital elements are indicated in **bold**. The average number of orbits is estimated by averaging the number of times each clone travels inside 10 au within 1 Myr across the entire swarm, excluding the current orbit. Previous orbital elements are measured when the comet is inbound at $r_h > 200$ au on the reconstructed previous orbit, except for C/2020 M3, whose aphelion is only 46 au.

A clone swarm that remains compact under backward integration suggests that the past dynamical evolution is robustly constrained. By contrast, rapid divergence of the clone trajectories indicates that the detailed past orbit is no longer uniquely recoverable, even if a broad dynamical classification may still be possible. The main purpose of these calculations is to estimate the previous levels of exposure of a comet to the inner Solar System; therefore, we paid particular attention to the previous perihelion distance, the time to the previous perihelion passage, and the number of entries into the inner Solar System recovered across the clone swarm. In order to estimate quantitatively how much alteration a comet may have undergone, we counted the number of times each clone crossed inward of 10 au over 1 Myr, and then averaged this quantity across the clone swarm. The results of our integrations are presented in Tab. 4.2. Values for the previous reciprocal semi-major axis $1/a_{\text{prev}}$ and perihelion distance q_{prev} are taken when the comet is inbound on its previous orbit at $r_h > 200$ au, by which point the osculating elements are expected to be much less sensitive to further strong planetary perturbations than within the inner Solar System.

4.2.2 Previous inner Solar-System exposure

The reconstructed dynamical histories reveal a broad range of previous inner Solar-System exposure across the sample (Fig. 4.2). Several comets show clear evidence of repeated previous returns and are therefore unlikely to preserve entirely pristine surfaces or near-surface volatile inventories, while a smaller subset remains consistent with a first approach to the planetary region, or at most with a previous return so distant that only limited alteration would be expected.

Among the clearly returning objects, C/2012 F6, C/2013 R1, and C/2020 M3 are the strongest cases for significant prior dynamical processing. For both C/2012 F6 and C/2013 R1, the clone swarms show highly unstable past evolution and do not support a simple first injection from the Oort Cloud. In both cases, the previous perihelion passage can nevertheless be robustly recovered, occurring 9750 yr ago for C/2012 F6 and 6902 yr ago for C/2013 R1, and every clone also completes at least one additional earlier orbit, although with increasing dispersion in orbital period. These two comets, therefore, appear to have been returning Long Period comets for at least several cycles, even if their more distant past evolution rapidly becomes chaotic.

C/2020 M3 is even more clearly evolved. Its clone swarm shows repeated prior returns through the planetary region, and unlike the more weakly bound Long Period cases, its recent orbital evolution appears quasi-periodic over many successive revolutions. The last perihelion passage occurred about 139 yr ago, and the clones remain mutually consistent over roughly a dozen such returns before diverging more strongly. This makes C/2020 M3 the clearest example in the sample of a comet that has undergone repeated previous exposure to the inner Solar System and is therefore likely to have experienced substantial dynamical and physical processing.

C/2009 P1 also appears dynamically old, although its case is somewhat less extreme in terms of deep previous inner Solar System exposure. While its clone swarm supports a returning-comet interpretation, the recovered past orbits do not, on average, penetrate very deeply into the inner Solar System. The number of previous passages within 10 au is only 4.66 ± 23.94 per clone over 1 Myr, indicating a broad and highly skewed distribution in which some clones undergo repeated returns while others show much more limited prior exposure. In that sense, C/2009 P1 appears dynamically old, but not necessarily strongly processed by repeated low-perihelion passages.

At the other end of the sample, C/2021 S3 is the clearest dynamically new object. Its clone swarm remains highly coherent backward in time and shows no evidence for any previous return through the inner Solar System.

A small subset of the sample occupies an intermediate regime between clearly dynamically new and clearly returning objects: C/2017 T2, C/2012 K1, and C/2020 V2 all show evidence for a possible previous orbit, with estimated previous perihelion times of approximately 5.1, 4.2, and 4.6 Myr, respectively. However, these cases should be treated with caution. At such long timescales, even when the clone swarm remains coherent in a broad sense, the detailed reconstruction of the previous orbit is necessarily more uncertain than for shorter and more compact backward integrations. That said, these results are not driven by a small number of outlying clones. In all three cases, the clone swarm follows the same large-scale orbital evolution and points to a previous return on Myr timescales, and remains well within 10^5 au in these integrations, and therefore never approaches the most weakly bound outer Oort-cloud regime where the omission of galactic tides would be expected to have the strongest effect. The uncertainty lies less in whether the swarm shares that broad trajectory than in how much

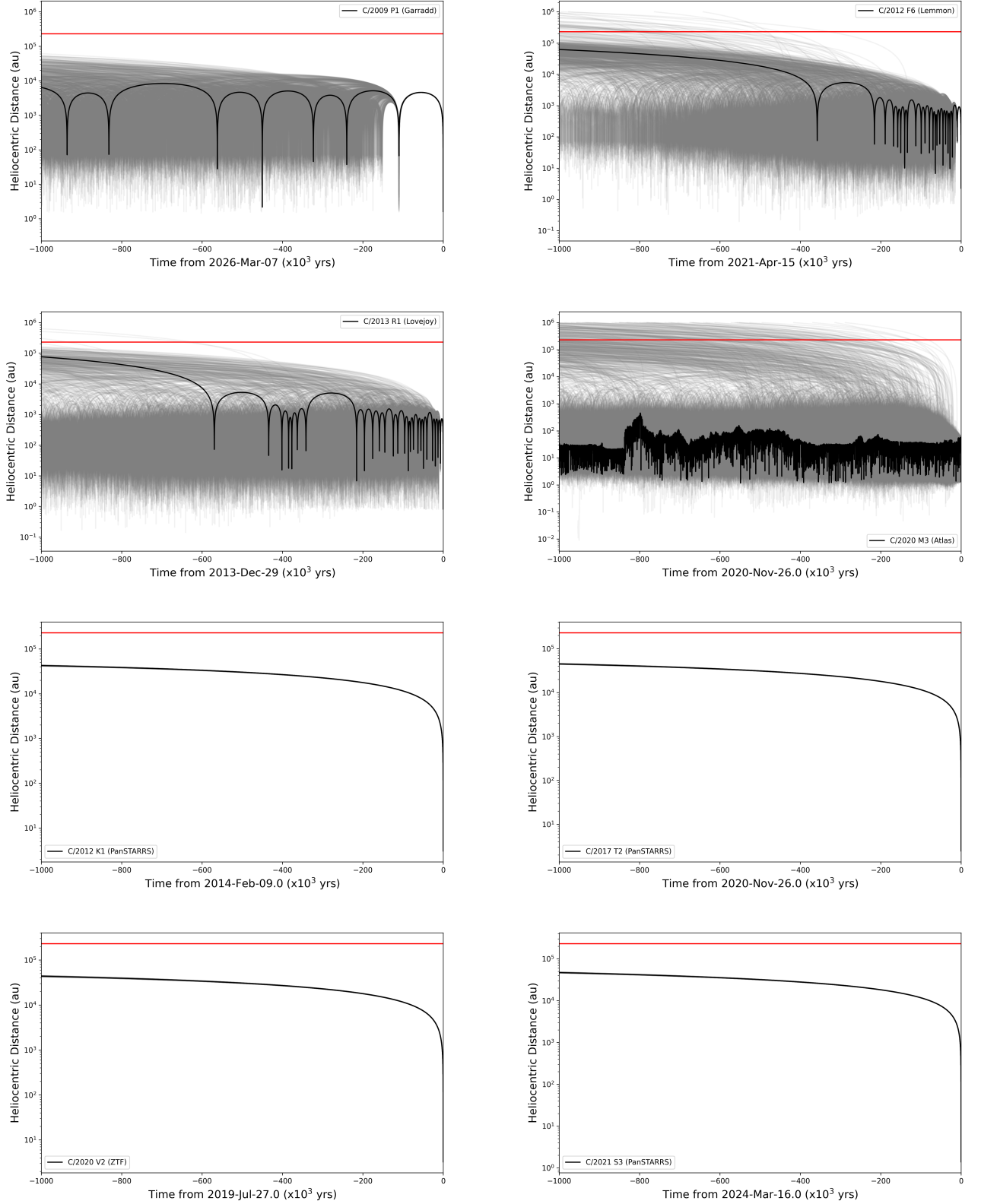


Figure 4.2: Heliocentric distance as a function of time over 1 Myr for the comets in this study. The nominal orbit of each comet is shown in black, while the associated clone swarm is shown in gray. The red line indicates the approximate heliocentric (2.3×10^5 au, [Chebotarev \(1965\)](#)) distance beyond which Galactic tides may become important for the long-term orbital evolution.

physical significance should be attached to the inferred previous perihelion distance and hence to the degree of prior Solar-System processing.

From the point of view of compositional alteration, the key result is that these possible previous returns appear to have been very distant. For C/2012 K1, none of the clones enter even within 100 au on the inferred previous orbit. For C/2020 V2 and C/2017 T2, fewer than 1% of clones reach inside 10 au. In other words, even if these comets are not strictly first-time visitors to the planetary region, the inferred previous passages were probably too distant to have caused any repeated thermal or physical processing. Taken together, these three comets are best regarded as dynamically new in a practical sense, but with the possibility of a previous, very distant perihelion passage on Myr timescales. If such a return did occur, it is unlikely to have significantly altered their present-day composition.

4.2.3 Comparison with other assessments

To place our classifications in context, we compared them with the *Catalogue of Cometary Orbits and their Dynamical Evolution* (CODE), which reconstructs original and previous comet orbits using Monte Carlo swarms and includes planetary, Galactic, and stellar perturbations (Dybczyński and Królikowska, 2025). In that framework, the most informative quantity is the previous perihelion distance, rather than the sign of the original reciprocal semimajor axis $1/a$ alone. This is broadly consistent with the approach adopted here, where the emphasis is placed on previous inner Solar-System exposure rather than on the simple dynamically new/dynamically old dichotomy.

The strongest agreement concerns the comets we classify as dynamically new or nearly so. In CODE, C/2017 T2, C/2020 V2, and C/2021 S3 are all consistent with dynamically new interpretations, with previous perihelion distances ranging from several hundred to more than 10^3 au. For C/2021 S3, the non-gravitational CODE solution gives a previous orbit at ~ 10 Myr, longer than our simulations explored. However, 100% of virtual comets have $q_{\text{prev}} > 20$ au, again supporting a dynamically new interpretation. For C/2017 T2 and C/2020 V2, the reconstructed previous-return times are of order several Myr, indicating that if an earlier return occurred, it was likely very distant and unlikely to have involved a previous deep passage into the inner Solar System. This interpretation is also consistent with more object-specific observational papers: Combi et al. (2021) describes C/2017 T2 as dynamically new and likely on its first orbit into the inner Solar System based on its original reciprocal semimajor axis. Likewise, Ahuja et al. (2025) explicitly categorizes C/2020 V2 as a dynamically new long period comet making its first approach to the inner Solar System. Overall, these external results are in good agreement with our conclusion that C/2017 T2, C/2020 V2, and C/2021 S3 are dynamically new in a practical sense, even if C/2017 T2 and C/2020 V2 may have undergone a very distant earlier perihelion passage on Myr timescales.

C/2012 K1 is a more nuanced case: in CODE, the preferred previous-orbit solution including both Galactic and stellar perturbations gives a previous perihelion distance of about 3985 au at -3.86 Myr, with all virtual comets satisfying $q_{\text{prev}} > 20$ au. This is in line with our own result: C/2012 K1 behaves as a dynamically new comet in most respects, but its status becomes less straightforward when the possibility of a distant previous return is considered. However, in the Galactic-tide-only variant, 100% of the clones have a $q_{\text{prev}} < 10$ au, so some alteration may have occurred.

C/2012 F6 has been described observationally as a dynamically old comet (Opitom et al., 2015a), with Biver et al. (2016) giving an original orbital period of about 9800 years, which is consistent with our classification of it as a previously processed Long Period comet. It is not

present in CODE. Similarly, C/2009 P1 is commonly described as dynamically young: [Bodewits et al. \(2014\)](#) note that it was likely not on its first passage through the inner Solar System, and [Gicquel et al. \(2015\)](#) estimate it has a periodicity of 127,000 yr. CODE, however, indicates a previous passage 5.4×10^5 years ago, with a perihelion distance of ~ 3.827 au.

For the remaining clearly returning objects in our sample, namely C/2013 R1 and C/2020 M3, we did not find equally strong dedicated previous perihelion studies in our literature survey. Their classifications in the present work should therefore be regarded as internally robust but less directly benchmarked against object-specific external dynamical reconstructions. Even so, the overall comparison with CODE and with the available observational literature is encouraging: the classifications derived here are consistent with other studies, while our clone-based integrations add a more explicit measure of previous inner Solar-System exposure, which is the quantity most relevant for interpreting the observed cometary compositions.

4.3 Observations and Data Reduction

We used the TRAPPIST telescopes ([Jehin et al., 2011](#)) to monitor the activity of four bright LPCs and four DNCs in the 2010-2024 period. We follow the evolution of the production rates of the gas species, e.g., OH, NH, CN, C₃, and C₂, using the HB narrow-band filters ([Farnham et al., 2000](#)). We also measure the magnitude and the $A(\theta)f\rho$ parameter, a proxy for dust production ([A’Hearn and Millis, 1984](#)), in the broad-band filters B, V, Rc, and Ic ([Bessell, 1990](#)) and in the narrow-band dust continuum filters BC, GC, and RC for blue, green, and red ([Farnham et al., 2000](#)).

Data calibration followed standard procedures using frequently updated master bias, flat, and dark frames. We removed the sky contamination, and the flux calibration was performed using zero points regularly updated by the observation of standard stars during photometric nights. In order to compute the gas production rates from the HB narrow-band images, we derived the median radial brightness profiles for these images. The BC images are used to remove the dust contamination, because it is less contaminated by cometary gas emission than other dust filters ([Farnham et al., 2000](#)). Fluorescence efficiencies (also called g-factors) from Schleicher’s website ² are used to convert fluxes into column densities. The profile is then fitted with the Haser model ([Haser, 1957](#); [Haser et al., 2020](#)) at 10,000 km from the nucleus. We use an outflow velocity of 1 km/s and the effective scale lengths from ([A’Hearn et al., 1995b](#)), scaled as r_h^2 . We would like to highlight that the Haser Model is not physically accurate, as it assumes a one-step photodissociation of the parent molecule into daughter molecules in a spherically symmetric coma. Despite its limitations, the Haser model is commonly used to determine the gas production rates from optical comet observations. It enables comparisons between observations made by various observers, as well as comparisons between different comets. The model adjustment is performed at a nucleocentric distance of around 10,000 km to avoid PSF and seeing effects around the optocenter. At greater nucleocentric distances, the signal usually becomes fainter, especially in the OH filter for which the signal-to-noise ratio is lower. For more details, we refer to previous works ([Hmiddouch et al., 2025](#); [Vander Donckt et al., 2026](#); [Moulane et al., 2018](#); [Opitom et al., 2015a](#)).

We compute the vectorially equivalent water production rates using the empirical relationship $Q(H_2O) = 1.361r_h^{-0.5}Q(OH)$ based on an $r_h^{-0.5}$ dependence of the H₂O outflow velocity, a photodissociation branching ratio for water to OH of 90%, and the heliocentric distance ([Schleicher et al., 1998](#)). We compute the $Af\rho$ parameter within 10,000 km from the nucleus, and

²<https://asteroid.lowell.edu/comet/gfactor.html>

we correct it for the phase angle effect according to the phase function normalized at $\theta=0^\circ$ described by Schleicher ³, which is a composite of two different phase functions from Schleicher et al., 1998 and Marcus, 2007.

4.3.1 Data analysis

This section presents the photometric analysis of the eight comets observed with TRAPPIST. We examine the evolution of their light curves across different filters and the corresponding coma dust colors, which shed light on dust properties and their temporal variability. We then investigate the gas production rates and the $Af\rho$ parameter, both before and after perihelion, along with their ratios, to assess the activity levels and compositional changes of these comets over time.

4.3.1.1 C/2009 P1 (Garradd)

Comet C/2009 P1 (Garradd), hereafter 09P1, was discovered by Gordon J. Garradd at Siding Spring Observatory, Australia, in August 2009 at a heliocentric distance of 8.7 au, already exhibiting a distinct dust coma at the time of discovery. The comet reached perihelion on December 23, 2011, at $r_h = 1.55$ au, and made its closest approach to Earth on March 5, 2012, at a geocentric distance of $\Delta = 1.27$ au. With a peak brightness of approximately 10 mag, the comet was well-suited for both ground- and space-based observations.

C/2009 P1 was notably dust-rich and displayed complex activity that evolved significantly with heliocentric distance, with substantial dust and gas production already occurring well beyond the water ice sublimation zone. Paganini et al. (2012) reported that the comet was CO-rich, with a CO-to-water production rate ratio of 12–13%. The water production rate exhibited a strong pre/post-perihelion asymmetry: it increased steeply before perihelion following an $\sim r^{-6}$ dependence, and subsequently declined more gradually post-perihelion following an $\sim r^{-4}$ relation (Bodewits et al., 2014; Feaga et al., 2014). This marked asymmetry was further confirmed by Combi et al. (2013), who found that the pre-perihelion activity was considerably higher than post-perihelion and varied in a notably irregular manner.

The production rates of the monitored gas species, along with the $Af\rho$ dust parameter and their associated uncertainties, are presented in Table C.2. The temporal evolution of these quantities is illustrated in Figures 4.10 and 4.8. Detection of CN, C₂, and C₃ was achieved from the beginning of May 2011 at $r_h = 3.33$ au, while OH was first recorded in the first week of June 2011 at $r_h = 2.96$ au. CN, C₂, and C₃ remained detectable up to 148 days after perihelion, with the last signals recorded at the end of May 2012 at $r_h = 2.48$ au. The production rates of all monitored species rose gradually from the onset of our observations, exhibiting a plateau-like behavior with a peak activity on October 4, 2011, at $r_h = 1.89$ au, 79 days before perihelion, with the OH production rate reaching 1.11×10^{29} molec s⁻¹. The logarithmic mean ratio $\log[Q(\text{C}_2)/Q(\text{CN})] = 0.053$ places comet 09P1 within the boundary defined by A'Hearn et al. (1995b) for carbon-chain typical comets. The mean dust-to-gas ratio is likewise consistent with the typical comet population (Table 4.5 and Figure 4.12), and we therefore classify 09P1 as a typical comet.

³<https://asteroid.lowell.edu/comet/dustphase.html>

4.3.1.2 C/2012 F6 (Lemmon)

Comet C/2012 F6 (Lemmon), hereafter 12F6, is an Oort Cloud comet discovered on March 23, 2012, by A. R. Gibbs at the Mount Lemmon Observatory when it was 5 au from the Sun. The comet's orbital parameters⁴, eccentricity $e = 0.998$, original semimajor axis $a = 458.08$ au, Tisserand parameter $T_j = 0.147$, and inclination $i = 82.6^\circ$, classify it as a nearly isotropic long period comet originating from the Oort Cloud. It reached its perihelion on March 24, 2013, at a distance of 0.73 au from the Sun. The comet started to brighten significantly (magnitude 15) in October 2012, after the recovery from the Sun conjunction that was in June 2012. The comet attained a maximum brightness of approximately magnitude 4.4 around perihelion by the JPL ephemeris⁵.

We initiated intensive monitoring of its activity with TRAPPIST-South on November 18, 2012 (2.26 au) until June 06, 2013 (1.54 au). All the daughter species (eg, CN, C₂, C₃, OH, and NH) were detected from the second week of December 2012 and remained detectable in TRAPPIST observations through the second week of June 2013 at 1.61 au from the Sun. The production rates of the monitored gas species and the $Af\rho$ dust parameter, along with their uncertainties, are given in Table C.3, and their evolution over time is shown in Figures 4.10 and 4.8. The production rates of all species grew steadily until the first week of March 2013, when the comet reached perihelion and its peak activity, with a maximum OH production rate of 2.20×10^{29} molec s⁻¹. The logarithmic mean ratio $\log[Q(C_2)Q(CN)] = 0.20$ is consistent with the carbon-chain typical comet class as defined by A'Hearn et al. (1995b). The dust-to-gas ratio is slightly above the mean value of typical comets.

4.3.1.3 C/2013 R1 (Lovejoy)

Comet C/2013 R1 (Lovejoy), hereafter 13R1, is a dynamically old, long period comet with an orbital period of approximately 7000 years (Wirström et al., 2016), following a highly inclined and eccentric orbit ($i = 64^\circ$, $e = 0.9924$). It was discovered on September 7, 2013, by Australian amateur astronomer Terry Lovejoy at a heliocentric distance of 1.98 au and an apparent magnitude of 14.4 (Guido et al., 2013), subsequently brightening to magnitude 4.5 around perihelion passage on December 22, 2013, at 0.81 au from the Sun. The comet proved to be an exceptional observational target and was extensively monitored across a broad range of wavelengths and instruments near perihelion. Taking advantage of TRAPPIST's rapid-response capability, observations were initiated using TRAPPIST-South only three days after discovery. The comet's visibility both pre- and post-perihelion, combined with its favorable brightness, made it particularly well-suited for a comprehensive study of its activity evolution and chemical composition, motivating an intensive TRAPPIST monitoring campaign with both narrow- and broad-band filters.

Observations of comet 13R1 began on September 11, 2013, at a heliocentric distance of $r_h = 1.91$ au, and continued until October 14, 2014, at $r_h = 4.21$ au post-perihelion. From the onset of observations right after the discovery, CN, C₂, C₃, and OH were detected immediately, with NH becoming detectable approximately 10 days later. OH and NH were last detected in the third week of April 2014 ($r_h = 2.20$ au), while C₃ was last recorded at the end of May 2014 ($r_h = 2.66$ au). CN and C₂ proved the most resilient species, remaining detectable until the first week of July 2014, 197 days after perihelion, at $r_h = 3.10$ au.

The production rates of the monitored gas species and the $Af\rho$ dust parameter, along with their associated uncertainties, are listed in Table C.4, and their temporal evolution is illustrated

⁴S. Nakano Note, NK 2452, <https://www.oaa.gr.jp/~oaacs/nk/nk2452.htm>

⁵JPL ephemeris <https://ssd.jpl.nasa.gov/horizons/app.html>

in Figures 4.10 and 4.8. The production rates of all monitored species rose gradually from the beginning of our observations, reaching peak activity on November 16, 2013, 48 days before perihelion (in our database), with a maximum OH production rate of 2.83×10^{28} molec s⁻¹. The logarithmic mean ratio $\log[Q(\text{C}_2)/Q(\text{CN})] = 0.079 \pm 0.005$ is consistent with the carbon-chain typical comet boundary as defined by A’Hearn et al. (1995b). The dust-to-gas ratio is slightly above the mean value of typical comets, and 13R1 is therefore classified as a typical comet.

4.3.1.4 C/2020 M3 (ATLAS)

Comet C/2020 M3 (ATLAS), hereafter 20M3, was discovered on June 27, 2020, by the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey in Hawaii. When first spotted, it was 18.8 au away from the Sun. 20M3 reached its perihelion on October 25, 2020, drawing as close as 1.26 au to the Sun. During this cosmic voyage, its luminance reached a magnitude of 13, capturing the attention of skywatchers and scientists alike.

Our observations of 20M3 began on September 11, 2020, when it was at a heliocentric distance of 1.43 au, and we monitored its radiant splendor until April 03, 2021, at a distance of 2.53 au after perihelion. We detected gas species CN, C₂, and C₃ that occurred from the beginning of our observations in early September 2020, with OH and NH identified one month later. NH remained detectable in TRAPPIST images until mid-December 2020 (rh=1.48 au), while CN, C₂, C₃, and OH signals persisted until the second week of February 2021, when the comet was at 2 au.

The production rates for individual gas species, the $Af\rho$ dust parameter, and their corresponding uncertainties are outlined in Table C.5. Their temporal evolution is depicted in Figures 4.10 and 4.8. Production rates for various species saw a gradual increase until the end of October 2020, when the comet reached its peak activity 5 days post-perihelion. We obtained a Logarithmic mean value of C₂/CN=0.114±0.01, which is defined in A’Hearn et al. (1995b) as part of the carbon-chain typical comets. This classifies comet 20M3 as typical, with a dust/gas ratio a bit smaller than the mean value of typical comets.

4.3.1.5 C/2012 K1 (PanSTARRS)

Comet C/2012 K1 (PanSTARRS), hereafter 12K1, is a dynamically new Oort Cloud comet making its inaugural voyage into the inner solar system (Nakano 2013 ⁶). 12K1 reached its perihelion on August 27, 2014, at $r_h = 1.05$ au and achieved its closest approach to Earth on October 31, 2014 ($\Delta = 0.95$ au).

Comet 12K1 has been extensively studied through various terrestrial and space telescopes, including the Spitzer Space Telescope. McKay et al. (2016) determined the CO₂/H₂O ratio, finding a ratio of $12.6 \pm 1.3\%$, close to the average abundance measured in comets at similar heliocentric distances. Cordiner et al. (2017) observed methanol (CH₃OH) emissions from 12K1 using the Atacama Large Millimeter/submillimeter Array on June 28, 2014. Their findings indicated that the methanol column density distributions were consistent with isotropic, uniform outflow from the nucleus, with no evidence for extended sources of methanol in the coma at nuclear distances of approximately 500 to 2500 km. Additionally, Roth et al. (2017) detected fluorescent emissions from six primary volatiles (H₂O, HCN, CH₄, C₂H₆, CH₃OH, and CO) and compared these with Oort Cloud comets. The gas abundance ratios in 12K1 for CO and HCN were consistent with those in Oort Cloud comets, whereas CH₃OH and C₂H₆

⁶Nakano, S. 2013, C/2012 K1 (PANSTARRS). Nakano Note NK 2588, <https://www.oaa.gr.jp/~oaacs/nk/nk2588.htm>

were enriched, and H₂CO, CH₄, and C₂H₂ were depleted.

We initiated our observations of comet 12K1 on March 28, 2013, at a heliocentric distance of 6.21 au, and continued monitoring its bright display until December 14, 2015, when it was 5.81 au post-perihelion. Early detection in the beginning of February 2014 revealed the presence of gas species CN, C₂, and C₃, with OH becoming apparent by mid-March 2014, and NH a bit later at the beginning of September 2014. OH and NH were visible in TRAPPIST images until the second week of December 2014 ($r_h=2$ au), OH and C₃ until the first week of January 2015 ($r_h=2.29$ au), while CN and C₂ were detectable until February 2015 at a distance of 2.58 au.

The production rates for each gas species, the $Af\rho$ dust parameter, and their associated uncertainties are presented in Table C.6. Figures 4.11 and 4.9 illustrate their temporal development. Production rates for the different species steadily increased until September 06, 2014, when the comet peaked, with an OH production rate peaking in our data at 6.72×10^{28} molec/s, 58 days after perihelion. We recorded a mean value of $\text{Log}[Q(\text{C}_2)/Q(\text{CN})]=0.18 \pm 0.004$, positioning it at the boundary defined by A’Hearn et al. (1995b) for carbon-chain typical comets. Consequently, comet 12K1 is classified as typical, albeit with a slightly lower dust/gas ratio compared to the average typical comets.

4.3.1.6 C/2017 T2 (PanSTARRS)

Comet C/2017 T2 (PanSTARRS), hereafter 17T2, is an Oort Cloud comet discovered on October 2, 2017, by the PANSTARRS survey when it was 9.2 au from the Sun. The closest approach to Earth was on December 28, 2019, at a geocentric distance of 1.52 au, and it reached its perihelion on May 4, 2020, at 1.61 au from the Sun. The comet reached a maximum magnitude of 12 by the end of May 2020. We started monitoring its activity with TRAPPIST-South on August 4, 2019 ($r_h=3.70$ au, $\Delta=4.17$ au), and one month later with TRAPPIST-North, until August 15, 2020 ($r_h=2.11$ au, $\Delta=2.42$ au). We started detecting CN, C₂, C₃, and OH at the beginning of November 2019, while NH was detected later in the second week of December. C₃, NH, and OH were still detected in TRAPPIST images in late June and early July 2020, at heliocentric distances of $r_h=1.80$ au and $r_h=1.84$ au, respectively. CN and C₂ emissions persisted to larger heliocentric distances, remaining detectable until mid-August 2020 at $r_h=2.11$ au. We did not observe the comet from March 10 to April 1, 2020, as it was too low at the Oukaimeden observatory.

The derived production rates for each gas species, the $A(0)f\rho$ dust parameter, and their uncertainties are summarized in Table C.7. Their time evolution is shown in Figures 4.11 and 4.9. The production rates of different species have been increasing slightly since the beginning of our monitoring until February 26, 2020, when the comet reached its maximum activity with a water-production rate peak of $(5.50 \pm 0.12) \times 10^{29}$ molec/s two months pre-perihelion. Then, the activity of the comet decreased rapidly post-perihelion. Schleicher et al. (2020) derived a water production of 6×10^{28} molec/s in early October 2019 at a distance of 3.15 au from the Sun, while we obtained $Q(\text{H}_2\text{O})=1.73 \pm 0.11 \times 10^{29}$ molec/s a month later ($r_h=2.60$ au). Relative abundances for different species were derived and summarized in Table 4.5. Logarithmic mean ratios are shown in Table 4.5, and the evolution of C₂/CN ratios is shown in Figure 4.13. We got a logarithmic mean value of 0.008 ± 0.005 for C₂/CN in agreement with the mean value of typical comets (A’Hearn et al., 1995b). We conclude that 17T2 has a typical coma composition, with a high dust/gas ratio.

4.3.1.7 C/2020 V2 (ZTF)

Comet C/2020 V2 (ZTF), hereafter 20V2, was discovered by the Zwicky Transient Facility (ZTF) in November 2020 at a heliocentric distance of 8.7 au. The comet reached perihelion on May 8, 2023, at $r_h = 2.22$ au. With a semimajor axis of $a = -1984$ au and an eccentricity of $e = 1.001^7$, V2 is classified as a dynamically new comet arriving from the Oort Cloud on its first passage through the inner Solar System.

Comet 20V2 was observed with both narrow-band and broad-band filters using the TN and TS telescopes. The observing campaign spanned from October 26, 2022 ($r_h = 3.10$ au, pre-perihelion) to August 13, 2024 ($r_h = 5.26$ au, post-perihelion), enabling a comprehensive analysis of the long-term evolution of the comet’s gas and dust activity. The production rates for each gas species, the $Af\rho$ dust parameter, and their associated uncertainties are presented in Table C.8. Figures 4.11 and 4.9, illustrate their temporal development. The gas species CN, C₂, C₃, and OH were detected from the onset of our observations in early November 2022. While C₃ and OH remained detectable in TRAPPIST images until September 1, 2023 ($r_h = 2.59$ au), CN and C₂ emissions persisted to larger heliocentric distances, with signals recorded through the first week of October 2023, when the comet had receded to $r_h = 2.81$ au. The production rates of all monitored species increased slowly from the beginning of our observations until March 03, 2023, when comet 20V2 reached its peak activity, with an OH production rate of $7.78 \pm 1.18 \times 10^{28}$ molec s⁻¹, 65 days before perihelion. Then they started to decrease in the same way again after perihelion. We got the last detection of gas (CN and C₂) in TRAPPIST images on October 08, 2023, at $r_h = 2.81$ au.

We don’t have data around perihelion because the comet was behind the Sun as seen from Earth, so observations were not possible. Relative abundances for the detected species were derived, with logarithmic mean ratios listed in Table 4.5 and the temporal evolution of the $\log[Q(C_2)/Q(CN)]$ ratio illustrated in Figure 4.13. We obtained a logarithmic mean value of $\log[Q(C_2)/Q(CN)] = -0.235 \pm 0.011$, which is among the lowest values in our sample, but still falls within the typical comet boundary as defined by A’Hearn et al. (1995b). We therefore classify 20V2 as a typical comet, with a dust-to-gas ratio slightly higher than the mean value of the typical comet population.

4.3.1.8 C/2021 S3 (PanSTARRS)

Comet C/2021 S3 (PanSTARRS), hereafter 21S3, was discovered on September 24, 2021, by the Pan-STARRS survey, at a heliocentric distance of ~ 8.6 au. Pre-discovery observations obtained as early as December 6, 2020, were subsequently identified in archival Pan-STARRS data. The comet reached perihelion on February 14, 2024, at $r_h = 1.32$ au. With a semimajor axis of $a \approx -5378.85$ au, an eccentricity of $e = 1.00024$, and an orbital inclination of $i = 58.53^8$, 21S3 is classified as a dynamically new comet originating from the Oort Cloud, likely making its first passage through the inner Solar System.

Photometric observations of comet C/2021 S3 were carried out using both narrow-band and broad-band filters with both telescopes. Our monitoring began on February 20, 2023 ($r_h = 4.60$ au) and extended to July 13, 2024 ($r_h = 2.47$ au, post-perihelion), spanning 80 nights in total and covering both the pre- and post-perihelion phases. Production rates for the monitored gas species and the $Af\rho$ parameter, along with their associated uncertainties, are listed in Table C.9, while their temporal evolution is displayed in Figures 4.11 and 4.9.

⁷S. Nakano Note, NK 2452, <https://www.oaa.gr.jp/~oaacs/nk/nk5539.htm>

⁸Orbital elements from the JPL Small-Body Database: https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=C%2F2021%20S3.

Among the detected species, CN and C₂ were identified one year from the start of our monitoring, at the beginning of February 2024 at $r_h = 1.33$ au; we got OH a few days later at $r_h = 1.33$ au. C₃ faded below the detection threshold by March 15, 2024 ($r_h = 1.39$ au, one month post-perihelion). After perihelion, OH was last recorded in TRAPPIST images on May 21, 2024 ($r_h = 1.92$ au), while CN, C₂, and C₃ persisted to larger heliocentric distances, with signals still measurable through the first week of July 2024, when the comet had receded to $r_h = 2.40$ au. The overall activity underwent a steady brightening throughout the monitoring period, peaking around perihelion with a maximum OH production rate of $1.38 \pm 0.23 \times 10^{28}$ molec s⁻¹ ($r_h = 1.32$ au), after which the activity declined progressively with increasing heliocentric distance.

The production rates of the monitored gas species and the $Af\rho$ dust parameter, along with their uncertainties, are listed in Table C.9, and their evolution over time is shown in Figures 4.11 and 4.9. The logarithmic mean ratio $\log[Q(\text{C}_2)/Q(\text{CN})] = -0.054 \pm 0.007$, consistent with the boundary defined by Schleicher (2008) and A'Hearn et al. (1995b) for carbon-chain typical comets. The dust-to-gas ratio is slightly above the mean value of typical comets.

4.4 Results and discussion

4.4.1 Light Curve Analysis

Figures 4.3 and 4.4 show the temporal evolution of the apparent magnitude measured within a 5 arcsec aperture in the B , V , R_c , and I_c broadband filters, alongside the magnitude predicted by the JPL ephemeris⁹. The photometric data are fitted using the standard cometary magnitude law:

$$M = M_0 + 5 \log_{10}(\Delta) + 2.5 n \log_{10}(r_h), \quad (4.1)$$

where M_0 is the absolute magnitude, n is the activity index, and Δ and r_h are the geocentric and heliocentric distances, respectively, with n and M_0 treated as free parameters in the fit. All eight comets were monitored in the four broadband filters throughout their entire passage through the inner Solar System.

4.4.1.1 LPCs Light Curves

The four Long Period Comets display a general brightening trend as they approach perihelion, followed by a fading during their outbound leg, consistent with the expected increase in solar heating and sublimation activity at decreasing heliocentric distances.

C/2009 P1 shows a gradual brightening, reaching a broad peak before perihelion (~ 2.18 au), followed by a prolonged and smooth fading extending beyond 5 au, with the observed magnitudes consistently offset from the JPL ephemeris prediction, suggesting outgassing activity stronger than geometrically expected.

C/2012 F6 shows steep, rapid brightening near perihelion. With a post-perihelion gap in the observations, but from the JPL ephemeris data, the comet reached its peak after perihelion, followed by a clear fading trend.

C/2013 R1 exhibits a smooth and well-sampled brightening over more than 100 days before

⁹JPL ephemeris, <https://ssd.jpl.nasa.gov/horizons/app.html#/>

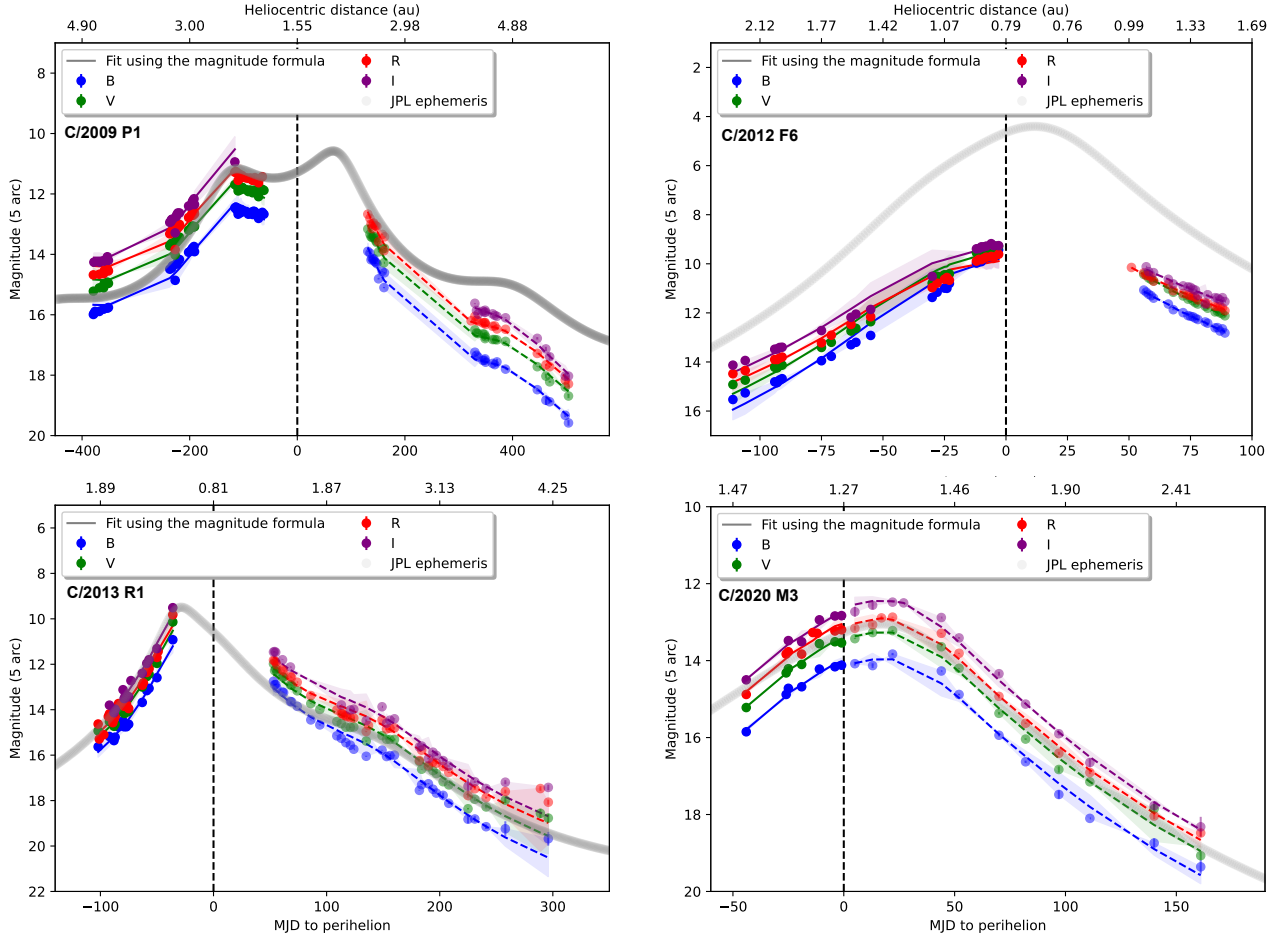


Figure 4.3: BVRI magnitudes within radius aperture of 5" as a function of days to perihelion, for the returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3. The vertical dashed line indicates the perihelion for each comet.

perihelion, reaching a sharp peak near perihelion before fading gradually over several hundred days, with all four BVRI filters following a consistent and well-fitted trend.

C/2020 M3 shows a relatively symmetric light curve, with a smooth brightening peaking after perihelion (+22 days, ~ 1.31 au) and a rapid post-perihelion decline, well reproduced by the magnitude formula fit.

Overall, the LPC light curves are characterised by relatively steep brightness increases close to perihelion, with peak activity occurring near or after perihelion.

4.4.1.2 DNC Light Curves

The four dynamically new comets display light curves that differ substantially from one another, but share a common feature of activity onset at significantly larger heliocentric distances compared to the LPCs.

C/2012 K1 shows a slow brightening from beyond 5 au, followed by a gradual post-perihelion (1.05 au) decline, though the observed brightness deviates noticeably from the JPL ephemeris, particularly around perihelion, indicating an early onset of activity.

C/2017 T2 presents a notably broad and flat light curve, with the brightness plateau extending from roughly -150 to -50 days before perihelion at a relatively large heliocentric distance

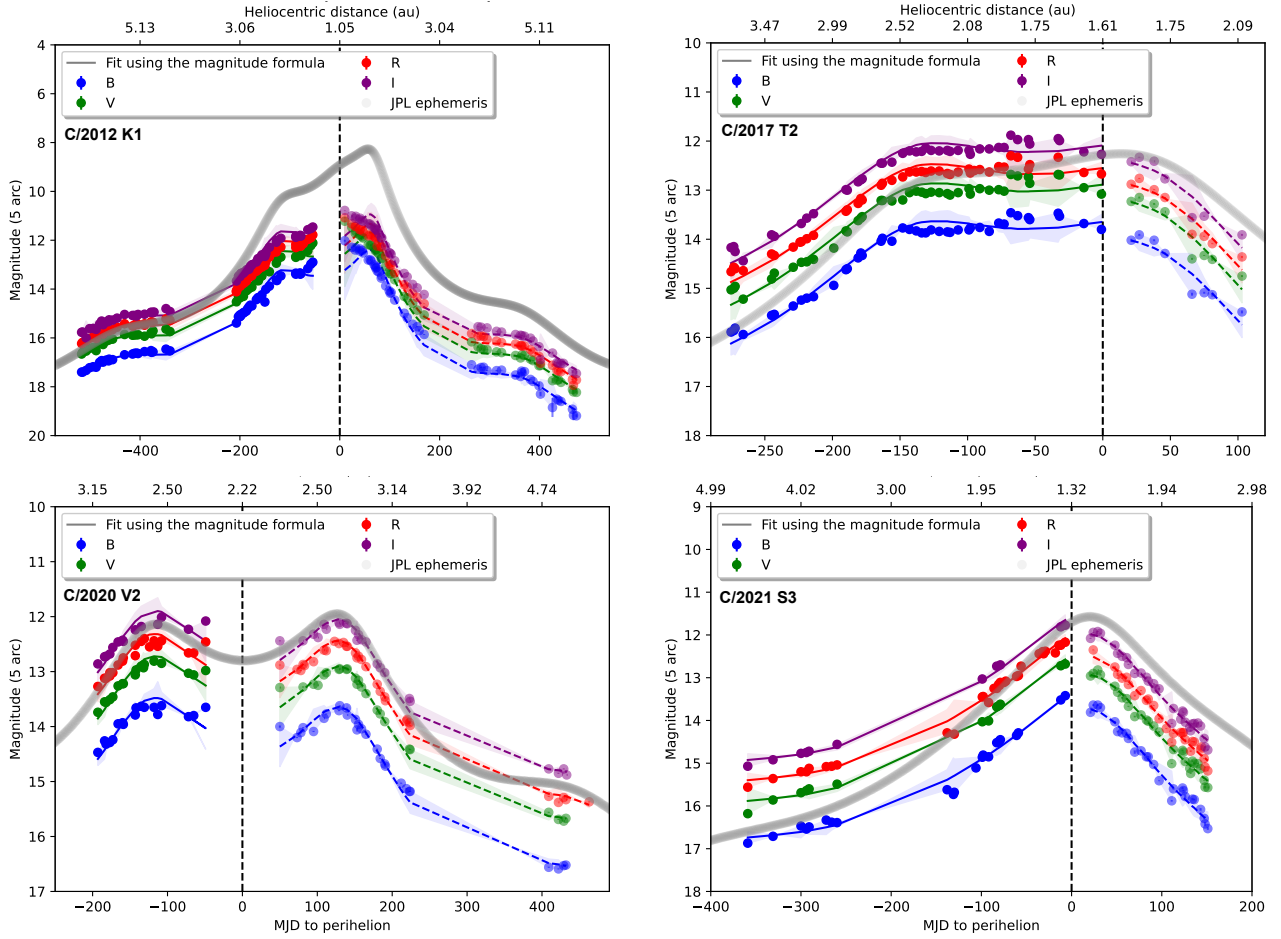


Figure 4.4: BVRI magnitudes within radius aperture of 5" as a function of days to perihelion, for the DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3. The vertical dashed line indicates the perihelion for each comet.

(1.75 au), suggesting sustained activity over a prolonged period before perihelion, followed by a moderate post-perihelion fading.

C/2020 V2 displays a peculiar light curve, with a first brightness maximum occurring well before perihelion (2.68 au), followed by a relative fading and then a second rise and peak in the post-perihelion phase around 2.63 au.

C/2021 S3 shows a smooth and well-sampled brightening from beyond 4 au, with a broad peak around perihelion (1.32 au) and a gradual post-perihelion fading, closely following the JPL ephemeris in the pre-perihelion phase but diverging slightly afterwards.

4.4.1.3 Comparison and Conclusion

The most striking difference between the two populations lies in the heliocentric distance at which significant activity is detected. The LPCs reach their brightest magnitudes close to or shortly after perihelion, with activity confined to relatively small heliocentric distances ($\lesssim 2$ au), whereas the DNCs show clear brightness enhancements already beyond 3–5 au, well before perihelion. This early onset of activity in DNCs is commonly attributed to the sublimation of supervolatile species such as CO and CO₂, which become active at larger heliocentric distances, and is consistent with the idea that DNCs are making their first close approach to the Sun, exposing pristine, volatile-rich surface material. In contrast, the LPCs, having under-

gone previous perihelion passages, have likely lost some of their most volatile surface ices [Holt et al. \(2024\)](#), resulting in activity predominantly driven by water-ice sublimation at smaller heliocentric distances.

C/2009 P1, classified as a returning LPC, displays a light curve more reminiscent of a DNC, with a broad double-peaked structure, suggesting unusually strong outgassing activity for a LPC. This behaviour may indicate that C/2009 P1 retains a significant reservoir of supervolatile material despite its returning nature, possibly because a large perihelion distance during previous passages limited its thermal processing.

Additionally, the LPC light curves tend to be more symmetric and steeper around perihelion. In contrast, the DNC light curves are generally broader and more asymmetric, with C/2012 K1 and C/2020 V2 displaying complex multi-peaked structures indicative of inhomogeneous or supervolatile-driven surface activity. These differences are broadly consistent with the expected compositional and evolutionary distinction between DNCs and LPCs, although the behaviour of C/2009 P1 highlights that this boundary is not always sharp, and that the degree of volatile preservation in LPCs may vary significantly depending on their individual past perihelion passage and thermal history.

4.4.2 Coma dust colors

We divided a sample of LPC comets from [Jewitt \(2015\)](#) into 13 DNCs and 12 LPCs, and compared their broadband colors with those of the eight comets studied in this work (see Table 3.4 and Figure 4.5). The color-color diagram displays the $B - V$ and $V - R$ color indices of the returning LPCs, shown in red, and DNCs, shown in green, with the solar colors indicated for reference (yellow circle). Both populations largely overlap in the central region of the diagram, clustering around $B - V \approx 0.75\text{--}0.90$ and $V - R \approx 0.40\text{--}0.50$, consistent with moderately red, solar-like to slightly reddened cometary surfaces. On average, the DNCs appear marginally redder than the LPCs, though the two distributions remain broadly consistent within their respective uncertainties. A notable exception is comet C/2012 F6, which stands out as a clear outlier, exhibiting an anomalously blue $V - R$ value accompanied by a large uncertainty, suggesting significant contamination by gaseous coma emission in the broadband filters.

Overall, the colors of both populations are consistent with Solar or moderately reddened colors, with no large systematic difference between LPCs and DNCs, suggesting that surface composition as probed by broadband colors does not strongly differentiate these two dynamical classes, which is also consistent with the result from [Holt et al. \(2024\)](#).

4.4.3 Reduced magnitude slopes

To characterise the activity evolution of each comet around perihelion, we fitted the reduced magnitude M_r (heliocentric total magnitude, [Holt et al. \(2024\)](#)) as a function of the logarithm of the heliocentric distance, separately for the pre- and post-perihelion phases, following the standard cometary magnitude formula (Eq. 4.1):

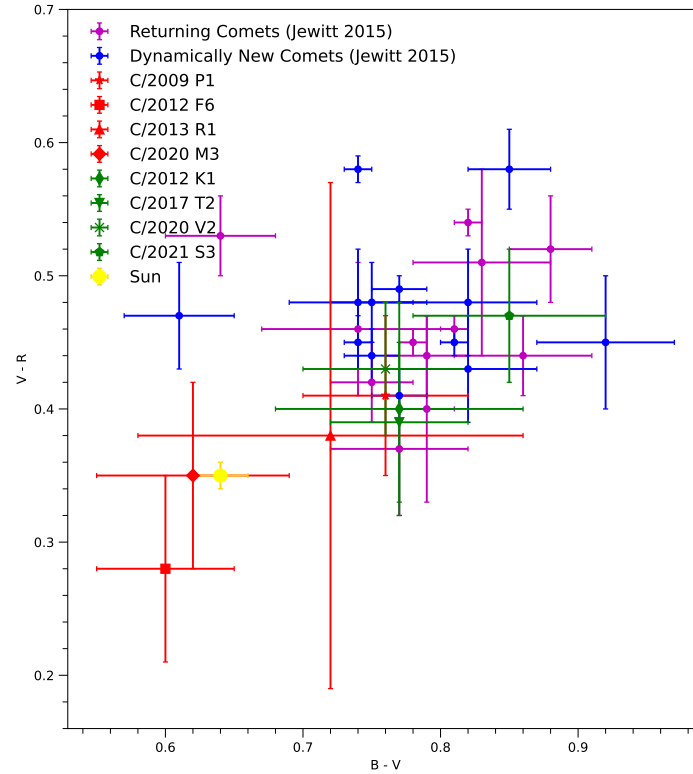
$$M_r = M - 5 \log_{10}(\Delta) = M_0 + 2.5 n \log_{10}(r_h) \quad (4.2)$$

where M is the observed R-band magnitude within a $5''$ aperture radius, Δ is the geocentric distance in au, r_h is the heliocentric distance in au, M_0 is the absolute magnitude, and n is the activity index describing how strongly the comet's brightness responds to changes in

Table 4.3: Colors comparison between comets in this work and a sample of 25 comets (13 DNCs and 12 LPCs) from [Jewitt \(2015\)](#).

Object	B - V	V - R	R - I	B - R
C/2009 P1	0.76±0.06	0.41±0.06	0.37±0.07	1.18±0.06
C/2012 F6	0.55±0.15	0.05±0.24	0.35±0.11	0.61±0.35
C/2013 R1	0.72±0.14	0.38±0.19	0.40±0.10	1.09±0.21
C/2020 M3	0.64±0.14	0.33±0.16	0.38±0.10	0.97±0.10
C/2012 K1	0.77±0.09	0.40±0.08	0.40±0.06	1.18±0.12
C/2017 T2	0.77±0.05	0.39±0.06	0.42±0.06	1.16±0.06
C/2020 V2	0.76±0.06	0.43±0.05	0.41±0.06	1.20±0.05
C/2021 S3	0.85±0.07	0.47±0.05	0.46±0.06	1.33±0.04
DNCs	0.76±0.05	0.49±0.05	0.42±0.02	1.26±0.07
RCs	0.80±0.05	0.48±0.05	0.37±0.09	1.28±0.05
Sun	0.64±0.02	0.35±0.01	0.33±0.01	0.99±0.02

Note: The mean color values of DNCs and RCs are from [Jewitt \(2015\)](#). The Sun color is from [Holmberg et al. \(2006\)](#).

**Figure 4.5:** Color-color plot comparing the four Long Period comets (red) and the four dynamically new comets (green) in this work, with the returning (orange) and dynamically new comets (blue) from [Jewitt \(2015\)](#). The color of the Sun is marked by a yellow circle.

heliocentric distance. For a purely reflective body, $n = 2$, while active comets typically show $n > 2$, with higher values indicating a steeper dependence of activity on solar heating. The fits were performed using a linear regression of the reduced magnitude versus $\log_{10}(r_h)$, and the resulting activity indices n , intercepts H_0 , and coefficients of determination R^2 are shown in Figures 4.6 and 4.7 for the LPCs and DNCs respectively, and summarised in Table 4.6.

4.4.3.1 LPC Magnitude Slopes

The four LPCs display a diverse range of activity indices, both before and after perihelion.

C/2009 P1 exhibits a remarkably low pre-perihelion activity index of $n = 1.26 \pm 0.21$, with a poor coefficient of determination ($R^2 = 0.474$), indicating that the comet's brightness does not follow a simple power-law dependence on heliocentric distance before perihelion. This is consistent with the complex, plateau-like light curve and $Af\rho$ profile discussed in previous and next sections, suggesting that its pre-perihelion activity is driven by supervolatile species whose sublimation rate does not increase steeply as r_h decreases. In contrast, the post-perihelion phase yields a much steeper and well-constrained index of $n = 8.56 \pm 0.17$ ($R^2 = 0.989$), indicative of a rapid fading as the comet recedes from the Sun, consistent with a transition to water-ice sublimation dominating the post-perihelion activity.

C/2012 F6 shows a steep and well-constrained pre-perihelion activity index of $n = 7.53 \pm 0.36$ ($R^2 = 0.955$), consistent with a strong dependence of brightness on solar heating as the comet approaches its very small perihelion distance (0.73 au). The post-perihelion index $n = 9.07 \pm 0.18$ ($R^2 = 0.992$) is even steeper, indicating a rapid post-perihelion fading, likely driven by the rapid reduction in solar heating at increasing heliocentric distances.

C/2013 R1 displays pre-perihelion and post-perihelion activity indices of $n = 5.79 \pm 0.82$ ($R^2 = 0.725$) and $n = 8.30 \pm 0.43$ ($R^2 = 0.913$) respectively, consistent with a gradual brightening before perihelion and a somewhat steeper fading afterwards, typical of water-ice-dominated activity.

C/2020 M3 stands out with the highest pre-perihelion activity index of the entire sample, $n = 12.68 \pm 3.52$, though with a relatively poor fit quality ($R^2 = 0.684$) and a large uncertainty, likely due to the limited number of pre-perihelion data points and the small heliocentric distance range covered. The post-perihelion index $n = 5.84 \pm 0.44$ ($R^2 = 0.945$) is more constrained and suggests a moderate post-perihelion fading rate.

4.4.3.2 DNC Magnitude Slopes

The four DNCs exhibit systematically lower pre-perihelion activity indices than most LPCs.

C/2012 K1 shows a low pre-perihelion activity index of $n = 2.32 \pm 0.11$ ($R^2 = 0.880$), close to the value expected for a purely reflective body ($n = 2$), suggesting that the pre-perihelion brightness of this comet increases only slowly with decreasing r_h . This is consistent with a supervolatile-driven activity that is already saturated at large heliocentric distances. The post-perihelion index $n = 3.87 \pm 0.19$ ($R^2 = 0.898$) is somewhat higher, indicating a moderate post-perihelion fading.

C/2017 T2 displays the lowest pre-perihelion activity index of the entire sample, $n = 1.02 \pm 0.22$ ($R^2 = 0.351$), with a very poor fit quality, fully consistent with the remarkably flat brightness profile already identified in the light curve and $Af\rho$ analyses. A value of $n \sim 1$ implies that its brightness is essentially independent of heliocentric distance before perihelion. The post-perihelion index $n = 8.30 \pm 1.95$ ($R^2 = 0.751$) is much steeper but poorly constrained

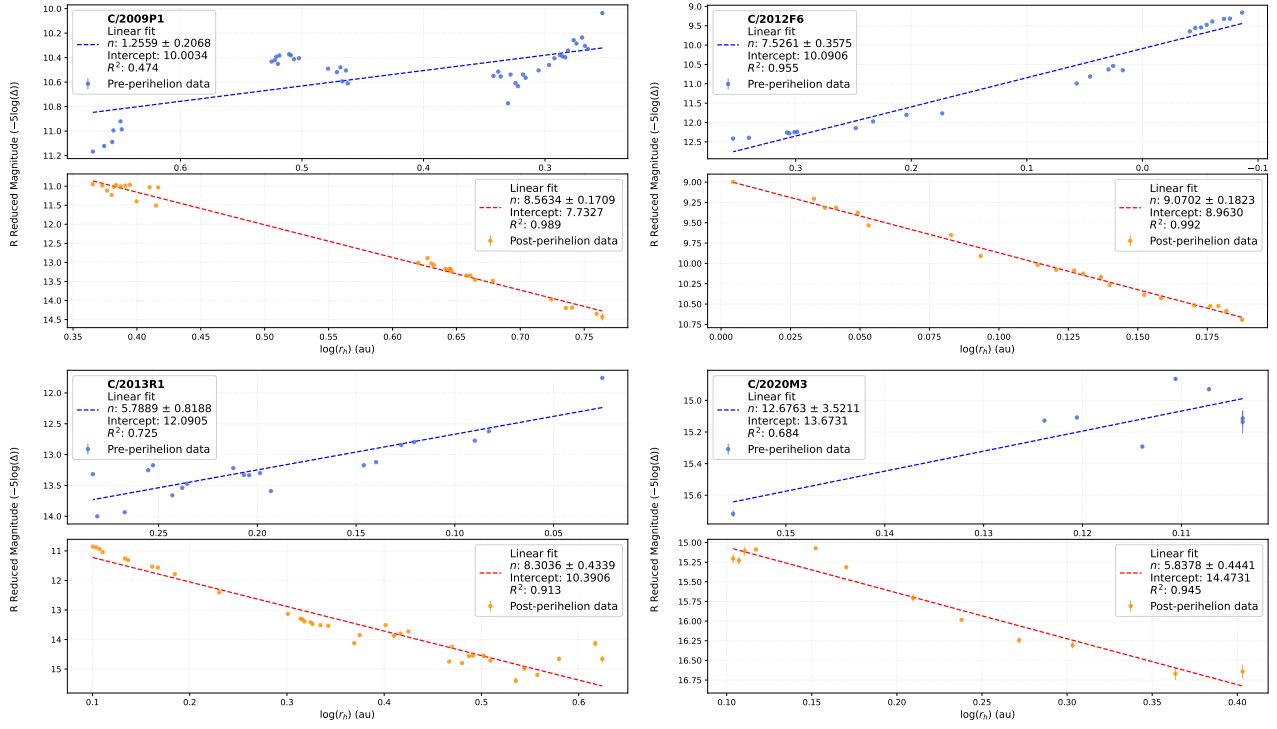


Figure 4.6: The linear fit of the reduced magnitude $m_r = m - 5 \log_{10}(\Delta)$ versus $\log_{10}(r_h)$, separately for the pre- and post-perihelion phases, for the four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3.

due to the limited post-perihelion data coverage.

C/2020 V2 presents a low and poorly constrained pre-perihelion activity index of $n = 2.80 \pm 0.89$ ($R^2 = 0.357$), consistent with the complex and asymmetric activity pattern already described, where the brightness peaks well before perihelion and then declines. The post-perihelion index $n = 3.37 \pm 0.18$ ($R^2 = 0.921$) is better constrained and moderate, suggesting a relatively slow post-perihelion fading.

C/2021 S3 shows a low pre-perihelion activity index of $n = 1.76 \pm 0.13$ ($R^2 = 0.871$), consistent with the gradual and sustained pre-perihelion brightening observed at large heliocentric distances. The post-perihelion index $n = 5.20 \pm 0.37$ ($R^2 = 0.889$) is significantly steeper, indicating a more rapid post-perihelion fading.

4.4.3.3 Comparison and Conclusion

The activity indices derived from the magnitude slope analysis reveal a clear and systematic difference between the two populations. The DNCs display significantly lower pre-perihelion activity indices ($n \sim 1-3$) compared to the LPCs ($n \sim 5-13$, excluding C/2009 P1), indicating that the brightness of DNCs increases much more slowly with decreasing heliocentric distance before perihelion. This is fully consistent with the interpretation that DNC activity is dominated by supervolatile species such as CO and CO₂, whose sublimation efficiency varies only weakly with r_h over the range 2–5 au, resulting in a flat or slowly rising brightness profile. In contrast, the LPCs C/2012 F6 and C/2013 R1 show steep pre-perihelion indices ($n \sim 5-8$), consistent with water-ice sublimation becoming increasingly efficient as r_h decreases within ~ 3 au.

The post-perihelion activity indices are generally higher than the pre-perihelion ones for most comets in both populations, with values ranging from $n \sim 3.4$ to ~ 9.1 , suggesting that

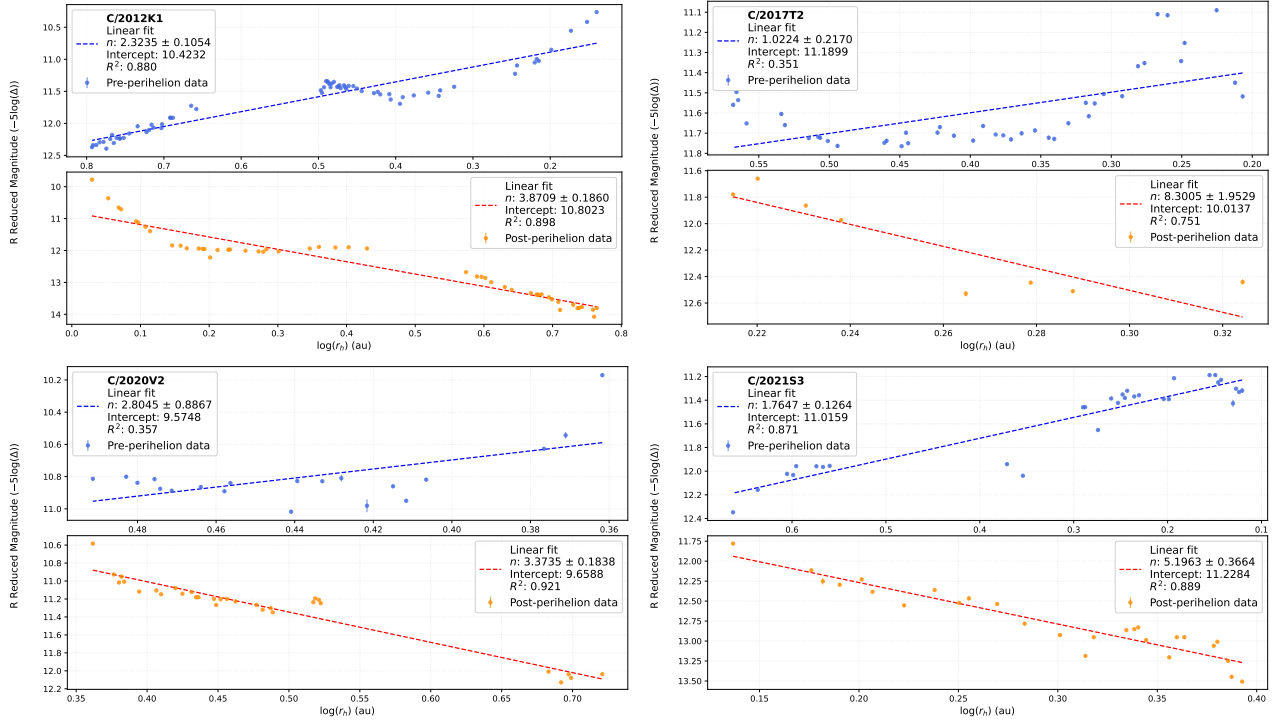


Figure 4.7: The linear fit of the reduced magnitude $m_r = m - 5 \log_{10}(\Delta)$ versus $\log_{10}(r_h)$, separately for the pre- and post-perihelion phases, for the four DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3.

the post-perihelion fading is systematically steeper than the pre-perihelion brightening. This pre/post perihelion asymmetry may reflect the thermal lag of the nucleus, whereby the surface continues to heat up slightly after perihelion before cooling, or the progressive depletion of the most volatile surface layers exposed during the inbound leg.

C/2009 P1 stands out as an anomalous LPC, with a very low and poorly constrained pre-perihelion index ($n = 1.26 \pm 0.21$, $R^2 = 0.474$) more typical of the DNC population, reinforcing the interpretation that this LPC retains an unusually large fraction of supervolatile material. Similarly, C/2017 T2, classified as a DNC, shows the lowest pre-perihelion index of the entire sample ($n \sim 1$), fully consistent with its flat brightness profile and first-passage nature.

Table 4.4: Activity index n , intercept H_0 , and coefficient of determination R^2 derived from the linear fit of the reduced magnitude $m_r = m - 5 \log_{10}(\Delta)$ versus $\log_{10}(r_h)$, separately for the pre- and post-perihelion phases, for the four returning LPCs and four DNCs.

Comets	Pre-perihelion			Post-perihelion		
	n	H_0	R^2	n	H_0	R^2
<i>LPCs</i>						
C/2009 P1	1.26 ± 0.21	10.00	0.474	8.56 ± 0.17	7.73	0.989
C/2012 F6	7.53 ± 0.36	10.09	0.955	9.07 ± 0.18	8.96	0.992
C/2013 R1	5.79 ± 0.82	12.09	0.725	8.30 ± 0.43	10.39	0.913
C/2020 M3	12.68 ± 3.52	13.67	0.684	5.84 ± 0.44	14.47	0.945
<i>DNCs</i>						
C/2012 K1	2.32 ± 0.11	10.42	0.880	3.87 ± 0.19	10.80	0.898
C/2017 T2	1.02 ± 0.22	11.19	0.351	8.30 ± 1.95	10.01	0.751
C/2020 V2	2.80 ± 0.89	9.57	0.357	3.37 ± 0.18	9.66	0.921
C/2021 S3	1.76 ± 0.13	11.02	0.871	5.20 ± 0.37	11.23	0.889

Note. The activity index n describes the dependence of the comet brightness on the heliocentric distance, with $n = 2$ corresponding to a purely reflective body and higher values indicating stronger sublimation-driven activity. H_0 is the intercept of the linear fit, corresponding to the absolute magnitude at $r_h = 1$ au. R^2 is the coefficient of determination of the linear fit.

Taken together, the magnitude slope analysis appears to provide further quantitative evidence consistent with the trends seen in the light curves. These results may suggest that DNCs are compositionally more pristine than LPCs, with supervolatile-driven activity potentially contributing to their low and relatively heliocentric-distance-independent brightness profiles before perihelion. In contrast, the steeper activity profiles observed for LPCs could indicate a stronger concentration of activity near perihelion, possibly associated with water-ice sublimation. The anomalous behaviour of C/2009 P1 highlights that the boundary between these two dynamical classes is not always sharp, and that the individual thermal history and the heliocentric distance of each comet play a key role in determining its observed activity profile.

4.4.4 $Af\rho$: The dust parameter proxy

4.4.4.1 $Af\rho$ evolution of LPCs

The $Af\rho$ profiles of the four LPCs reveal a diverse range of dust production behaviours, though all four show a general trend of increasing dust activity as the comet approaches perihelion.

C/2009 P1 displays high $Af\rho$ values of ~ 6000 – $12\,000$ cm already at heliocentric distances beyond 3 au pre-perihelion, with a broad peak around $12\,500$ cm reached at ~ 195 days before perihelion (~ 3 au). After this peak, the $Af\rho$ decreases to ~ 8000 cm closer to perihelion, and then continues to decline post-perihelion, reaching values of ~ 600 cm by ~ 500 days after perihelion. This behaviour, where peak dust production occurs well before perihelion, suggests that its activity is driven by supervolatile species that are more efficient at large heliocentric distances, with water-ice sublimation becoming dominant only closer to perihelion.

C/2012 F6 displays the most dramatic $Af\rho$ evolution of the LPC sample, with values rising steeply from a few thousand cm at ~ 100 days before perihelion to a sharp peak exceeding $20\,000$ cm near perihelion, indicating an intense and rapid increase in dust production in the final weeks of the inbound leg. The post-perihelion data, though sparser, show a clear decline toward ~ 5000 cm at ~ 75 – 100 days after perihelion.

C/2013 R1 shows a more gradual pre-perihelion increase, with $Af\rho$ values rising from ~ 800 cm at ~ 100 days before perihelion, followed by a rapid and monotonic post-perihelion decline extending over several hundred days, reaching values below 400 cm by ~ 300 days after perihelion.

C/2020 M3 exhibits the lowest $Af\rho$ values of the LPC sample, with a smooth increase from 90 cm at ~ 44 days before perihelion to a peak of ~ 256 cm 5 days after perihelion (~ 1.27 au), followed by a smooth post-perihelion decline. The overall low $Af\rho$ levels suggest a relatively dust-poor coma compared to the other LPCs in the sample.

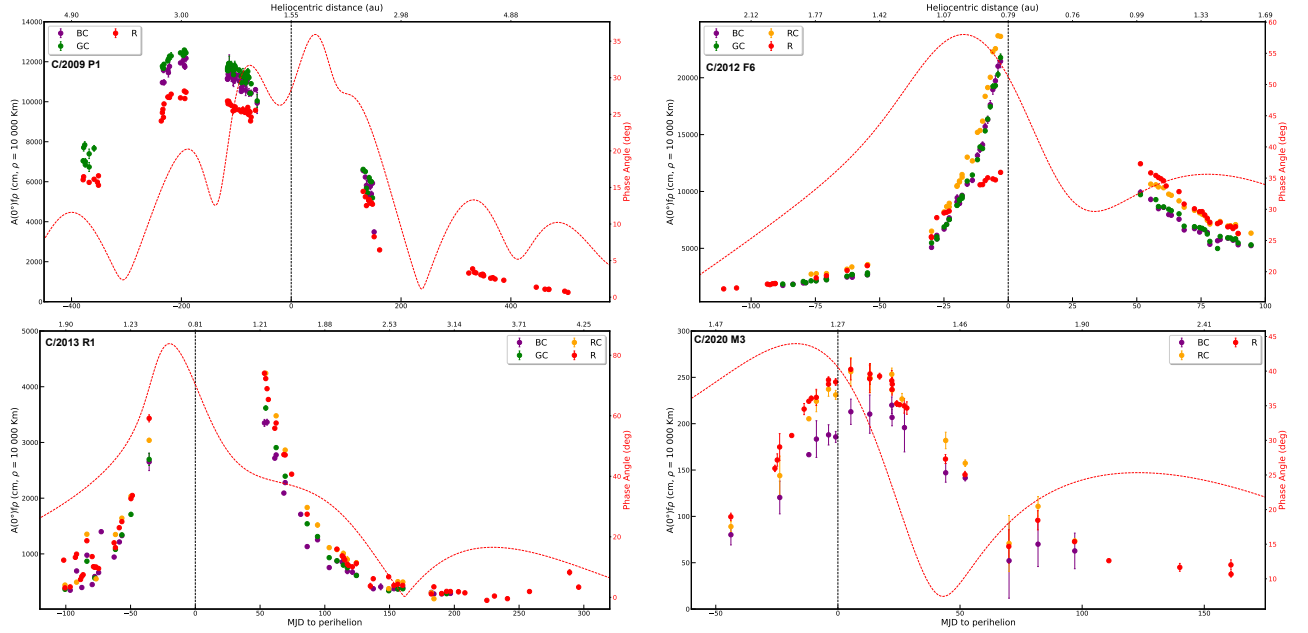


Figure 4.8: The $Af\rho$ parameter within a radius aperture of 10 000 Km from the broad- and narrow-band filters, as a function of time and the heliocentric distance, for the four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3.

4.4.4.2 $Af\rho$ evolution of DNCs

The $Af\rho$ profiles of the four DNCs are characterised by generally higher $Af\rho$ values and activity detected at significantly larger heliocentric distances compared to the LPCs, consistent with the early onset of sublimation of supervolatile species.

C/2012 K1 shows elevated values of ~ 4000 – 6000 cm measured from beyond 5 au pre-perihelion, followed by a broad plateau near perihelion. Post-perihelion, the $Af\rho$ declines steadily over several hundred days, reaching ~ 800 cm at ~ 470 days after perihelion, broadly consistent with a gradual reduction in dust-producing activity.

C/2017 T2 presents a remarkably flat and extended $Af\rho$ profile, with values hovering between ~ 3000 and ~ 6000 cm over the entire pre-perihelion baseline, suggesting a sustained and relatively constant level of dust production at large heliocentric distances. After that, the $Af\rho$ starts to drop sharply to below ~ 2000 cm within a few tens of days, even though the comet is still before perihelion, indicating a rapid decrease in dust activity.

C/2020 V2 presents a high and relatively flat $Af\rho$ profile of ~ 8000 – 10000 cm throughout the pre-perihelion phase from ~ 200 days before perihelion, with a maximum peak 130 days before perihelion (2.08 au). The post-perihelion evolution shows a gradual decline from ~ 7000 cm to

~ 4000 cm over ~ 500 days, with the overall profile remaining relatively flat compared to the other DNCs.

C/2021 S3 pre-perihelion $Af\rho$ values, measured only in the R filter beyond ~ 4 au, remain relatively high and roughly constant at ~ 3000 – 3300 cm from ~ 400 days before perihelion, before showing a slight decrease to ~ 2500 cm around ~ 140 days before perihelion (~ 2.35 au). Post-perihelion, the $Af\rho$ drops rapidly, with values in the R filter declining from ~ 2400 cm just after perihelion to ~ 760 cm by ~ 150 days (2.47 au).

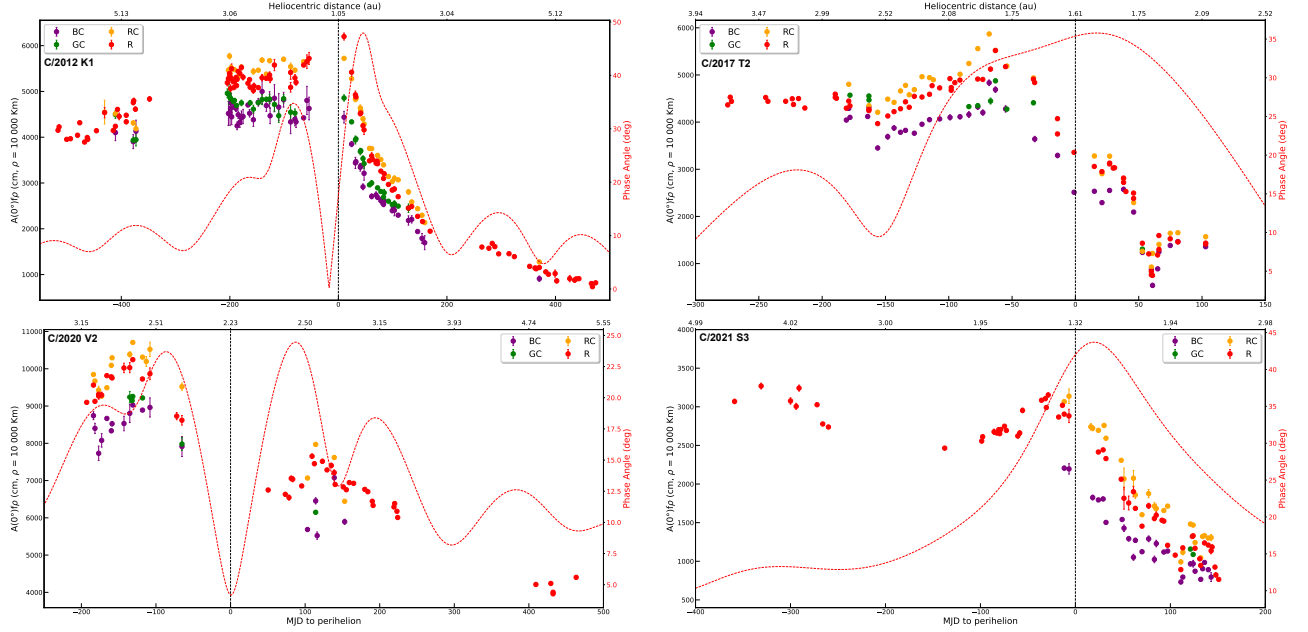


Figure 4.9: The $Af\rho$ parameter within a radius aperture of 10 000 Km from the broad- and narrow-band filters, as a function of time and the heliocentric distance, for the DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3.

4.4.4.3 Comparison and Conclusion

The $Af\rho$ profiles of the LPCs and DNCs reveal clear differences between the two populations. The most notable distinction is the heliocentric distance at which significant dust production is detected: the DNCs exhibit elevated $Af\rho$ values already beyond 3–5 au, whereas the LPCs, with the exception of C/2009 P1, show a significant increase in dust activity only within ~ 2 au of the Sun. This is consistent with the light curve analysis and further supports the interpretation that DNCs harbour more pristine, volatile-rich surface material that drives activity at large heliocentric distances through the sublimation of supervolatile species such as CO and CO₂ (Jewitt et al., 2017, 2019).

In terms of $Af\rho$ values, the DNCs generally reach higher peak dust production levels compared to most LPCs, with the notable exception of C/2012 F6, which reaches $\sim 20\,000$ cm near perihelion due to its very small perihelion distance (0.73 au). The LPC C/2020 M3 stands out as particularly dust-poor, with $Af\rho$ values remaining below ~ 260 cm throughout its apparition. C/2009 P1, classified as an LPC, displays $Af\rho$ values of ~ 6000 – $12\,500$ cm already beyond 3 au, with a peak well before perihelion, behaviour far more typical of DNC than of LPC. This suggests that it might have a larger nucleus, or retain an unusually large reservoir of supervolatile material for a LPC, possibly due to limited thermal processing during previous perihelion passage. Regarding the pre-perihelion behaviour, a striking feature shared by

the DNCs is the presence of a relatively flat or plateau-like $Af\rho$ profile from large heliocentric distance until perihelion. This suggests that the dust production is already sustained by supervolatile-driven activity beyond 3–5 au. In contrast, the LPCs show a steep and rapid rise in $Af\rho$ around 3 au towards perihelion, consistent with water-ice sublimation as the dominant driver of dust activity at small heliocentric distances. The post-perihelion $Af\rho$ evolution also differs between the two populations: while most LPCs show a steep and rapid decline after perihelion, the DNCs generally maintain relatively elevated $Af\rho$ values for hundreds of days post-perihelion, consistent with a more extended and sustained level of activity driven by the progressive exhaustion of supervolatile reservoirs. Comet C/2009 P1 again behaves more like a DNC in this regard, with a prolonged and smooth post-perihelion decline extending beyond 400 days after perihelion.

These differences in $Af\rho$ behaviour reinforce the conclusions drawn from the light curve analysis, namely that DNCs are compositionally more pristine than LPCs, with activity dominated by supervolatile sublimation at large heliocentric distances. In contrast, LPCs have undergone sufficient thermal processing during previous perihelion passages to deplete their most volatile surface material.

4.4.5 Production Rates

The production rate profiles of the LPCs and DNCs reveal differences consistent with those observed in the light curves and $Af\rho$ analysis.

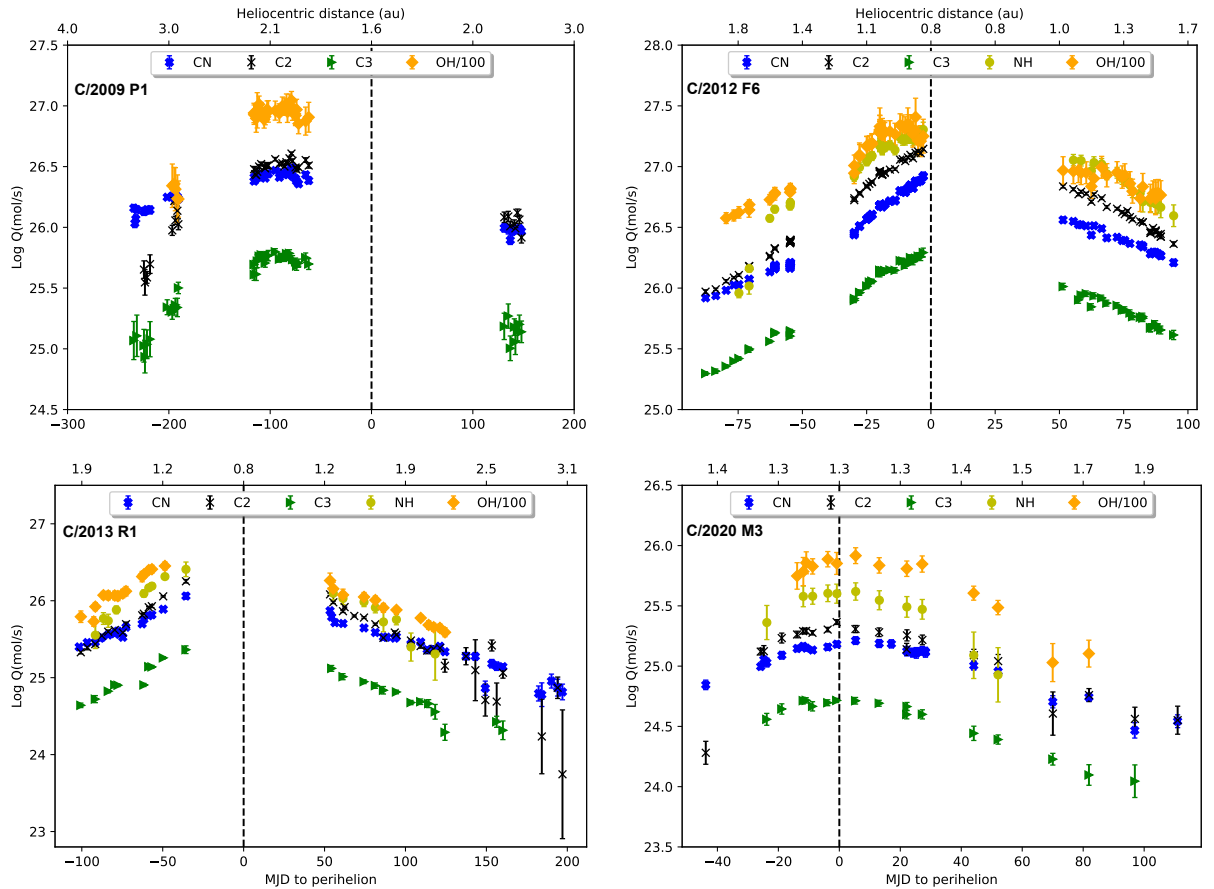


Figure 4.10: Logarithmic production rates of OH, NH, CN, C₂, and C₃ as a function of time and the heliocentric distance, for the four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3. The vertical dashed line indicates the perihelion for each comet.

The most notable distinction remains the heliocentric distance at which molecular activity is detected: the DNCs show measurable production rates of OH, CN, C₂, and C₃ already beyond 3 au from the Sun, whereas the LPCs, with the exception of C/2009 P1, exhibit significant molecular activity only within ~ 2 au of perihelion. This confirms that DNCs harbour a larger reservoir of supervolatile-driven outgassing, consistent with their pristine, first-passage nature. In terms of absolute production rates, the two populations span a comparable range. The highest production rates are found in comet C/2012 F6 among the LPCs, largely due to its very small perihelion distance (0.73 au), and in comet C/2020 V2 among the DNCs. The lowest production rates in both populations are found in C/2020 M3 (LPC) and C/2021 S3 (DNC), both of which have relatively larger perihelion distances, consistent with the expected dependence of cometary activity on heliocentric distance. However, comet C/2009 P1 deviates from this general picture; classified as an LPC, it shows production rates detectable already beyond 3 au pre-perihelion, with OH peaking well before perihelion at ~ 2.17 au, a behaviour far more reminiscent of DNCs than of typical LPCs. This suggests that C/2009 P1 retains an unusually large reservoir of supervolatile material for a LPC, consistent with the anomalous behaviour already identified in the light curve and $Af\rho$ analyses (Fig. 4.3 and 4.8).

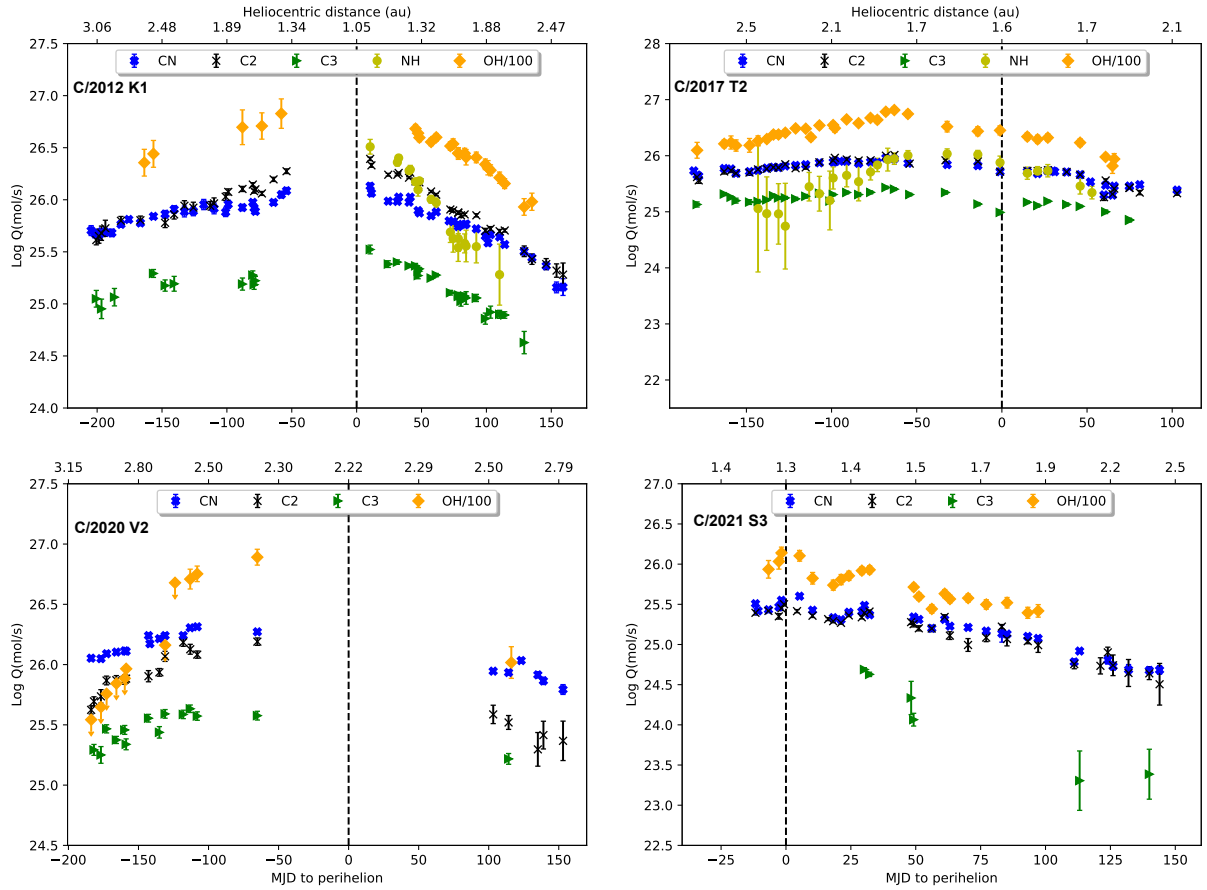


Figure 4.11: Logarithmic production rates of OH, NH, CN, C₂, and C₃ as a function of time and the heliocentric distance, for the DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3. The vertical dashed line indicates the perihelion for each comet.

In the case of DNCs, it seems that the production rates reach their maximum values well before perihelion and then decline toward and after perihelion passage. This behaviour is a strong indicator of supervolatile-dominated activity (Womack et al., 2017), and is fully consistent with the $Af\rho$ profiles discussed in Sect. 4.4.4.2. In contrast, the LPCs show a steep and rapid rise in production rates confined to the pre-perihelion distances within ~ 3 au of the Sun,

consistent with activity predominantly driven by water-ice sublimation, which becomes efficient only at such distances (Meech et al., 2004). Taken together, the production rate analysis reinforces the conclusions drawn from both the light curve and $Af\rho$ analyses, namely that DNCs are compositionally more pristine than LPCs, with a more extended activity profile detected at large heliocentric distances, likely driven by supervolatile activity. In contrast, LPCs exhibit more confined behaviour concentrated near perihelion, likely dominated by water-ice outgassing.

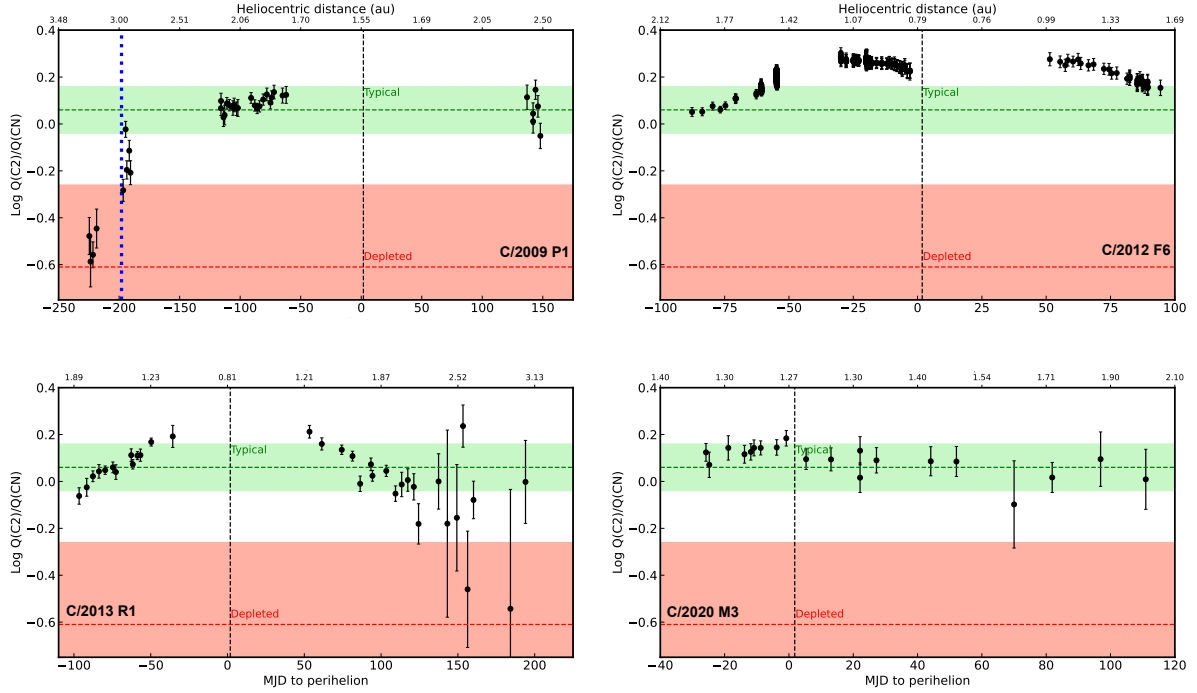


Figure 4.12: Production rate ratios as a function of time and the heliocentric distance, for the four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3.

Table 4.5: Average logarithmic production rates and $A(0)f\rho$ ratios of all comets in comparison with A’Hearn et al. (1995b) taxonomic classes.

Comets	Log production rate ratios				Log dust-to-gas ratios
	C_2/CN	C_2/OH	C_3/OH	CN/OH	$A(0)f\rho/OH$
C/2009 P1 (Garradd)	0.053 ± 0.005	-2.440 ± 0.019	-3.209 ± 0.019	-2.506 ± 0.017	-24.891 ± 0.015
C/2012 F6 (Lemmon)	0.201 ± 0.001	-2.395 ± 0.005	-3.143 ± 0.007	-2.594 ± 0.004	-25.285 ± 0.008
C/2013 R1 (Lovejoy)	0.079 ± 0.005	-2.398 ± 0.013	-3.179 ± 0.016	-2.438 ± 0.013	-25.003 ± 0.013
C/2020 M3 (Atlas)	0.114 ± 0.01	-2.551 ± 0.022	-3.161 ± 0.022	-2.650 ± 0.022	-25.500 ± 0.022
C/2012 K1 (PanSTARRS)	0.181 ± 0.004	-2.536 ± 0.011	-3.337 ± 0.012	-2.682 ± 0.012	-25.027 ± 0.014
C/2017 T2 (PanSTARRS)	0.008 ± 0.005	-2.623 ± 0.014	-3.196 ± 0.014	-2.650 ± 0.012	-24.927 ± 0.012
C/2020 V2 (ZTF)	-0.235 ± 0.011	-2.661 ± 0.045	-3.202 ± 0.045	-2.497 ± 0.041	-24.825 ± 0.044
C/2021 S3 (PanSTARRS)	-0.054 ± 0.007	-2.464 ± 0.016	-3.399 ± 0.048	-2.399 ± 0.014	-24.513 ± 0.015
Typical comets	0.06 ± 0.10	-2.44 ± 0.20	-3.59 ± 0.29	-2.50 ± 0.18	-25.82 ± 0.40
Depleted comets	-0.61 ± 0.3	-3.30 ± 0.35	-4.18 ± 0.28	-2.69 ± 0.14	-25.30 ± 0.29

Note: The $A(0)f\rho$ values used were computed from the images taken with the BC narrow-band filter.

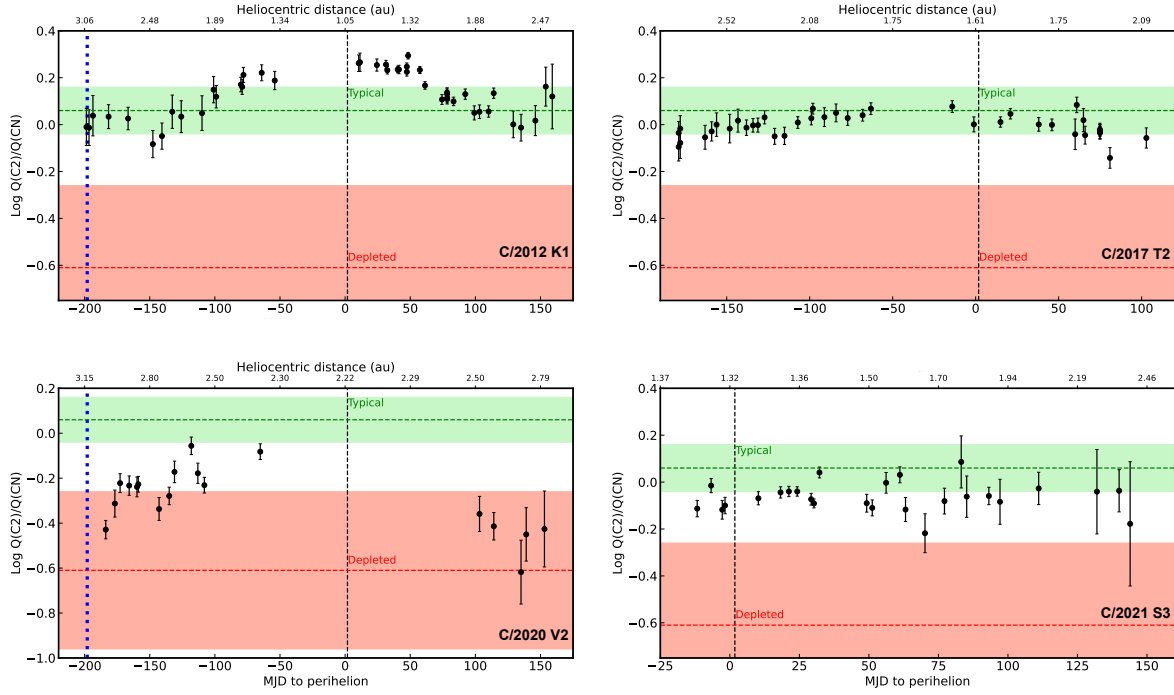


Figure 4.13: Production rate ratios as a function of time and the heliocentric distance, for the four DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3.

4.4.5.1 Production rates slopes

To quantify the heliocentric-distance dependence of the gas production rates, we fitted each species with a single power law of the form $Q \propto r_h^{-n}$, where r_h is the heliocentric distance and n is the power-law index (hereafter the slope). The pre- and post-perihelion measurements were fitted independently, so that each comet has, where the data coverage allows, a separate inbound and outbound slope for every species. The resulting slopes are shown in Figures 4.14, 4.15, and summarized in Table 4.6, the upper half of which lists the LPCs and the lower half the DNCs.

A clear differentiation once again emerges between the two dynamical classes. For the LPCs, the pre-perihelion slopes are systematically steeper than the post-perihelion values. This is well illustrated by C/2013 R1, for which the OH slope decreases from $m = 3.59 \pm 0.26$ inbound to 2.49 ± 0.23 outbound, and by C/2012 F6, where the CN slope falls from 2.59 ± 0.01 to 1.69 ± 0.08 . The same trend of steeper pre- than post-perihelion is reproduced across OH, NH, CN, C₃, and C₂ for essentially every LPC with bilateral coverage. This behaviour is consistent with the expected response of a thermally processed nucleus: previous perihelion passages have built a devolatilised, low-conductivity surface layer that retards the warming of the interior, so the activity ramps up only gradually at large distances and then rises steeply as the nucleus approaches the Sun. After perihelion, sub-surface heat stored during the inbound leg sustains the sublimation, producing a comparatively shallower decline. For C/2020 M3, the computed steep pre-perihelion production-rate slopes are consistent with the expected stronger heliocentric dependence of LPC activity before perihelion; however, their large uncertainties likely reflect the limited number of pre-perihelion observations, and the derived slopes should therefore be interpreted with caution.

4.4. RESULTS AND DISCUSSION

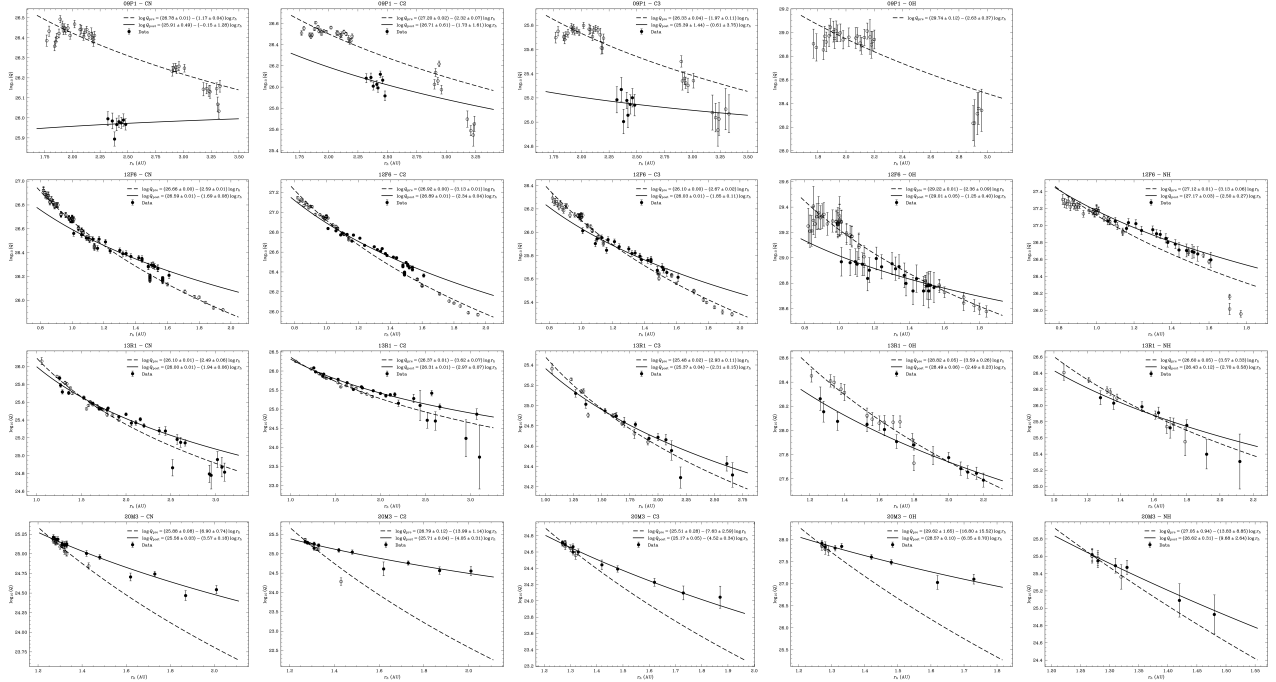


Figure 4.14: Power-law slopes n of the gas production rates, fitted as $Q \propto r_h^{-n}$, for the four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3.

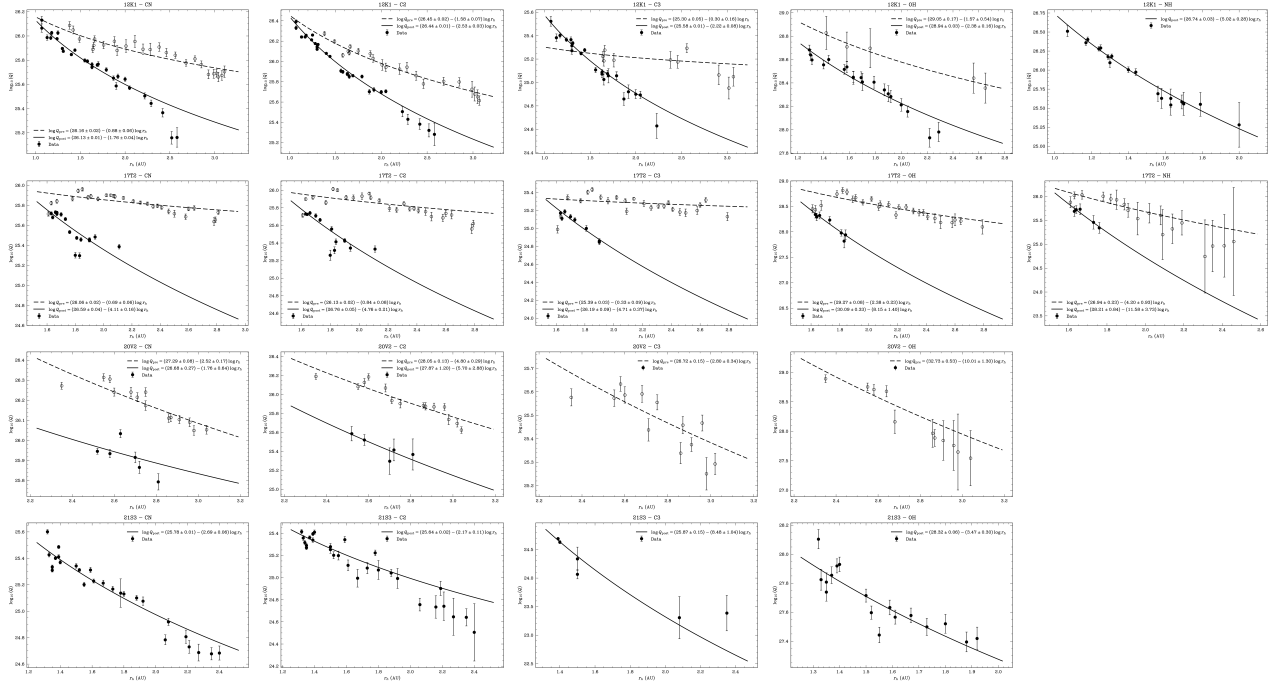


Figure 4.15: Power-law slopes n of the gas production rates, fitted as $Q \propto r_h^{-n}$, for the four DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3.

The DNCs display the opposite trend: their post-perihelion slopes are steeper than their pre-perihelion counterparts. In C/2017 T2, for example, the CN slope increases from 0.69 ± 0.06 inbound to 4.11 ± 0.16 outbound, and the C_2 slope from 0.84 ± 0.08 to 4.76 ± 0.21 ; C/2012 K1 shows the same reversal for every species with bilateral coverage. The shallow inbound slopes are consistent with a pristine, volatile-rich surface that sustains sublimation even at large heliocentric distances, so that the activity is already appreciable far from the Sun and rises only gradually as the comet approaches. The steeper post-perihelion decline, however, is less

straightforward to interpret. It may reflect the rapid exhaustion of the most accessible, near-surface volatiles once the nucleus recedes from peak insolation, or a seasonal/geometry-driven effect on the freshly exposed active areas, but a definitive explanation is not yet established.

The only DNC that does not follow this pattern is the CN slope of C/2020 V2, which is steeper before perihelion ($m = 2.32 \pm 0.17$) than after (1.76 ± 0.64). Given the limited post-perihelion data coverage for this object, however, this single deviation is insufficient to establish a robust contrary trend.

Table 4.6: Power-law slopes n of the gas production rates, fitted as $Q \propto r_h^{-n}$, for the returning long period comets (upper section) and dynamically new comets (lower section).

Comet	OH		NH		CN		C ₃		C ₂	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
C/2009 P1	2.63 ± 0.37	-	-	-	1.17 ± 0.04	-	1.97 ± 0.11	-	2.32 ± 0.07	1.73 ± 1.61
C/2012 F6	3.26 ± 0.09	1.25 ± 0.40	3.13 ± 0.06	2.50 ± 0.27	2.59 ± 0.01	1.69 ± 0.08	2.67 ± 0.02	1.85 ± 0.11	3.13 ± 0.01	3.24 ± 0.04
C/2013 R1	3.59 ± 0.26	2.49 ± 0.23	3.57 ± 0.33	2.70 ± 0.58	2.49 ± 0.06	1.94 ± 0.06	2.93 ± 0.11	2.31 ± 0.15	3.62 ± 0.07	2.97 ± 0.07
C/2020 M3	16.86 ± 15.5	26.35 ± 0.7	13.83 ± 8.85	9.68 ± 2.64	6.90 ± 0.74	3.57 ± 0.18	7.63 ± 2.59	4.52 ± 0.34	13.99 ± 1.14	4.05 ± 0.31
C/2012 K1	1.57 ± 0.54	2.38 ± 0.16	-	5.02 ± 0.28	0.88 ± 0.06	1.76 ± 0.04	0.30 ± 0.16	2.22 ± 0.08	1.58 ± 0.07	2.53 ± 0.03
C/2017 T2	3.32 ± 0.23	8.15 ± 1.40	4.20 ± 0.93	11.58 ± 3.73	0.69 ± 0.06	4.11 ± 0.16	0.33 ± 0.09	4.71 ± 0.37	0.84 ± 0.08	4.76 ± 0.21
C/2020 V2	10.01 ± 1.30	-	-	-	2.32 ± 0.17	1.76 ± 0.64	2.80 ± 0.34	-	4.80 ± 0.29	5.70 ± 2.88
C/2021 S3	-	3.47 ± 0.30	-	-	-	2.69 ± 0.06	-	8.48 ± 1.04	-	2.17 ± 0.11

Note. Pre- and post-perihelion data were fitted independently; an em dash (–) indicates that insufficient coverage prevented a reliable fit for that species and epoch. Slopes are listed for OH, NH, CN, C₃, and C₂, with the quoted uncertainties representing the 1σ errors on the fitted index n .

4.5 Summary and conclusions

In this chapter, I presented a comprehensive photometric analysis of eight long period comets, divided into four returning LPCs C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3) and four DNCs C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3). For each comet, we analysed the light curves, the broad-band colours, the magnitude slopes, the dust proxy $Af\rho$, the molecular production rates of OH, NH, CN, C₂, and C₃, and their slopes, to compare the physical and compositional properties of the two dynamical populations. Our main findings can be summarised as follows:

1. **Light curves.** The LPCs generally brighten steeply and symmetrically close to perihelion, with peak activity occurring near or shortly after perihelion passage, consistent with water-ice sublimation dominating their activity within ~ 3 au of the Sun. In contrast, the DNCs show a clear brightness increase already beyond 3–5 au before perihelion, indicative of early-onset supervolatile-driven activity.
2. **Magnitude slopes.** The DNCs display significantly lower pre-perihelion activity indices ($n \sim 1$ –3) compared to most LPCs ($n \sim 5$ –13), confirming that the brightness of DNCs increases much more slowly with decreasing heliocentric distance before perihelion, consistent with supervolatile-dominated activity. The post-perihelion activity indices are generally higher (steeper slopes) than the pre-perihelion ones for most comets in both populations.
3. **Colours.** The broad-band colours of both populations are broadly consistent with solar or moderately reddened surfaces, with no systematic differences between LPCs and DNCs.

Broad-band colours alone are not a strong discriminator between the two dynamical classes.

4. **$Af\rho$ profiles.** The dust production profiles confirm the picture drawn from the light curves. The DNCs display elevated and relatively flat $Af\rho$ values until perihelion, consistent with sustained supervolatile-driven dust production already beyond 3-5 au. The LPCs, in contrast, show a steep rise in dust production only within ~ 2 au of the Sun.
5. **Production rates.** The DNCs show detectable OH, CN, C_2 , and C_3 production rates already beyond 3 au before perihelion, while the LPCs exhibit significant molecular activity only within ~ 3 au of the Sun. The relative ordering of species production rates ($OH > NH > C_2 \approx CN > C_3$) is broadly consistent across both populations, suggesting a similar overall coma chemistry despite their different dynamical histories. C_3 remains systematically the weakest detected species in all comets of both samples.
6. **Production rate slopes.** Returning LPCs exhibit systematically steeper pre-perihelion and shallower post-perihelion heliocentric-distance dependence slopes, consistent with thermally evolved nuclei that retain subsurface heat after perihelion. In contrast, DNCs generally show shallow inbound and much steeper outbound slopes, indicating activity sustained by pristine near-surface volatiles at large distances followed by a rapid decline after perihelion.
7. **The case of C/2009 P1.** This comet, classified as a returning LPC, displays activity profiles across all light curves, $Af\rho$, production rates, and magnitude slope that are far more typical of a DNC, suggesting that this comet has retained an unusually large fraction of its primordial supervolatile material despite having undergone previous perihelion passages. This behaviour is plausibly explained by a large perihelion distance during its previous passage, which would have limited the thermal processing of its surface.

Our results confirm the general picture that DNCs are compositionally more pristine than LPCs, with activity dominated by supervolatile sublimation at large heliocentric distances, while LPCs have undergone sufficient thermal processing during previous perihelion passages to deplete their most volatile surface material, leaving them with a more confined, water-ice-dominated activity profile concentrated near perihelion. However, the behaviour of C/2009 P1, likely linked to a large perihelion distance during its previous passage, illustrates that the boundary between these two dynamical classes is not always sharp, and that the individual thermal history of each comet plays a key role in determining the degree of volatile preservation and the resulting activity profile. These findings underline the importance of long-term, multi-wavelength monitoring campaigns for building a more complete picture of the physical and compositional diversity within the LPC population, and further motivate the need for a dedicated space mission to a pristine DNC. The upcoming ESA Comet Interceptor mission, designed to explore a DNC, will provide an unprecedented opportunity to directly probe the surface composition and activity of a first-passage comet, complementing the ground-based multi-wavelength monitoring of these comets.

Conclusions and perspectives

Comets are among the most primitive bodies in the Solar System, preserving material from the earliest stages of its formation some 4.6 billion years ago. Studying their activity and composition provides a unique window into the physical and chemical conditions of the early solar nebula, the processes that shaped the outer Solar System, and the dynamical histories of the different cometary reservoirs. In particular, comparing the properties of long-period comets (LPCs) and dynamically new comets (DNCs) offers the opportunity to probe the degree of thermal and chemical processing that these objects have undergone, and to quantify the differences between comets that have made previous perihelion passages and those encountering the inner Solar System for the first time.

This thesis was structured around two complementary observational studies of comets from the Oort Cloud, both carried out primarily with the TRAPPIST telescopes. Chapter 1 provided the general scientific context, covering the physical and chemical properties of comets, their dynamical classification, and the current understanding of their reservoirs and evolutionary pathways. Chapter 2 described the observational setup, the TRAPPIST telescopes and their instrumentation, as well as the data reduction procedures and analysis methods applied throughout this work.

Chapter 3 presented a detailed multiwavelength study of comet C/2017 K2 (PanSTARRS), a dynamically new Oort Cloud comet that displayed remarkable activity at unusually large heliocentric distances. By combining long-term TRAPPIST photometric monitoring with high-resolution spectroscopic observations obtained with UVES and CRIRES⁺ at the Very Large Telescope, we investigated the temporal evolution of the cometary activity and molecular composition across a wide range of heliocentric distances. The analysis revealed a smooth and progressive brightening with no evidence for major outbursts, stable optical colors indicative of uniform dust properties, and a gradual increase in gas production rates approaching perihelion. The combined optical and infrared data allowed us to identify HCN as the primary source of CN in the coma, and to attribute the production of C₂ primarily to the photodissociation of C₂H₂. A transient decrease in activity observed before perihelion was interpreted as a partial exhaustion of near-surface supervolatile ices, followed by a resumption of activity as water-ice sublimation became dominant within ~ 3 au. These results contribute to the broader understanding of the long-term physical and chemical evolution of dynamically new comets and the role of supervolatile species in sustaining activity at large heliocentric distances.

Chapter 4 presented a comprehensive comparative photometric study of eight comets observed with the TRAPPIST telescopes between 2010 and 2024, comprising four returning LPCs (C/2009 P1, C/2012 F6, C/2013 R1, and C/2020 M3) and four DNCs (C/2012 K1, C/2017 T2, C/2020 V2, and C/2021 S3). For each comet, we analysed the light curves, broad-band colours, magnitude slopes, dust proxy $Af\rho$, and the molecular production rates of OH, NH, CN, C₂, and C₃. We also investigated the dynamical origins of the studied comets by reconstructing their past orbital evolution through N-body integrations of their nominal orbits and clone swarms. The simulations, performed with MERCURY and independently checked with REBOUND, allowed

us to assess the effects of previous passages through the inner Solar System and constrain the likely dynamical origins of the comets.

The most striking result of this study is the systematic difference in the heliocentric distance at which significant activity is detected between the two populations. The returning LPCs generally display steep brightness increases confined within ~ 3 au of the Sun, consistent with water-ice sublimation as the dominant driver of activity, while the DNCs show clear brightness enhancements already beyond 3–5 au before perihelion, indicative of early-onset supervolatile-driven activity. This contrast is further quantified by the activity index n , derived from the reduced magnitude versus $\log(r_h)$, which is systematically lower for DNCs ($n \sim 1\text{--}3$) than for most LPCs ($n \sim 5\text{--}13$), and is consistently reflected in the $Af\rho$ dust production profiles and the molecular production rates of OH, CN, C₂, and C₃, all of which are detectable at larger heliocentric distances in the DNC population. The relative ordering of species production rates (OH > NH > C₂ $\approx$ CN > C₃) remains broadly consistent across both populations, suggesting a similar overall coma chemistry despite their different dynamical histories. The broad-band colours, on the other hand, show no significant systematic difference between LPCs and DNCs, confirming that colours alone do not constitute a reliable discriminator between the two dynamical classes.

One comet stands out as a notable exception to these general trends. C/2009 P1, classified as a returning LPC, displays activity profiles across all light curves, $Af\rho$, production rates, and magnitude slope that are far more typical of a DNC, suggesting that this comet has retained an unusually large fraction of its primordial supervolatile material despite having undergone previous perihelion passages. This behaviour is plausibly explained by a large perihelion distance during its previous passage, which would have limited the thermal processing of its surface.

Taken together, these results confirm that DNCs are compositionally more pristine than LPCs, with activity probably dominated by supervolatile sublimation at large heliocentric distances, while LPCs have undergone sufficient thermal processing during previous perihelion passages to deplete their most volatile surface material. The behaviour of C/2009 P1, likely linked to a large perihelion distance during its previous passage, illustrates that the boundary between these two dynamical classes is not always sharp, and that the individual thermal history of each comet plays a key role in determining the degree of volatile preservation and the resulting activity profile.

The results presented in this thesis open several directions for future investigation, both in terms of extending the observational sample and in terms of the methods applied. The sample of eight comets analysed in Chapter 4, while already providing statistically meaningful trends, remains limited in size. Extending this study to a larger sample of LPCs and DNCs, monitored over wider heliocentric distance ranges and with more complete pre- and post-perihelion coverage, will be essential to confirm and refine the differences identified here. In particular, increasing the number of comets with well-constrained dynamical histories will allow a more robust quantification of the relationship between prior Solar System exposure and observed activity profiles. The TRAPPIST telescopes, with their robotic and long-term monitoring capabilities, using many filters, including gas and dust bands, are ideally suited for this task, and ongoing observational campaigns will continue to build on the database presented in this work.

A key next step in this research program is the combination of the photometric monitoring presented in this thesis with spectroscopic observations of the same targets. Alongside the TRAPPIST photometric data, spectroscopic observations will be pursued in order to obtain a more complete picture of the coma composition and to directly constrain the nature and abundance of parent volatile species. In particular, optical spectroscopy will provide access to additional molecular species and enable a more detailed characterisation of the coma chemistry,

while infrared spectroscopy will allow the direct detection of parent molecules such as H_2O , CO , CO_2 , CH_4 , C_2H_6 , and CH_3OH , whose relative abundances are key diagnostics of the formation environment and thermal history of the nucleus. Combining photometric production rates of daughter species with spectroscopic measurements of parent molecules will enable direct tests of the photodissociation chains assumed in the Haser model, as demonstrated for comet C/2017 K2 in Chapter 3. This joint photometric and spectroscopic approach will provide a more complete and physically consistent picture of the composition and activity of LPCs and DNCs, and will help to disentangle the effects of dynamical history, thermal processing, and intrinsic compositional diversity on the observed coma properties.

The dynamical analysis presented in Chapter 4 relied on N-body integrations of clone swarms to reconstruct the past orbital histories of the eight comets in the sample. While this approach provided robust classifications for most objects, several comets occupy an intermediate regime between clearly dynamically new and clearly returning LPCs, where the detailed reconstruction of previous perihelion passages remains uncertain on Myr timescales. Future improvements in orbital solutions, driven by continued astrometric monitoring and the inclusion of non-gravitational forces, will help to reduce these uncertainties. In addition, incorporating the effects of galactic tides and stellar perturbations in a self-consistent manner will provide a more complete picture of the long-term dynamical evolution of these objects and of the Oort Cloud population as a whole.

The results of this thesis are directly relevant to the preparation and scientific exploitation of the ESA Comet Interceptor mission, which is designed to fly by a dynamically new comet or an interstellar object on its first passage through the inner Solar System. The ground-based photometric and spectroscopic characterisation of comets, as pursued in this work, will play an important role in constraining the expected properties of the mission target and in interpreting the *in situ* measurements that will be returned by the spacecraft. In particular, the systematic differences in activity onset, dust production, and molecular composition identified between returning LPCs and DNCs provide a quantitative framework against which the Comet Interceptor target can be compared and placed in the broader context of Oort Cloud comet evolution. Long-term monitoring campaigns of newly discovered returning LPCs, DNCs, or interstellar comets, carried out with facilities such as TRAPPIST, will remain essential in the years ahead to identify and characterise potential targets for the mission, and to build the ground-based context needed to maximise the scientific return of this unique space mission.

Appendix

Appendix A

Overview of TRAPPIST Telescopes Performance and Observational Statistics

A.1 Introduction

The TRAPPIST telescopes have been operating continuously for more than a decade, providing a large amount of observational data for both Solar System and exoplanet science. During the period of this thesis (2022–2026), the telescopes maintained a regular monitoring program focused primarily on cometary and asteroid observations, while also contributing to the follow-up and characterization of transiting exoplanets and to educational activities and projects within the Space Sciences master program at the University of Liège and Cadi Ayyad University.

To evaluate the observational efficiency and scientific productivity of the facilities, we compiled statistical indicators describing the telescope usage and time allocation. These statistics include the fraction of observing time dedicated to small bodies (comets and asteroids), exoplanet observations, master student training activities, as well as time lost due to weather conditions or technical issues. Such metrics provide a quantitative overview of the operational performance of the instruments throughout the thesis period.

The two TRAPPIST telescopes operate at different sites: TRAPPIST-North is installed at the Oukaimeden Observatory in Morocco, while TRAPPIST-South is located at the La Silla Observatory in Chile. The fraction of observing time lost due to weather reflects the atmospheric conditions specific to these two astronomical sites. Consequently, the weather statistics presented here provide useful information about the overall observing conditions at both observatories and can be considered representative of the general meteorological constraints affecting observations at these locations.

In the following sections, we present and discuss the observational statistics for both telescopes. Monthly and yearly distributions of observing time are analyzed, together with the relative contributions of the different scientific programs and operational losses. These results allow us to assess the overall performance of the facilities and their contribution to cometary science during the course of this thesis.

A.2 TRAPPIST-North observational statistics

A.2.1 Year 2022

The observing statistics for TRAPPIST-North in 2022 provide an overview of the distribution of telescope time among the different scientific programs and operational constraints. Figure A.1 summarizes the monthly allocation of observing time from January to December 2022. The statistics include the fraction of time dedicated to comet and asteroid observations (hereafter referred to as *cometime*), exoplanet monitoring (*exotime*), student observing programs within the framework of the *Astronomical Observations* course, and master’s theses, as well as time lost due to weather conditions and technical issues.

The cumulative time allocation for TRAPPIST-North over the entire year 2022 is summarised in Figure A.2, which provides a global overview of the telescope’s operational performance across all twelve months. Over the full year, weather loss constituted the dominant share of the total available time, accounting for 48.76% (1742h 31m), consistent with the challenging meteorological conditions typical of the Oukaimeden Observatory site, especially during the summer months. Technical loss represented the second largest fraction at 21.60% (771h 47m), a notably high value driven primarily by the severe technical difficulties encountered during the spring months, particularly in April and May, where technical loss exceeded 60% of the monthly available time, because of an internet issue and a problem with the mount of the telescope, which took several months to fix because of COVID-19 instructions. *Cometime* accounted for 19.28% (688h 59m) of the total time, reflecting the broad range of small-body scientific programmes conducted with the telescope. *Exotime*, dedicated to exoplanet transit observations, represented 9.45% (337h 50m) of the total available time, with the majority of these observations concentrated in the more favourable autumn and winter months, as discussed above. Finally, *studenttime* accounted for a marginal fraction of 0.91% (32h 25m), reflecting its limited allocation to only two months of the year, namely February and March. Taken together, these figures highlight that while TN remained scientifically active throughout 2022, a substantial portion of the year, nearly one fifth of the total available time, was lost to technical issues, underscoring the need for improved instrumental maintenance and stability in subsequent observing seasons.

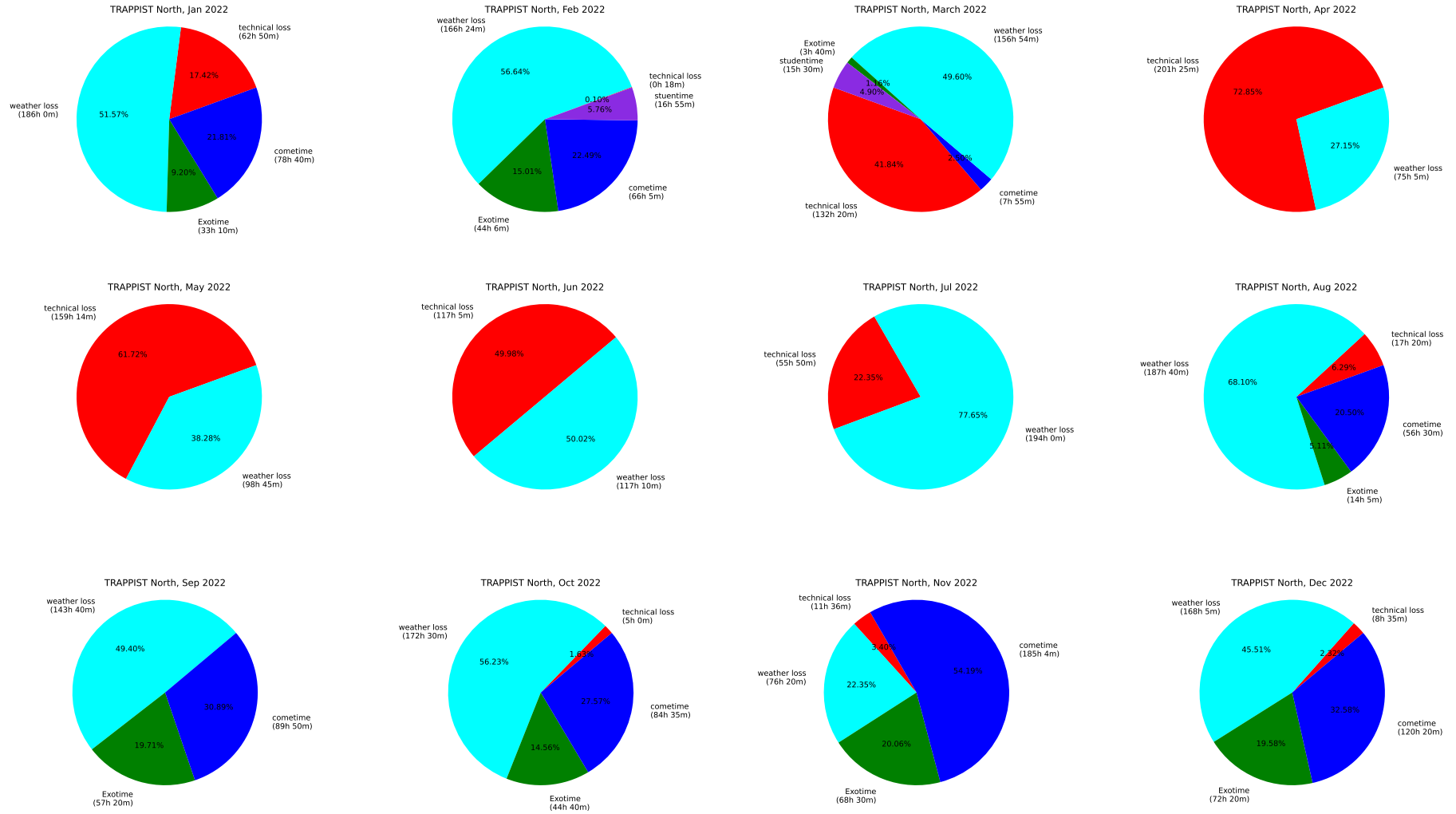


Figure A.1: Monthly observing statistics for TRAPPIST-North during 2022. Each panel shows the distribution of telescope time between comet and asteroid observations (cometime), exoplanet monitoring (exotime), student observing programs, and time lost due to weather conditions or technical issues.

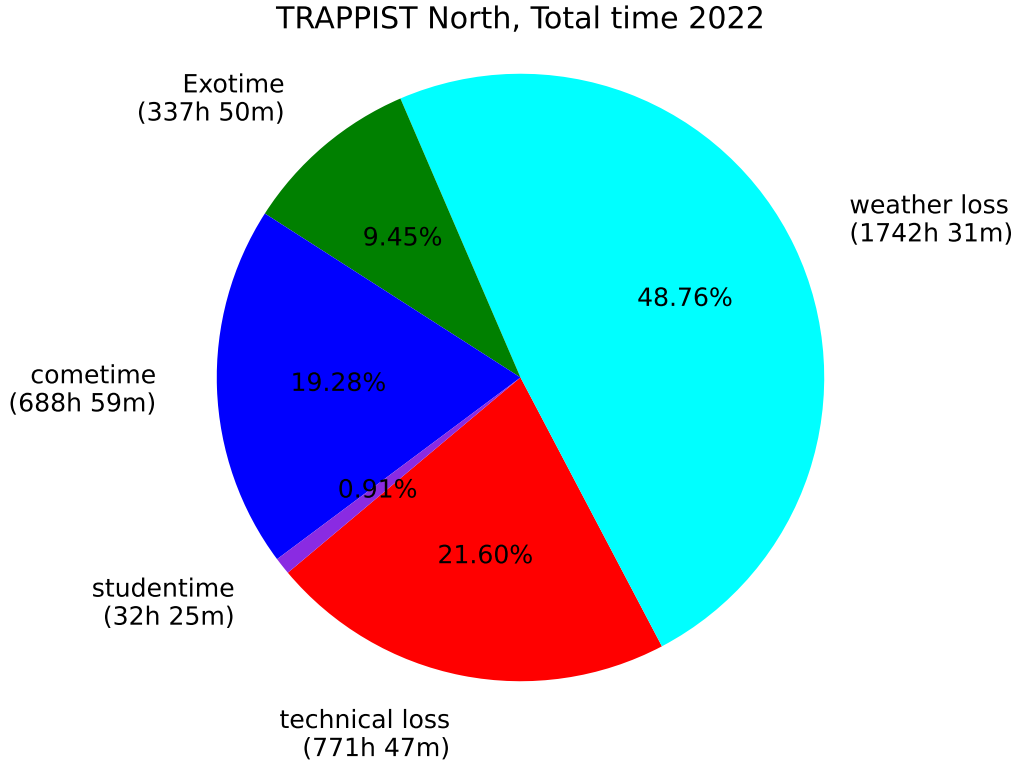


Figure A.2: Total time allocation statistics for TRAPPIST-North (TN) during the year 2022. The pie chart displays the distribution of total available time among the different operational categories: *Cometime*, *Exotime*, *Studenttime*, *Weather loss*, and *Technical loss*. Time fractions are expressed as percentages of the total available time over the full year.

A.2.2 Year 2023

Figure A.3 presents the monthly time allocation statistics for TRAPPIST-North (TN) throughout the year 2023. Compared to 2022, the year 2023 shows a notably improved overall scientific output, with *Exotime* and *cometime* featuring more prominently across virtually all months.

The cumulative time allocation for TRAPPIST-North over the entire year 2023 is summarised in Figure A.4, which provides a global overview of the telescope’s operational performance across all twelve months. The most striking feature of the 2023 annual statistics is the dramatic reduction in technical loss compared to 2022, dropping from 21.60% to only 4.62% (158h 40m), representing a substantial improvement in instrumental reliability and telescope maintenance over the course of the year. Weather loss, however, remained the dominant source of time loss, accounting for 41.42% (1422h 40m) of the total available time, with a slight decrease with respect to the 1742h recorded in 2022, largely attributable to the exceptionally poor meteorological conditions experienced in February 2023. *Exotime* and *cometime* achieved balanced allocations, representing 26.94% (925h 20m) and 27.02% (927h 50m) of the total available time, respectively, together accounting for over half of the year’s total time budget at 53.96%. This stands in sharp contrast to 2022, where scientific time was severely limited by technical difficulties. It is also worth noting that while a negligible amount of time was occasionally dedicated to student projects during 2023, this fraction was sufficiently small to be omitted

from the total statistics, unlike in 2022 where *studenttime* accounted for a recorded 0.91% of the total available time. Taken together, the 2023 statistics reflect a year of improved scientific productivity for TRAPPIST-North, tempered by persistent and at times severe weather losses that remained the primary limiting factor for observations throughout the year.

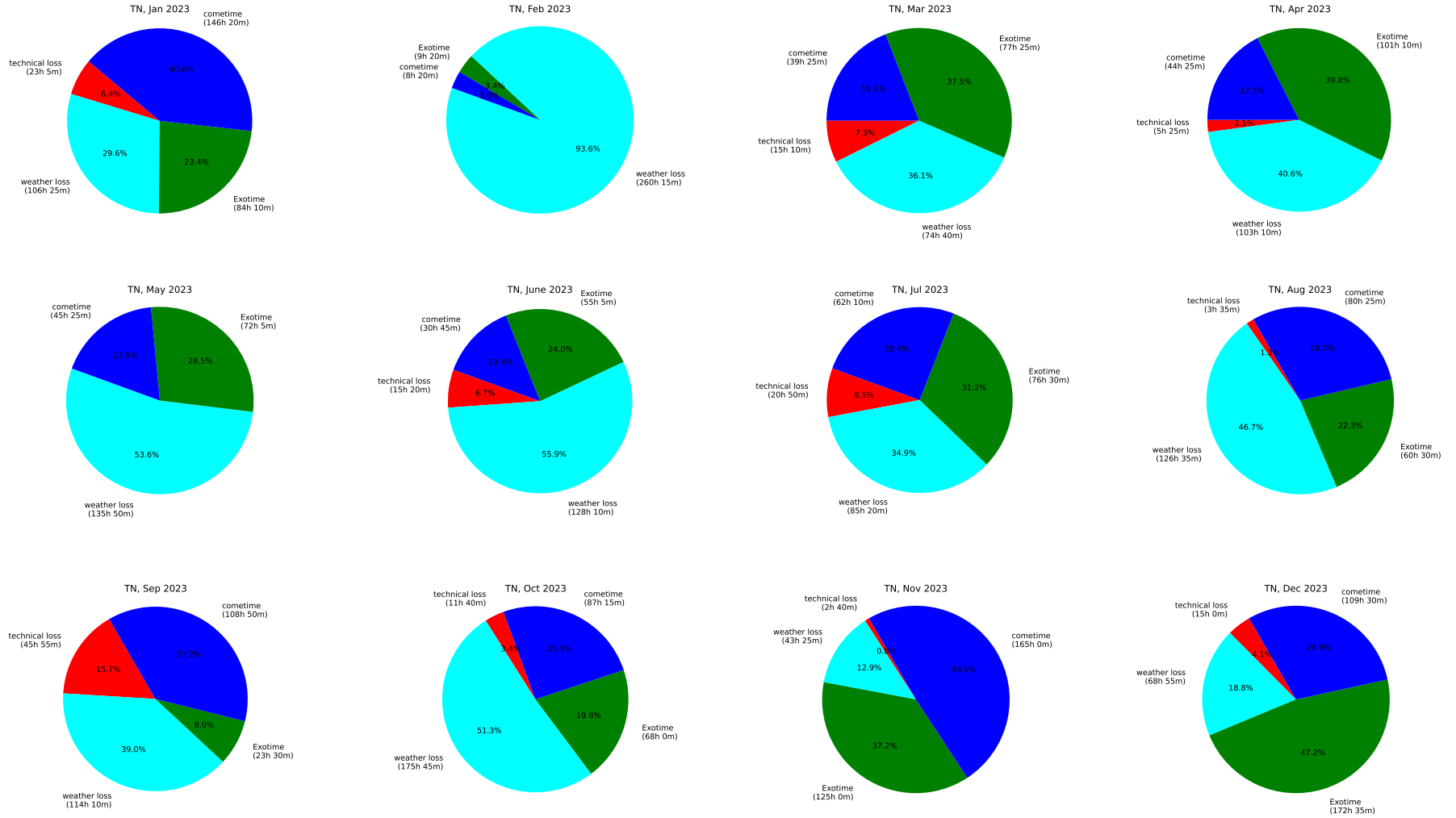


Figure A.3: Monthly observing statistics for TRAPPIST-North during 2023. Each panel shows the distribution of telescope time between comet and asteroid observations (cometime), exoplanet monitoring (exotime), and time lost due to weather conditions or technical issues.

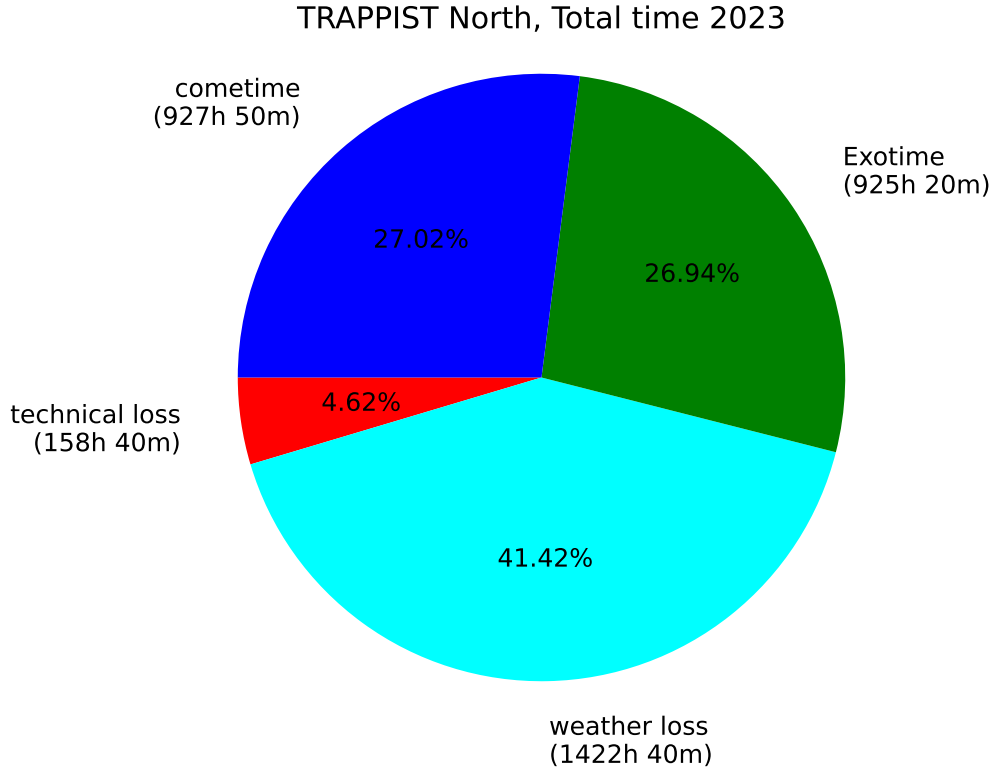


Figure A.4: Total time allocation statistics for TRAPPIST-North (TN) during the year 2023. Time fractions are expressed as percentages of the total available time over the full year.

A.2.3 Year 2024

Figure A.5 presents the monthly time allocation statistics for TRAPPIST-North (TN) throughout the year 2024.

The cumulative time allocation for TRAPPIST-North over the entire year 2024 is summarised in Figure A.6, which provides a global overview of the telescope's operational performance across all twelve months. The most prominent feature of the 2024 annual statistics is the dominance of weather loss, which accounted for 45.29% (1632h 35m) of the total available time, the highest annual weather loss recorded for TN across the three previous years, reflecting the particularly unfavourable meteorological conditions that affected the Oukaimeden Observatory site throughout the year, most notably during the spring and final quarter. *Cometime* constituted the largest share of scientific time at 38.09% (1373h 00m), while *Exotime* represented 14.31% (515h 50m) of the total available time. Technical loss continued its downward trend, reaching only 2.32% (83h 30m), consolidating the instrumental improvements observed since the critically high technical loss of 21.60% in 2022 and confirming the overall reliability of TN during 2024. As in 2023, a negligible amount of time was dedicated to student projects during 2024, though this fraction was sufficiently small to be omitted from the total statistics. Taken together, the 2024 statistics paint a picture of a technically reliable telescope operating under increasingly challenging weather conditions, with scientific productivity, particularly in terms of *Exotime*, significantly constrained by the high weather loss accumulated over the course of the year.

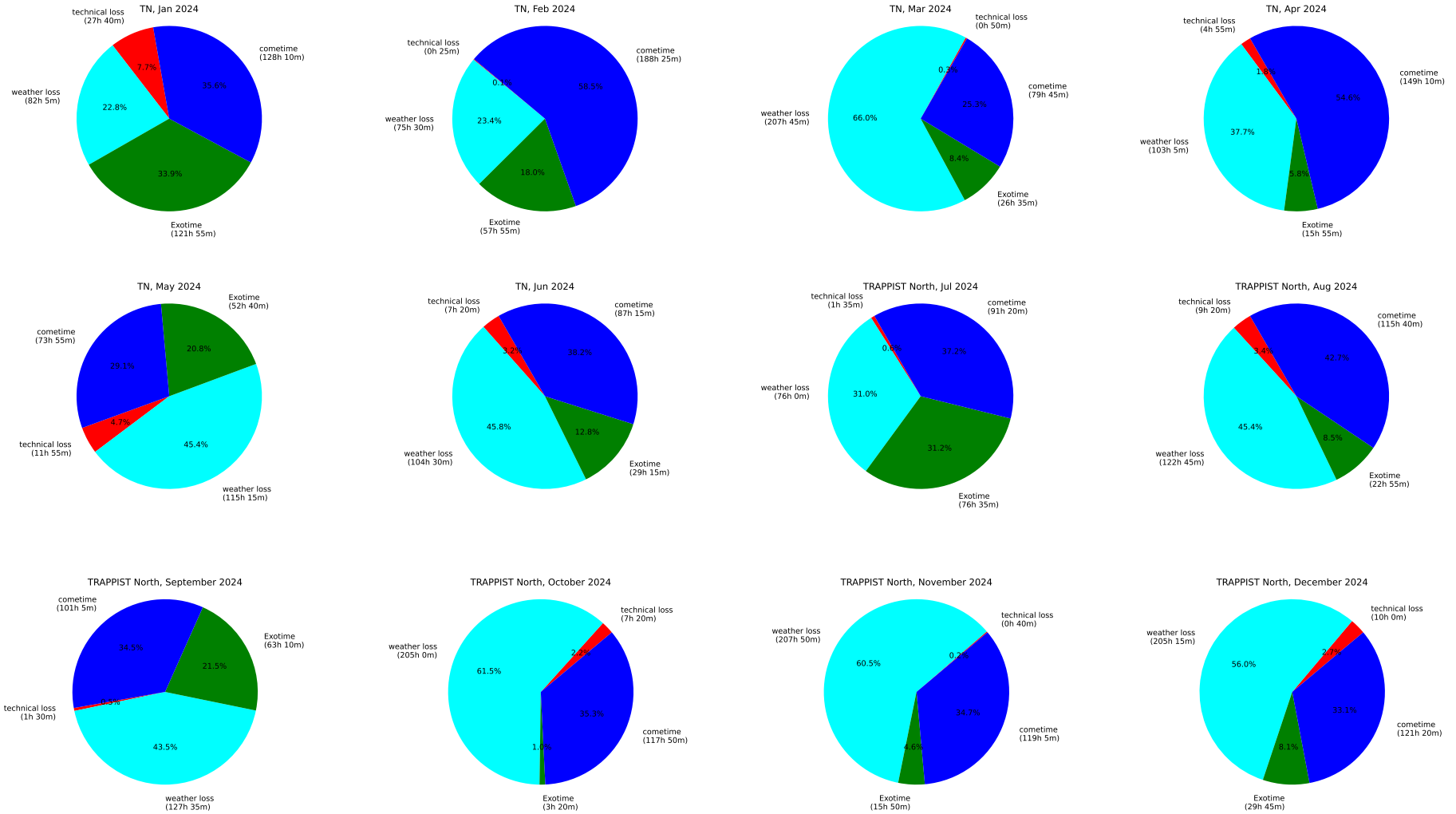


Figure A.5: Monthly observing statistics for TRAPPIST-North during 2024. Each panel shows the distribution of telescope time between comet and asteroid observations (cometime), exoplanet monitoring (exotime), and time lost due to weather conditions or technical issues.

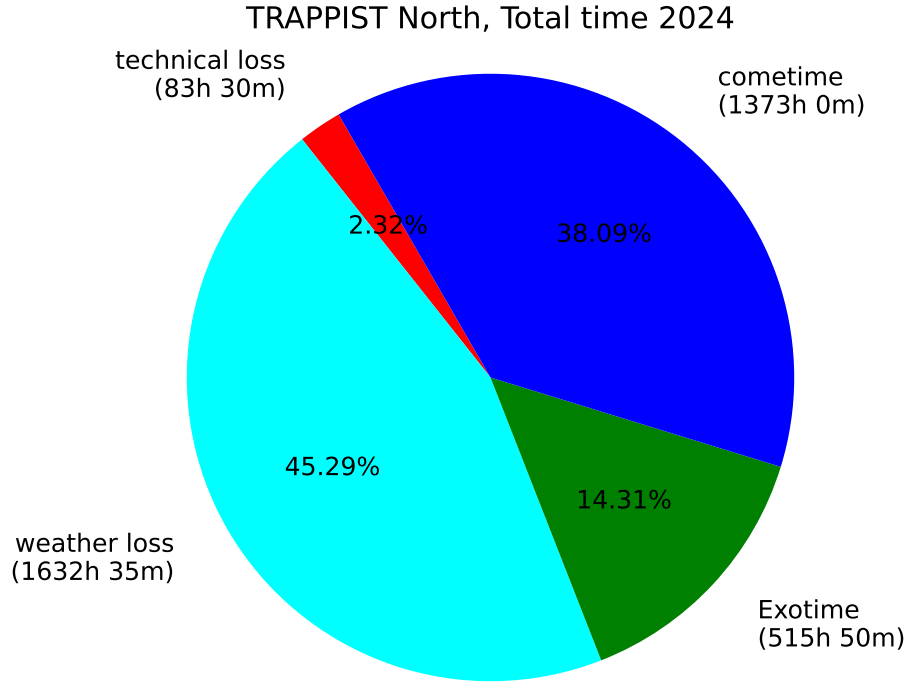


Figure A.6: Total time allocation statistics for TRAPPIST-North (TN) during the year 2024. Time fractions are expressed as percentages of the total available time over the full year.

A.2.4 Year 2025

Figure A.7 presents the monthly time allocation statistics for TRAPPIST-North (TN) throughout the year 2025. Overall, 2025 was the most operationally challenging year for TRAPPIST-North across the period studied, characterised by a severe and prolonged instrumental failure that rendered the telescope largely non-operational from August through November, and persistently high weather losses throughout the remainder of the year.

The cumulative time allocation for TRAPPIST-North over the entire year 2025 is summarised in Figure A.8, which provides a global overview of the telescope’s operational performance across all twelve months. The 2025 annual statistics reveal the severe instrumental failure that affected TN during the late summer and autumn months. Technical loss surged to 25.72% (931h 15m), representing the highest annual technical loss recorded for TN since 2022. Weather loss remained substantial at 38.67% (1400h 20m), comparable to the levels recorded in 2023 and 2024. As a direct consequence of these combined losses, scientific productivity was severely impacted, with *Exotime* falling to only 9.51% (344h 20m) and *cometime* reduced to 23.17% (839h 10m), the lowest scientific time recorded across all years studied. A particularly noteworthy feature of the 2025 statistics is the reappearance of a significant *studentime* allocation, accounting for 2.93% (105h 55m) of the total available time, the highest annual *studentime* recorded for TN across the entire period, driven largely by the exceptional allocation observed in March 2025. Taken together, the 2025 statistics underline the critical impact that instrumental failures can have on the overall scientific output, and highlight the importance of rapid and effective technical interventions to minimise downtime and preserve observing efficiency.

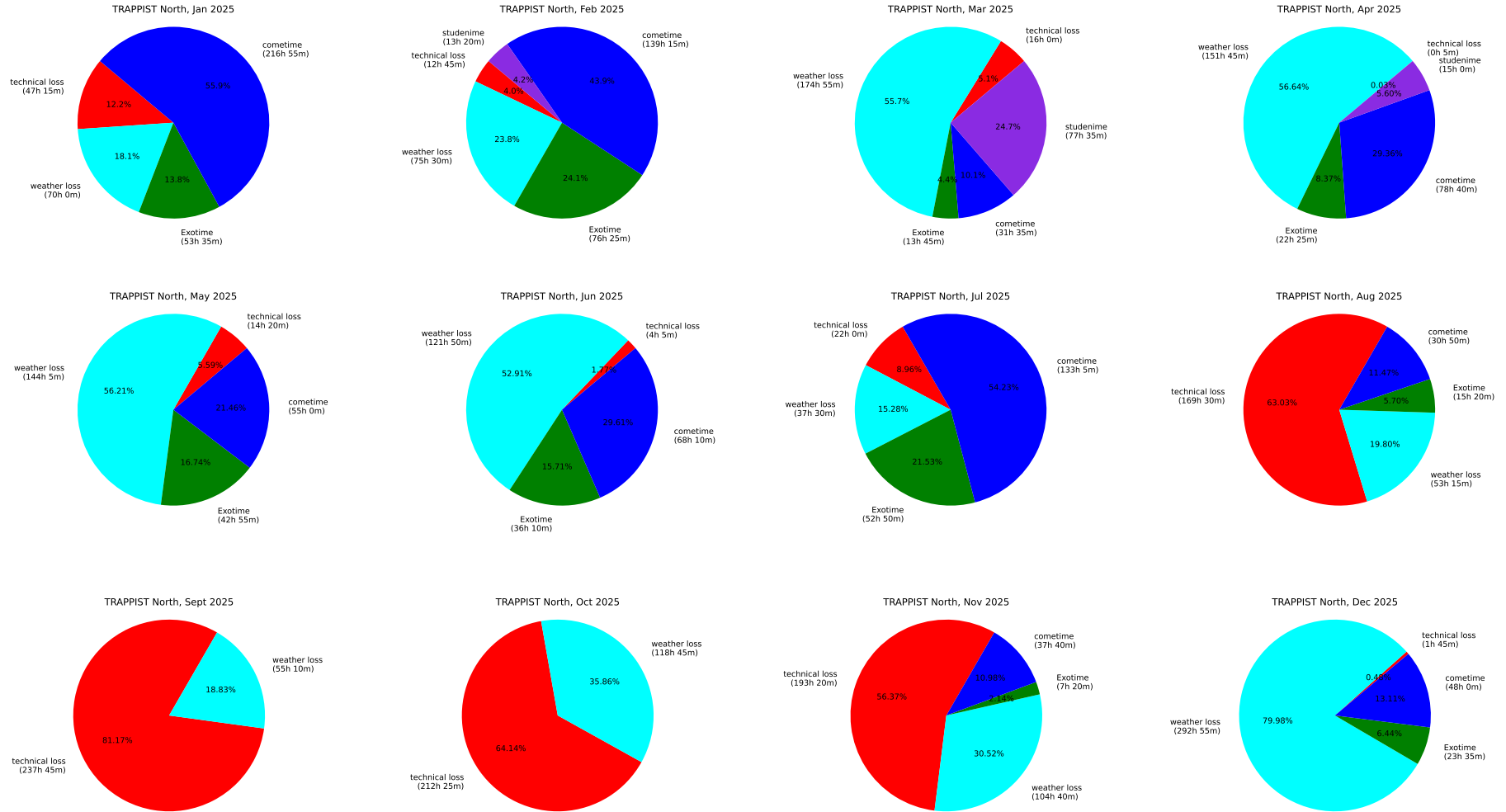


Figure A.7: Monthly observing statistics for TRAPPIST-North during 2025. Each panel shows the distribution of telescope time between comet and asteroid observations (cometime), exoplanet monitoring (exotime), and time lost due to weather conditions or technical issues.

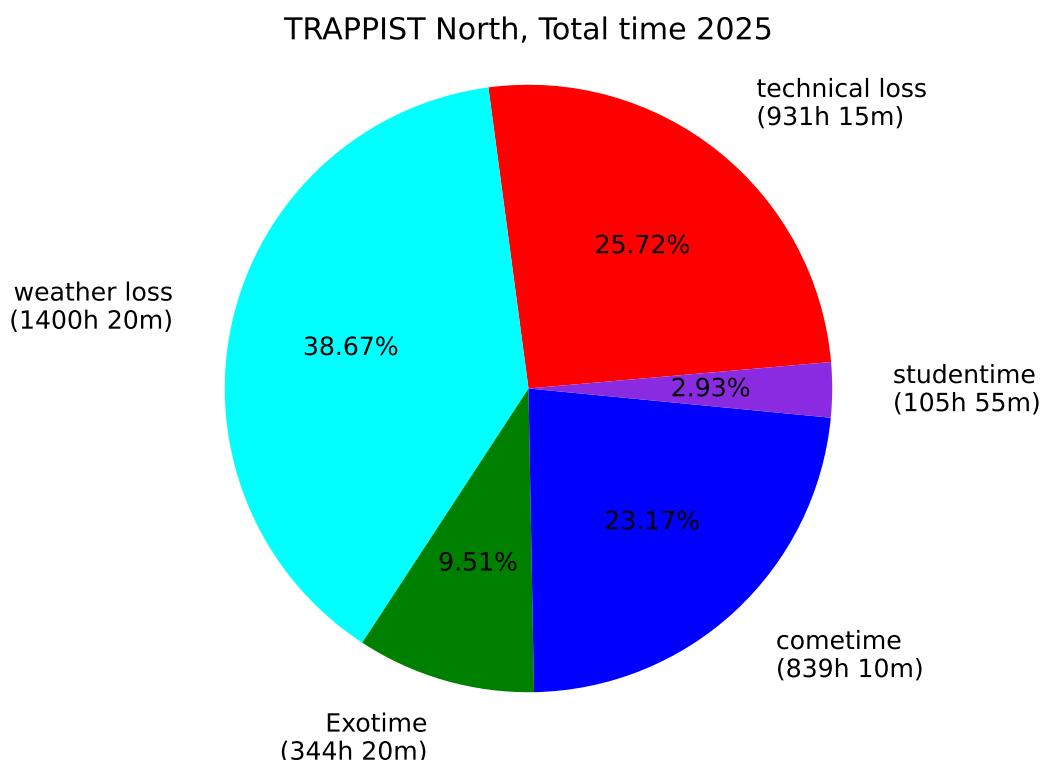


Figure A.8: Total time allocation statistics for TRAPPIST-North (TN) during the year 2025. Time fractions are expressed as percentages of the total available time over the full year.

A.2.5 Weather loss analysis at the Oukaimeden Observatory: A multi-year perspective (2018–2025)

Figure A.9 presents the monthly weather loss in hours recorded by TRAPPIST-North from 2018 to 2025, offering a broader multi-year perspective on the meteorological conditions prevailing at the Oukaimeden Observatory site. This extended analysis allows for the identification of recurring seasonal patterns as well as anomalous years that deviate significantly from the long-term trend. Examining the data across all eight years, it is immediately apparent that weather loss is far from uniformly distributed throughout the year, and that certain months consistently exhibit higher losses than others, reflecting the characteristic climate of the High Atlas Mountains. February stands out as one of the most recurrently affected months, with weather losses remaining elevated across most years and reaching a peak of 260.25 hours in 2023, the highest single-month weather loss recorded across the entire dataset with the exception of December 2025. March and April also consistently display substantial weather losses, frequently exceeding 150 hours, with March 2021 recording 199 hours and March 2024 reaching 207.75 hours, suggesting that the late winter and early spring period represents the most meteorologically challenging season for observations at Oukaimeden. October similarly emerges as a persistently problematic month, with weather losses ranging from 103.25 hours in 2020 to 213.1 hours in 2018, and remaining above 100 hours in virtually every year of the dataset. In contrast, the summer months of June and July consistently record the lowest weather losses of the year, with July in particular showing values as low as 37.5 hours in 2025 and 44.67 hours in 2021, confirming that the summer season, despite its shorter nights, generally offers the most stable and clear atmospheric conditions at the site. August, however, deviates from this

summer trend in certain years, most notably in 2022, when it reached 187.66 hours, suggesting occasional monsoon-related or convective weather intrusions during this period. December 2025 recorded the highest single-month weather loss of the entire dataset at 292.92 hours, an exceptional value that underscores the exceptional winter with a lot of snowfall reaching 1 meter for several weeks. From an inter-annual perspective, 2022 and 2023 stand out as the years with the most widespread and severe weather losses distributed across multiple months, while 2019 and 2021 appear comparatively more favourable in several months, particularly in the summer and early autumn. Taken together, this multi-year analysis provides important context for interpreting the annual statistics of TRAPPIST-North, confirming that weather loss is an unavoidable constraint on scientific operations at the Oukaimeden Observatory, with a seasonal cycle characterised by peak losses in late winter and spring, a relative minimum in summer, and a secondary maximum in autumn.

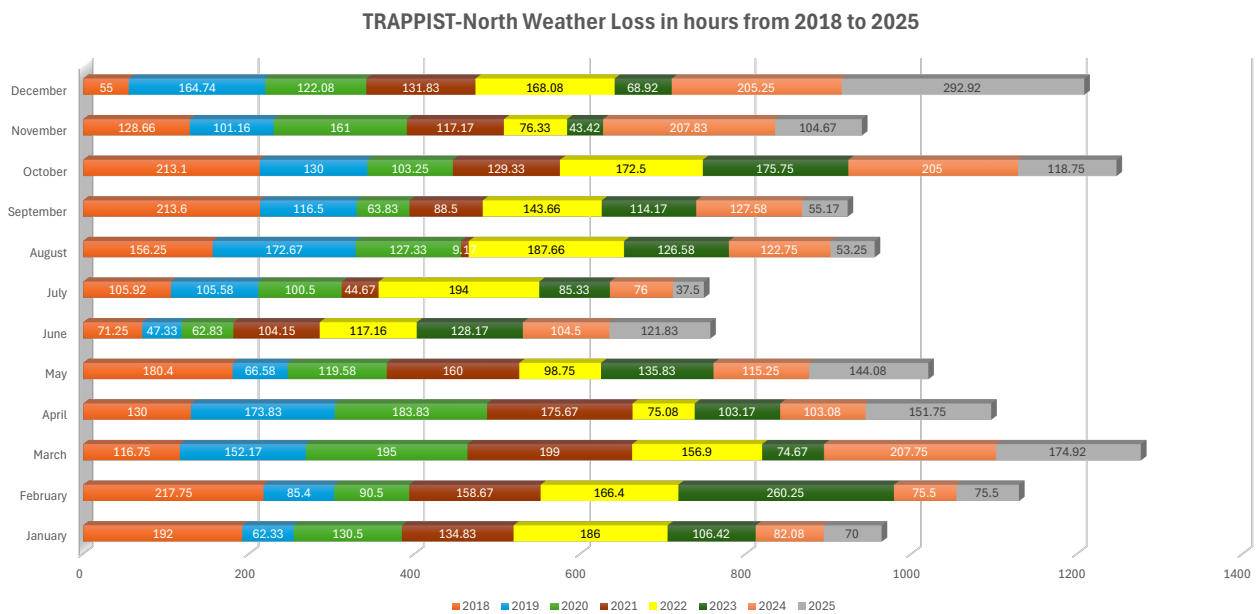


Figure A.9: Monthly weather loss in hours recorded by TRAPPIST-North (TN) at the Oukaimeden Observatory from 2018 to 2025. Each bar represents the cumulative weather loss for a given month, broken down by year.

A.2.6 Small bodies observation time at TRAPPIST-North: A multi-year perspective (2018–2025)

Figure A.10 presents the monthly time allocated to small bodies observations, encompassing both comets and asteroids, at TRAPPIST-North (TN) from 2018 to 2025. This extended multi-year overview provides a comprehensive picture of the telescope’s contribution to solar system science over the period studied, and reveals both the evolution of the small bodies programme over time and the strong dependence of observation time on the availability of scientifically interesting targets. The year 2018 stands out as the least active year for small bodies observations, with monthly allocations remaining very low throughout most of the year, particularly between January and October, where values rarely exceeded 55 hours, before rising sharply in December to 138.62 hours, suggesting the emergence of a notable target of interest towards the end of that year. In contrast, 2019 marked a significant increase in small bodies activity, with January recording 150.33 hours, the highest value of that year, followed by a gradual decline through the spring and summer months before recovering strongly in November (132.33 hours), reflecting the episodic nature of comet and asteroid visibility windows. The year

2020 exhibited the most uniformly distributed small bodies programme across all months, with consistently high allocations ranging from 38 hours in March to 139.33 hours in December, and particularly elevated values during the summer and autumn months, indicative of a rich and varied target list throughout the year. A striking feature of the 2021 data is the complete absence of any small bodies observations from August through December, with zero hours recorded across five consecutive months. This gap is directly attributable to the telescope controller being out of service during that period, which rendered TN non-operational and consequently prevented any small bodies observations from being carried out during the second half of the year. Similarly, 2022 shows a gap in small bodies observations between April and July, a period during which TN was severely affected by a technical issue with the telescope mount, which rendered the instrument non-operational for an extended period and prevented any observations from being scheduled during those months, before resuming in August and reaching its annual peak in November at 185.07 hours. The year 2023 presents a more regular distribution, with small bodies time present in every month of the year, peaking in January (146.33 hours) and November (165 hours), and maintaining a steady contribution throughout the summer and autumn. The year 2024 stands out as the most productive year for small bodies observations across the entire dataset, with consistently high monthly allocations throughout the year, most notably in February, where 188.42 hours were recorded, the highest single-month value across all years with the exception of January 2025. Indeed, January 2025 recorded the absolute maximum of the entire dataset at 216.92 hours, reflecting an exceptionally active period for small bodies observations at the start of that year. However, 2025 also exhibits complete gaps in September and October, with zero hours recorded in both months, consistent with the severe instrumental failure that affected TN during that period, which was similarly caused by a critical issue with the telescope mount, rendering the instrument entirely non-operational. Taken together, this multi-year analysis highlights the highly dynamic and target-driven nature of the small bodies programme at TRAPPIST-North, with observation time fluctuating significantly both within and across years in response to the visibility and scientific interest of available cometary and asteroidal targets, while also being inevitably constrained by weather losses and occasional instrumental difficulties.

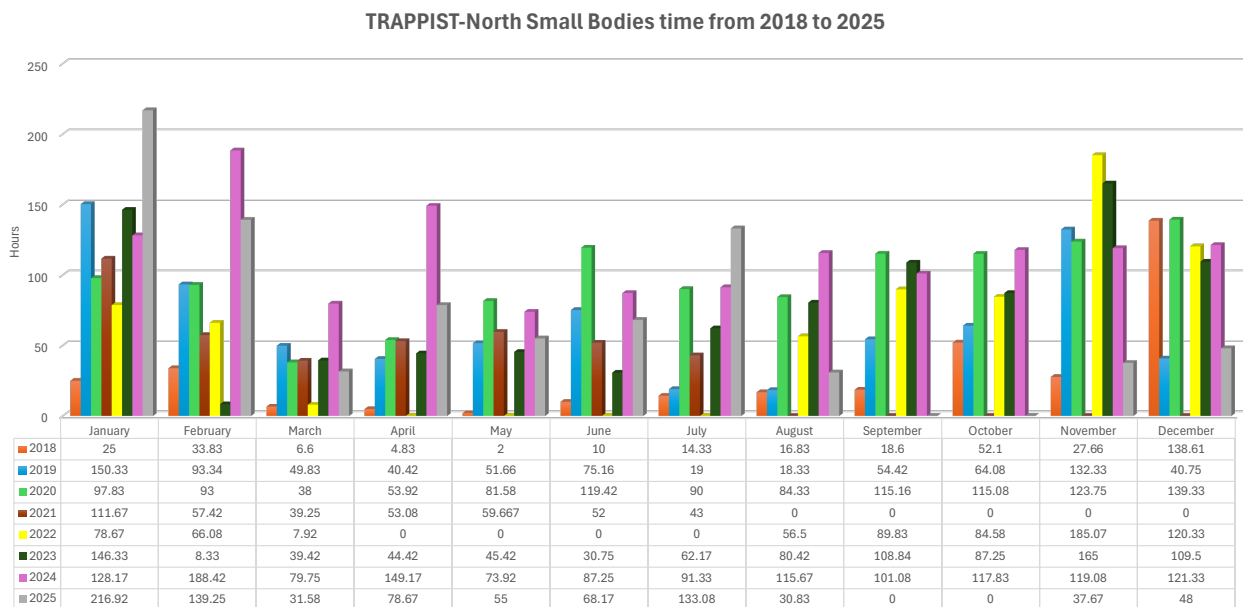


Figure A.10: Monthly time allocated to small bodies observations (comets and asteroids) at TRAPPIST-North (TN), expressed in hours. Each group of bars represents a given month, with individual bars corresponding to each year from 2018 to 2025.

A.3 TRAPPIST-South observational statistics

A.3.1 Year 2022

Figure [A.11](#) presents the monthly time allocation statistics for TRAPPIST-South (TS) at the La Silla Observatory in Chile throughout the year 2022. Overall, TS demonstrated a considerably stronger scientific output compared to TN during the same year, benefiting from the generally more favourable meteorological conditions at the La Silla site. The southern hemisphere seasonal cycle is clearly reflected in the data, with the austral summer months of January through March exhibiting particularly low weather losses and high scientific productivity.

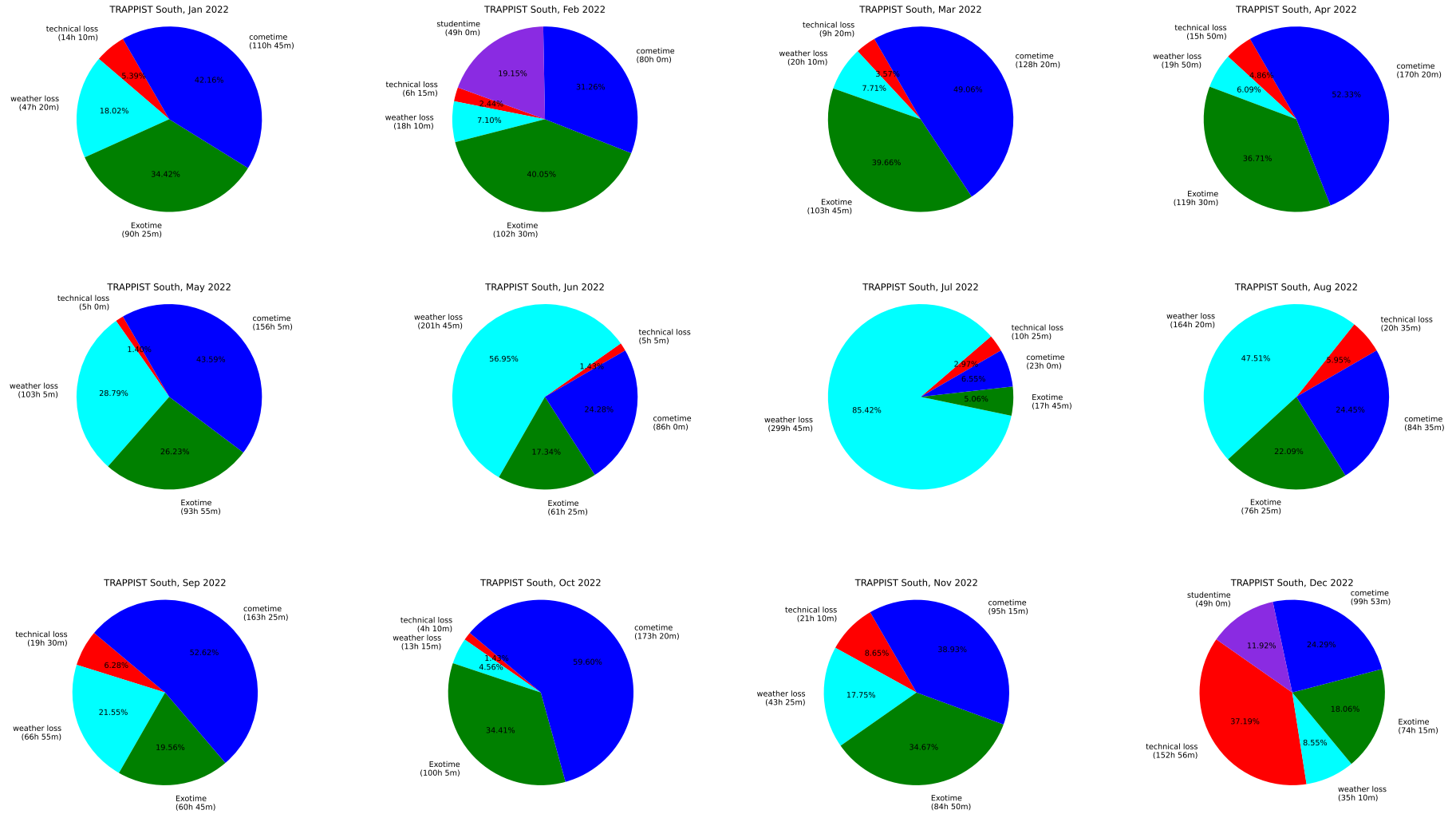


Figure A.11: Monthly observing statistics for TRAPPIST-South during 2022. Each panel shows the distribution of telescope time between comet and asteroid observations (*cometime*), exoplanet monitoring (*Exotime*), student observing programs (*studenttime*), and time lost due to weather conditions or technical issues.

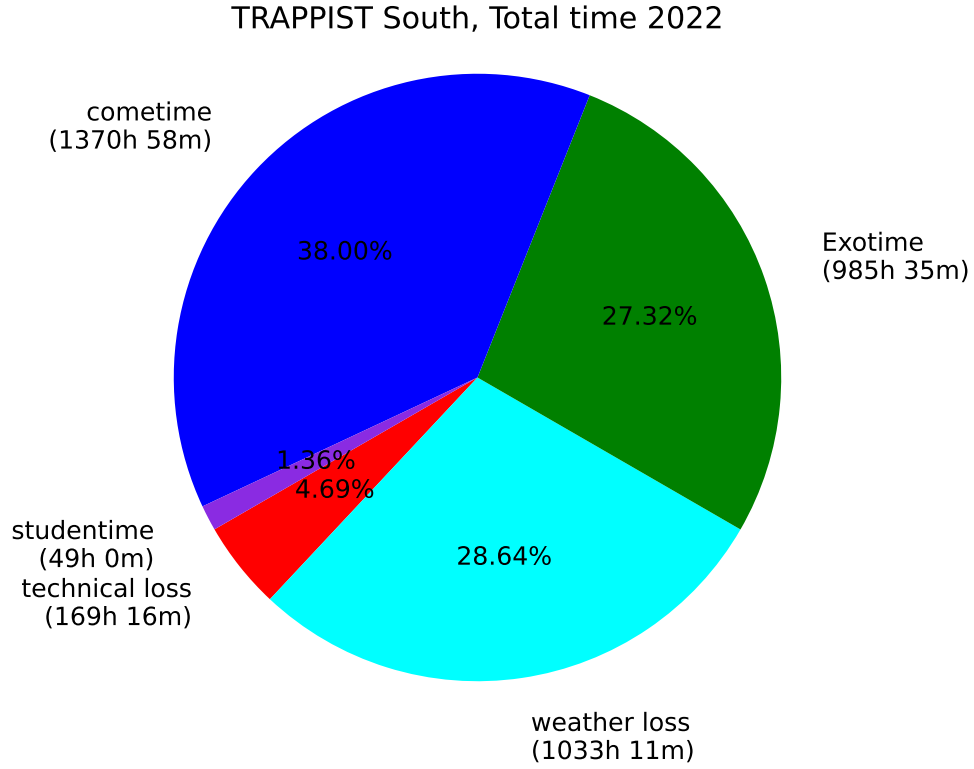


Figure A.12: Total time allocation statistics for TRAPPIST-South (TS) during the year 2022. Time fractions are expressed as percentages of the total available time over the full year.

The cumulative time allocation for TRAPPIST-South over the entire year 2022 is summarised in Figure A.12, which provides a global overview of the telescope’s operational performance across all twelve months. The annual statistics confirm the overall strong scientific productivity of TS during 2022, with combined scientific time (*Exotime* and *cometime*) accounting for 65.32% of the total available time. *Cometime* constituted the largest share of the total available time at 38.00% (1370h 58m), reflecting the broad range of small bodies and other scientific programmes conducted with TS throughout the year. *Exotime* represented a substantial 27.32% (985h 35m), underlining the important role of TS in the exoplanet transit monitoring programme of the TRAPPIST network. Weather loss accounted for 28.64% (1033h 11m) of the total available time, a value smaller than that recorded for TN in 2022 (1742h 31m), though it should be noted that the overall scientific productivity of TS remained significantly superior to that of TN during the same year, as the latter was severely impacted by technical losses concentrated in the spring months, reaching as high as 21.60% annually, rather than by meteorological conditions. Despite the pronounced weather losses experienced during the austral winter months of June and July. Technical loss remained relatively modest at 4.69% (169h 16m), though this figure was largely driven by the exceptional technical loss recorded in December because of the technical mission to TS and the mirror coating. *Studenttime*, corresponding to the time dedicated to master students, represented 1.36% (49h 00m) of the total available time, recorded exclusively in February and December. It is worth noting that no Chilean time, allocated to Chilean researchers under the ESO convention, was recorded during 2022.

A.3.2 Year 2023

Figure [A.13](#) presents the monthly time allocation statistics for TRAPPIST-South at the La Silla Observatory throughout the year 2023. The year was characterised by generally strong scientific productivity during the austral summer and autumn months, moderate weather losses during the austral winter, and a notable appearance of Chilean time allocations in the final quarter of the year.

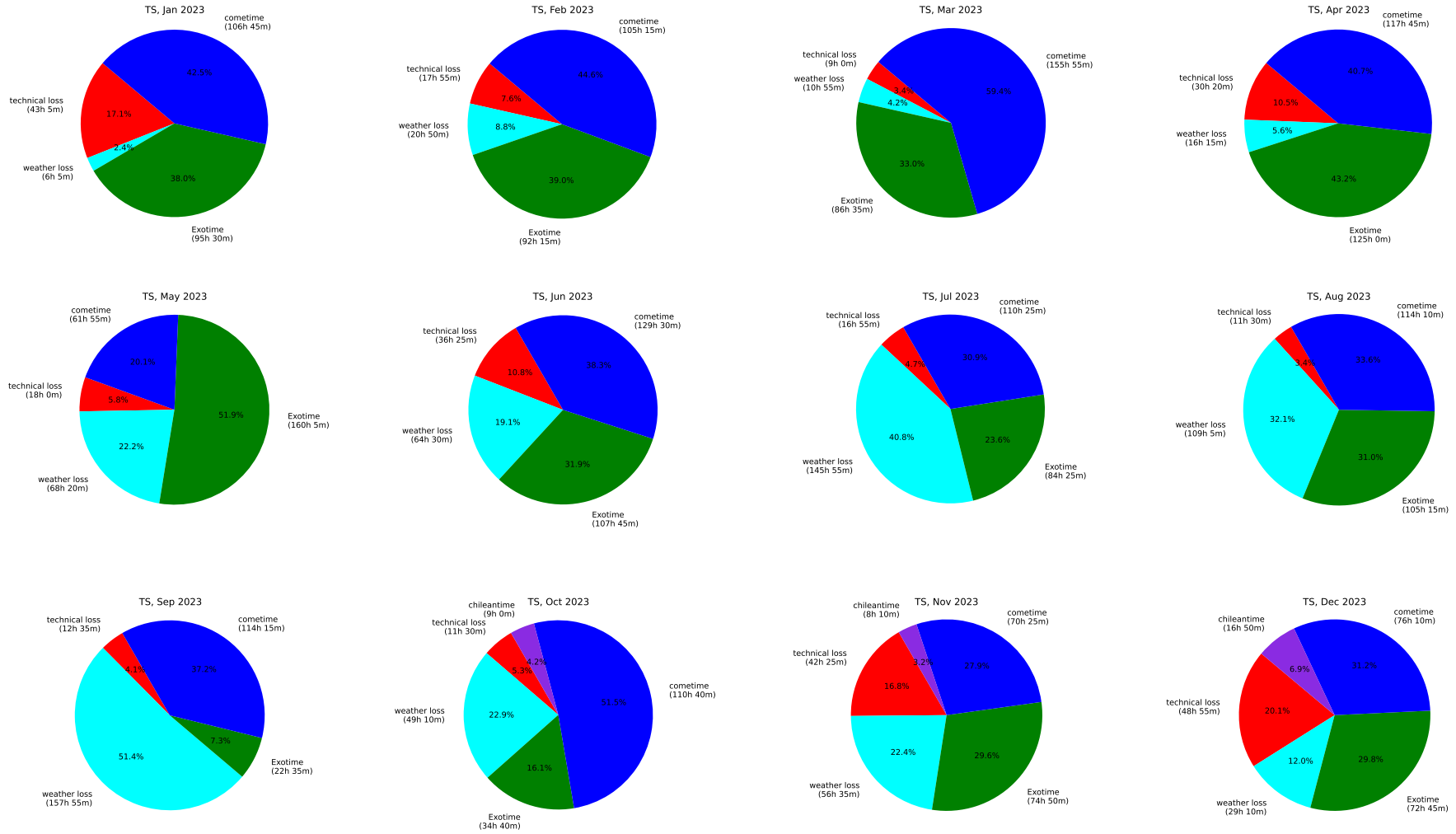


Figure A.13: Monthly observing statistics for TRAPPIST-South during 2023. Each panel shows the distribution of telescope time between comet and asteroid observations (*cometime*), exoplanet monitoring (*Exotime*), Chilean researcher observing programs (*Chileantime*), and time lost due to weather conditions or technical issues.

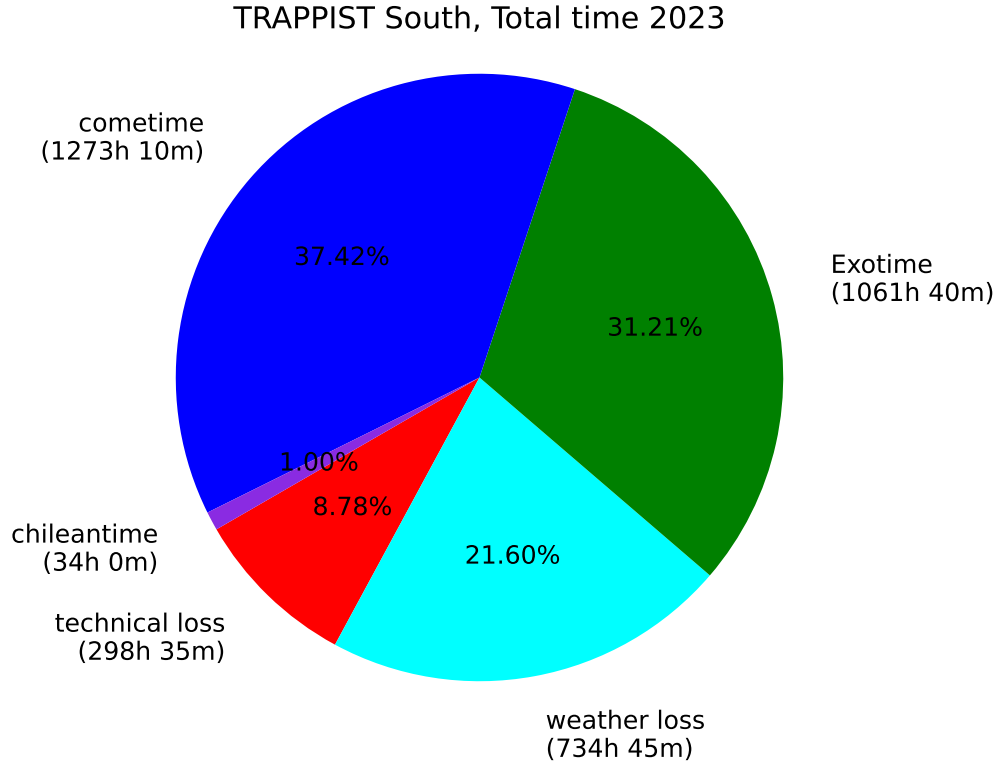
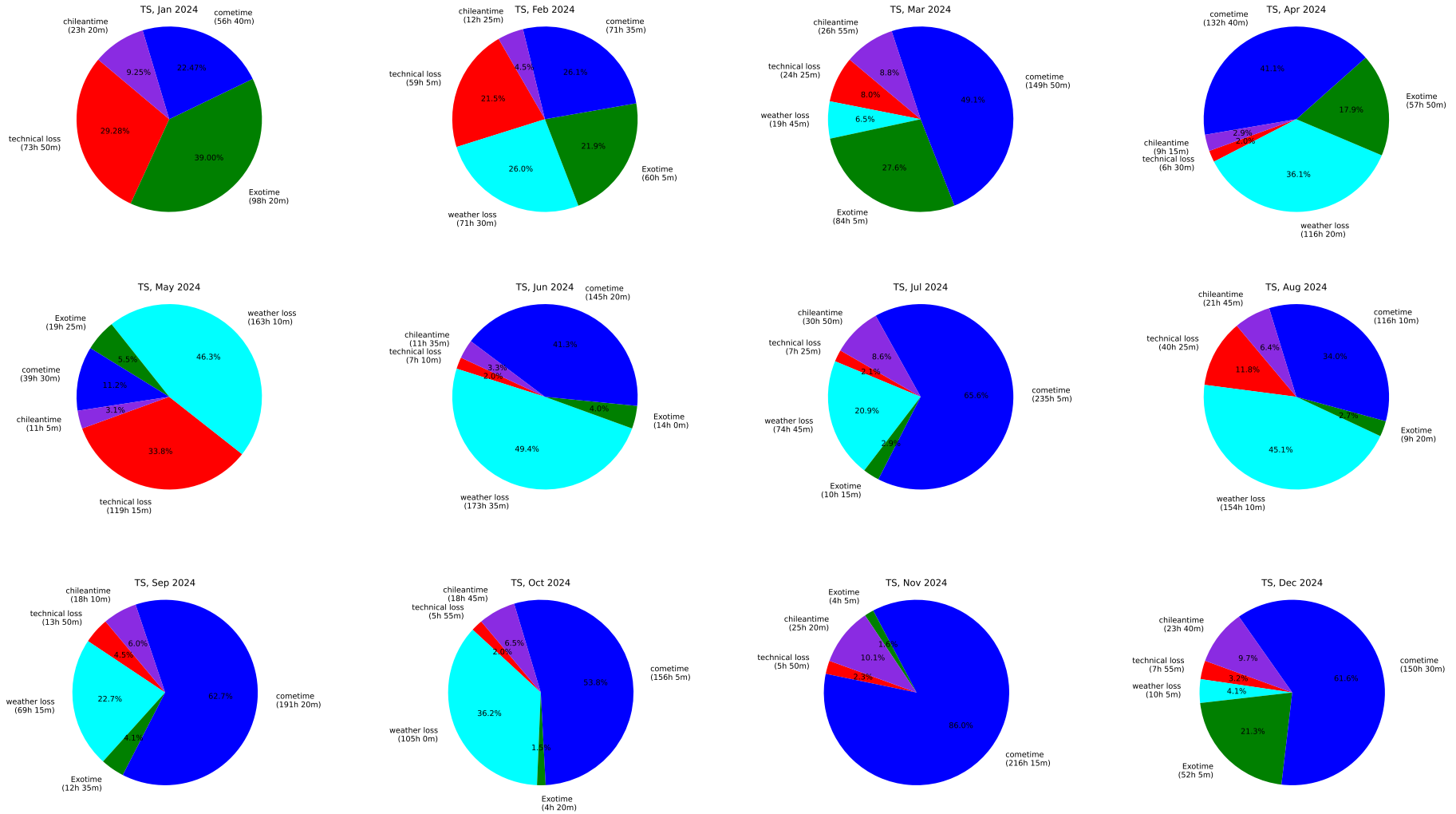


Figure A.14: Total time allocation statistics for TRAPPIST-South (TS) during the year 2023. Time fractions are expressed as percentages of the total available time over the full year.

The cumulative time allocation for TRAPPIST-South over the entire year 2023 is summarised in Figure A.14, which provides a global overview of the telescope’s operational performance across all twelve months. The 2023 annual statistics reveal a highly productive year for TS, with combined scientific time (*Exotime* and *cometime*) accounting for 68.63% of the total available time, a slight improvement over the 65.32% recorded in 2022. *Cometime* represented a 37.42% (1273h 10m) from the total allocated time, while *Exotime* represented a substantial 31.21% (1061h 40m), a notable increase compared to the 27.32% recorded in 2022. Weather loss accounted for 21.60% (734h 45m) of the total available time, a significant reduction compared to the 28.64% recorded in 2022, confirming the comparatively milder meteorological conditions experienced at La Silla during 2023, particularly during the austral winter months. Technical loss stood at 8.78% (298h 35m), higher than the 4.69% recorded in 2022, driven primarily by the elevated technical losses observed in January, April, June, November, and December. A notable feature of the 2023 annual statistics is the appearance of *chileantime*, representing 1.00% (34h 00m) of the total available time, allocated exclusively during the final quarter of the year across October, November, and December, reflecting the activation of the Chilean researchers observing programme under the ESO convention during that period.

A.3.3 Year 2024

Figure A.15 presents the monthly time allocation statistics for TRAPPIST-South at the La Silla Observatory throughout the year 2024. A distinctive and immediately striking feature of the 2024 statistics is the presence of *chileantime* in every single month of the year, reflecting a significantly expanded allocation of time to Chilean researchers under the ESO convention.



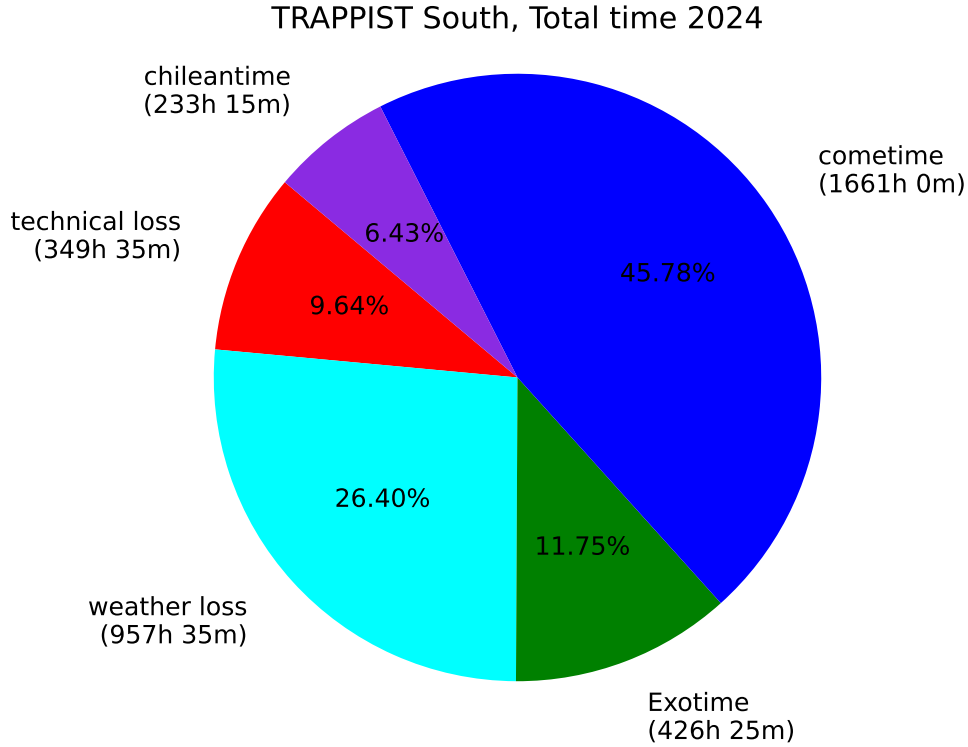


Figure A.16: Total time allocation statistics for TRAPPIST-South (TS) during the year 2024. Time fractions are expressed as percentages of the total available time over the full year.

The cumulative time allocation for TRAPPIST-South over the entire year 2024 is summarised in Figure A.16, which provides a global overview of the telescope’s operational performance across all twelve months. The most prominent feature of the 2024 annual statistics is the dominance of *cometime*, which accounted for 45.78% (1661h 00m) of the total available time, the highest annual *cometime* fraction recorded for TS across all years studied, reflecting the intensive monitoring of comets and asteroids carried out throughout the year, most notably during the exceptional months of July and November. Weather loss stood at 26.40% (957h 35m), slightly higher than the 21.60% recorded in 2023 but lower than the 28.64% of 2022, confirming the generally favourable meteorological conditions at the La Silla Observatory site while acknowledging the impact of the challenging austral autumn and winter period, particularly in May and June. The 9.64% (349h 35m) technical loss was about the same compared to the 8.78% in 2023, driven primarily by the significant technical difficulties experienced in January, February, and May, though it remained at a manageable level overall. *Exotime* represented 11.75% (426h 25m) of the total available time, a notable decrease compared to the 31.21% recorded in 2023. A defining characteristic of the 2024 annual statistics is the substantial *chileantime* allocation of 6.43% (233h 15m), by far the largest annual Chilean time fraction recorded across all years studied for TS, consistent with the expanded and regularised scheduling of Chilean researcher observing programmes throughout every month of the year.

A.3.4 Year 2025

Figure A.17 presents the monthly time allocation statistics for TRAPPIST-South throughout the year 2025. A notable contrast with 2024 is the significantly reduced presence of *chilean-*

time, which appeared in every month of 2024 but was recorded in only three months of 2025, namely January, October, and November. A distinct feature of the early part of the year was the appearance of *studenttime* allocations in February, March, and April, representing time dedicated to student research projects.

The cumulative time allocation for TRAPPIST-South over the entire year 2025 is summarised in Figure A.18, which provides a global overview of the telescope’s operational performance across all twelve months. The 2025 annual statistics reveal a highly productive year for TS, with combined scientific time (*Exotime*, *cometime*, *chileantime*, and *studenttime*) accounting for an impressive 70.03% of the total available time, the highest combined scientific fraction recorded for TS across all years studied. *Cometime* (comets and asteroids) remained the dominant category at 46.37% (1649h 10m), virtually identical to the 45.78% recorded in 2024, confirming the continued emphasis on small bodies monitoring programmes at TS during this period. *Exotime* recovered significantly to 19.06% (677h 50m), a notable improvement compared to the 11.75% recorded in 2024, reflecting a renewed investment in exoplanet transit monitoring during 2025. Weather loss continued its overall downward trend, reaching 20.05% (712h 55m), the lowest annual weather loss recorded for TS across all years studied, further confirming the generally excellent meteorological conditions at the La Silla Observatory site. Technical loss stood at 8.93% (317h 35m), broadly consistent with the 9.64% recorded in 2024, suggesting a stable level of instrumental reliability at TS during this period. A particularly noteworthy feature of the 2025 statistics is the significant reappearance of *studenttime*, accounting for 4.47% (158h 55m) of the total available time, a substantial increase compared to previous years, reflecting an expanded master student observing programme at TS during 2025. *Chilean-time* represented 1.13% (40h 05m) of the total available time, a marked reduction compared to 6.43% in 2024. Taken together, the 2025 statistics establish that TRAPPIST-South operated at peak scientific efficiency, delivering its strongest combined scientific output across all years studied, under the most favourable meteorological conditions recorded at La Silla throughout the period.

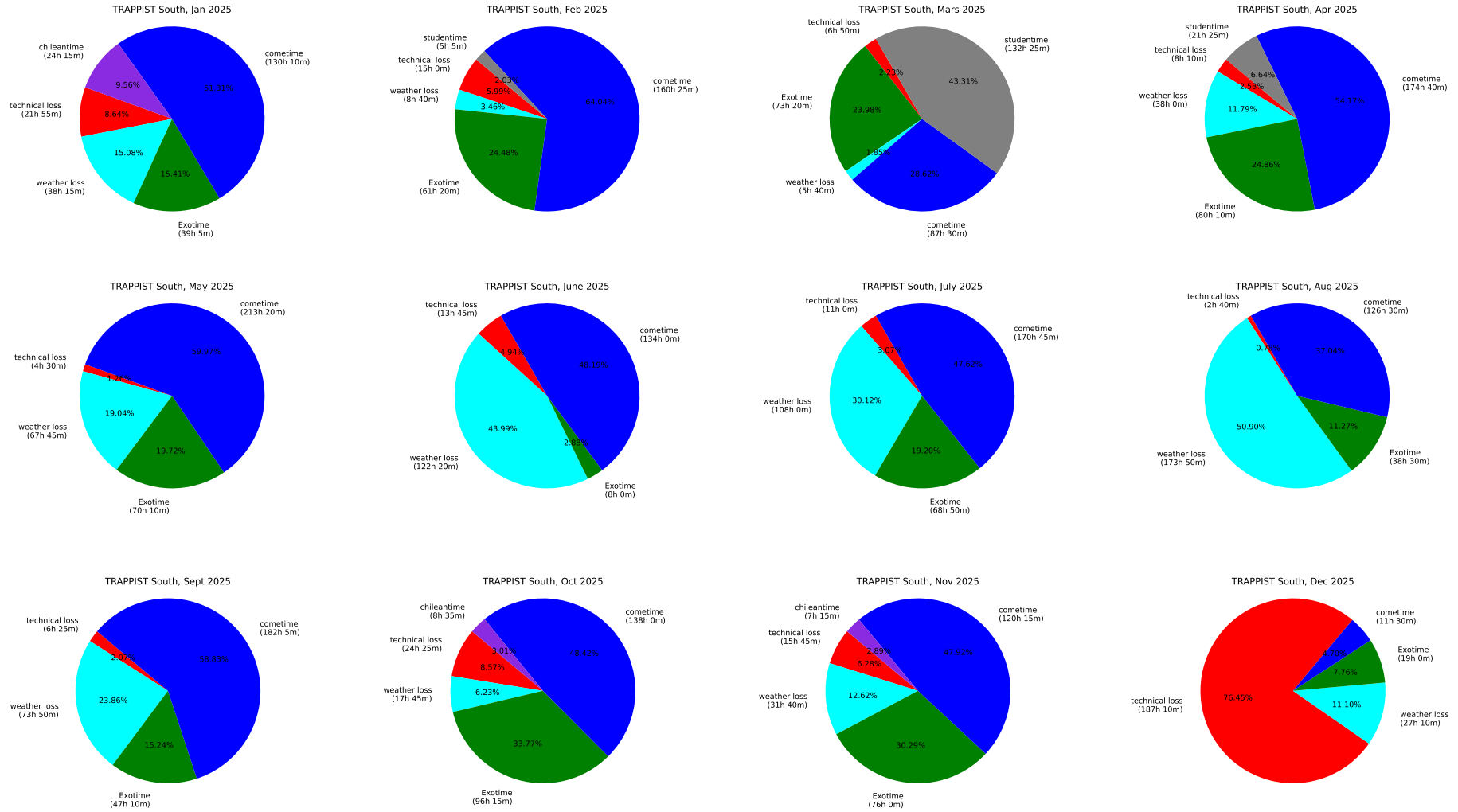


Figure A.17: Monthly observing statistics for TRAPPIST-South during 2025. Each panel shows the distribution of telescope time between comet and asteroid observations (*comettime*), exoplanet monitoring (*Exotime*), Chilean researcher observing programs (*Chileantime*), student observing programs (*studenttime*), and time lost due to weather conditions or technical issues.

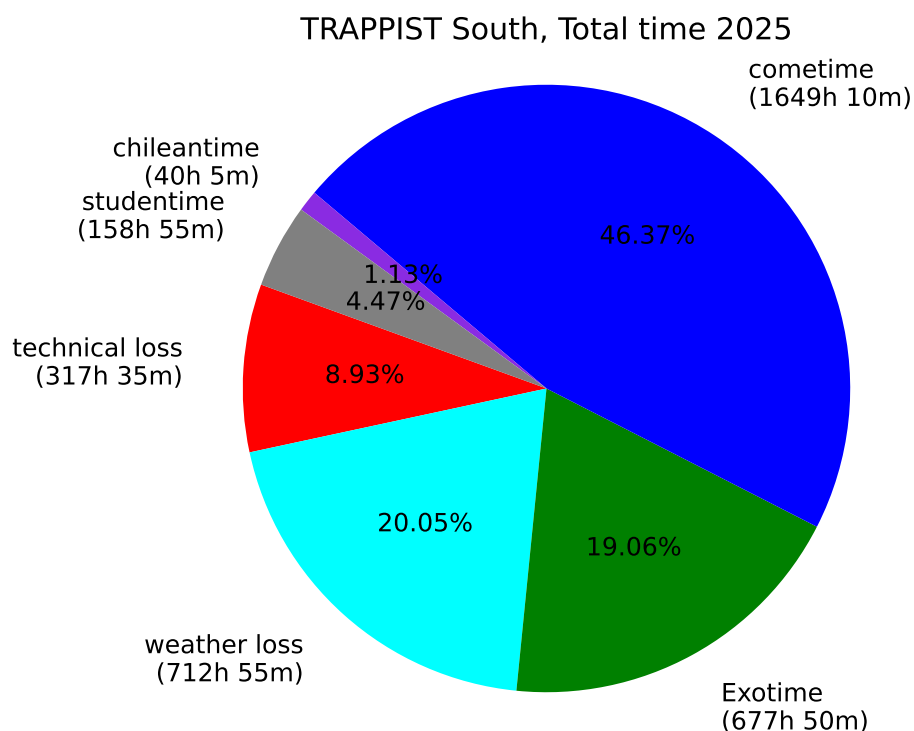


Figure A.18: Total time allocation statistics for TRAPPIST-South (TS) during the year 2025. Time fractions are expressed as percentages of the total available time over the full year.

A.3.5 Weather loss analysis at La Silla Observatory: A multi-year perspective (2018–2025)

Figure A.19 presents the monthly weather loss in hours recorded by TRAPPIST-South from 2018 to 2025, offering a broader multi-year perspective on the meteorological conditions prevailing at the La Silla Observatory site in Chile. This extended analysis allows for the identification of recurring seasonal patterns as well as anomalous years that deviate significantly from the long-term trend, and provides important context for interpreting the annual statistics discussed in the preceding sections. Examining the data across all eight years, it is immediately apparent that weather loss follows a well-defined seasonal cycle that is broadly consistent from year to year, reflecting the characteristic climate of the Atacama region and the southern hemisphere seasonal rhythm.

The austral winter months of June, July, and August consistently emerge as the most meteorologically challenging period of the year, with weather losses regularly exceeding 100 hours per month, and in several cases reaching exceptional values. July stands out as the single most affected month across the entire dataset, with losses ranging from 70 hours in 2020 to a remarkable 299.75 hours in 2022, the highest single-month weather loss recorded for TS across all years studied, because of a big storm that hit La Silla at the end of July 2022, which caused no electricity and the evacuation of the ESO staff. June similarly displays persistently elevated losses throughout the dataset, with values ranging from 64.5 hours in 2023 to 201.75 hours in 2022, while August shows a progressive worsening trend in recent years, rising from 51.25 hours in 2019 to 173.83 hours in 2025, the highest August value of the entire dataset.

May also emerges as a recurrently affected month, with weather losses frequently exceeding 100 hours, most notably reaching 183.16 hours in 2019 and 163.16 hours in 2024, reflecting the gradual deterioration of observing conditions as the austral autumn advances. September similarly displays substantial and variable losses across the dataset, ranging from 61.5 hours in 2020 to 157.92 hours in 2023, suggesting that the transition from austral winter to spring can be meteorologically unstable.

In contrast, the austral summer months of December, January, February, and March consistently record the lowest weather losses of the year, confirming that this season generally offers the most favourable observing conditions at La Silla. March is particularly remarkable in this regard, with weather losses remaining exceptionally low across virtually all years, reaching values as low as 0 hours in 2018, 7 hours in 2020, and 5.67 hours in 2025, making it the most consistently clear month of the entire dataset. February and December similarly display low and stable weather losses across most years, rarely exceeding 30 hours, with the notable exception of February 2019, which reached 71.5 hours. January shows somewhat more variability, with losses ranging from 0 hours in 2024 to 78.67 hours in 2020, though it generally remains among the least affected months of the year.

From an inter-annual perspective, 2022 stands out as the most severely affected year, with exceptionally high weather losses distributed across multiple months, most notably July (299.75 hours), June (201.75 hours), and May (103.09 hours), making it by far the most meteorologically challenging year in the dataset. In contrast, 2023 presents a more mixed picture, with a relatively mild austral winter but an unusually high September loss of 157.92 hours. The years 2020 and 2021 appear comparatively more favourable during the austral winter, with July losses of only 70 and 116 hours respectively, well below the multi-year average (146.5 hours) for that month. Taken together, this multi-year analysis provides important context for interpreting the annual statistics of TRAPPIST-South, confirming that weather loss is a structural and unavoidable constraint on scientific operations at La Silla Observatory, with a well-defined seasonal cycle characterised by a pronounced minimum during the austral summer months, particularly March, and a clear maximum during the austral winter, with July representing the single most vulnerable month across the entire observing record.

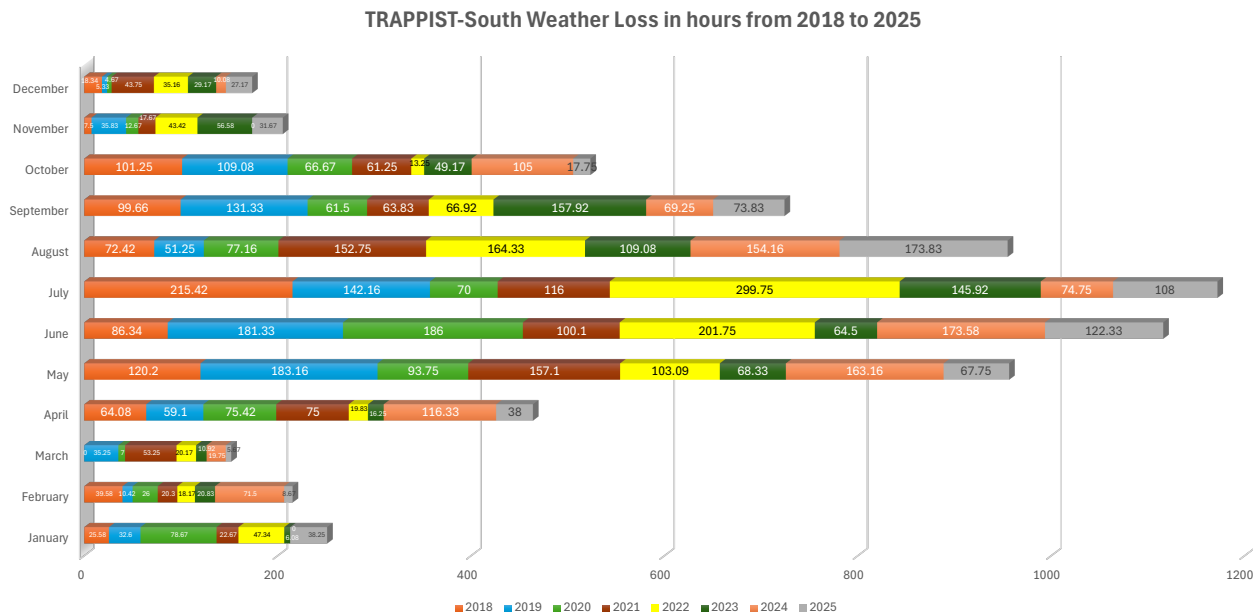


Figure A.19: Monthly weather loss in hours recorded by TRAPPIST-South (TS) at La Silla Observatory from 2018 to 2025. Each bar represents the cumulative weather loss for a given month, broken down by year.

A.3.6 Small bodies observation time at TRAPPIST-South: A multi-year perspective (2018–2025)

Figure A.20 presents the monthly time allocated to small bodies observations, encompassing both comets and asteroids, at TRAPPIST-South (TS) from 2018 to 2025. This extended multi-year overview provides a comprehensive picture of the telescope’s contribution to solar system science over the period studied, and reveals both the evolution of the small bodies programme over time and the strong dependence of observation time on the availability of scientifically interesting targets.

The year 2018 stands out as by far the least active year for small bodies observations across the entire dataset, with monthly allocations remaining exceptionally low throughout the first half of the year, particularly between January and April where values barely exceeded 8.5 hours, before rising gradually through the summer and autumn to reach more reasonable values of around 85–88 hours in the final quarter of the year. This pattern may reflect a combination of significant technical difficulties limiting operational time and a relatively sparse target list, with few scientifically compelling cometary or asteroidal targets available for most of the year during that period. The year 2019 marked a significant step forward, with January recording 100 hours and a relatively well-distributed programme across all twelve months, ranging from 33.16 hours in May to 141.1 hours in August, the latter being the annual peak and reflecting the visibility of particularly interesting targets during the austral winter period.

A striking and anomalous feature of the 2020 data is the complete absence of any small bodies observations from April through September, with zero hours recorded across six consecutive months. This extended gap is the longest such interruption recorded for TS across the entire dataset and is attributable to a combination of a technical issue affecting the telescope and the COVID-19 pandemic, which severely restricted the presence of staff members at the La Silla Observatory in person, preventing the technical issue from being resolved on time and consequently rendering TS non-operational for an extended period during that year. Despite this severe disruption, the programme recovered strongly in the final quarter of the year, with October, November, and December recording 87.58, 135.33, and 106.25 hours respectively.

The year 2021 stands out as one of the most consistently productive years of the dataset, with small bodies time present in every single month and monthly allocations remaining uniformly high throughout the year, ranging from 62.08 hours in January to 192.58 hours in March, the highest single-month value of that year. This remarkable regularity and the sustained high level of allocations across all seasons reflect an exceptionally rich and varied target list, with scientifically interesting cometary and asteroidal targets available throughout the entire year. The year 2022 similarly maintained a strong and broadly distributed small bodies programme, with notable peaks in April (170.34 hours), May (156.08 hours), September (163.42 hours), and October (173.33 hours), though July recorded a sharp decline to only 23 hours, consistent with the exceptionally high weather loss of 299.75 hours recorded at La Silla during that month, which severely curtailed all observing activities.

The year 2023 presents a remarkably uniform distribution of small bodies time across all twelve months, with allocations remaining consistently between 61.92 and 155.92 hours throughout the year and no month recording a complete absence of observations, reflecting a stable and well-maintained target programme. The year 2024 stands out as the most productive year for small bodies observations across the entire dataset in terms of peak values, with July recording an exceptional 235.08 hours, the highest single-month small bodies allocation recorded for TS across all years studied, and November reaching 216.25 hours, the second highest value of the dataset. These exceptional values likely reflect the visibility of particularly scientifically compelling cometary and asteroidal targets during those periods, driving an unusually high

allocation of telescope time to the small bodies programme.

The year 2025 maintained a very high and broadly sustained level of small bodies observations throughout most of the year, with consistently elevated allocations from January through November, most notably May recording 213.33 hours, the second highest single-month value of the entire dataset, and July reaching 170.75 hours. However, December 2025 recorded a dramatic collapse to only 11.5 hours, the lowest single-month value of 2025 and one of the lowest of the entire dataset outside of 2018, directly attributable to the extraordinary technical loss of 76.45% that rendered TS largely non-operational during that month, as discussed in the annual statistics section. Taken together, this multi-year analysis highlights the highly dynamic and target-driven nature of the small bodies programme at TRAPPIST-South, with observation time fluctuating significantly both within and across years in response to the visibility and scientific interest of available cometary and asteroidal targets, while also being inevitably shaped by weather losses, instrumental difficulties, and in the exceptional case of 2020, by external circumstances entirely beyond the control of the observatory.

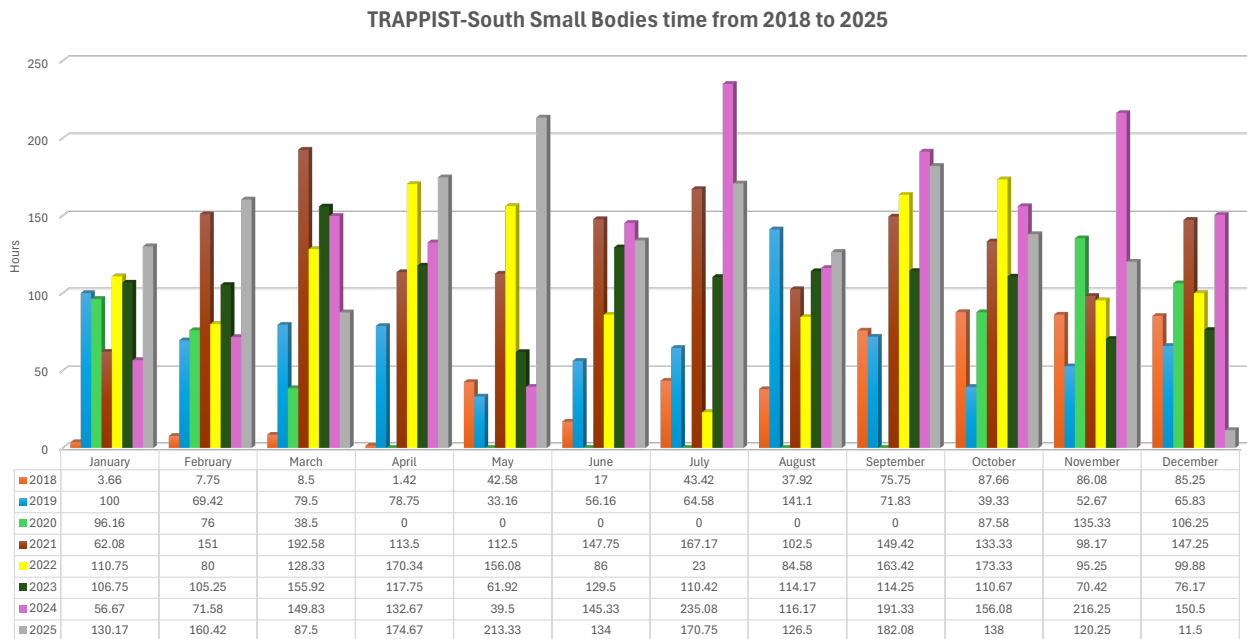


Figure A.20: Monthly time allocated to small bodies observations (comets and asteroids) at TRAPPIST-South (TS), expressed in hours. Each group of bars represents a given month, with individual bars corresponding to each year from 2018 to 2025.

Appendix B

Comets Observed with the TRAPPIST Telescopes (2022–2026)

Table B.1: Summary of TRAPPIST observations of long-period comets and the third interstellar comet between 2022 and 2026. For each object, the number of observing nights, broadband images (BB), and narrowband images (NB) obtained with TRAPPIST-North (TN) and TRAPPIST-South (TS) are listed.

Object	TRAPPIST-North			TRAPPIST-South		
	Nights	BB	NB	Nights	BB	NB
0003I	40	1279	150	40	2097	0
CK14UR1N	0	0	0	160	1279	0
CK17K020	80	604	39	118	823	443
CK19E030	0	0	0	91	603	0
CK19L030	13	89	66	43	262	101
CK19T040	28	188	1	16	114	12
CK19U050	14	104	34	16	97	12
CK20K010	0	0	0	38	214	8
CK20R070	0	0	0	8	58	0
CK20S040	14	100	0	15	94	0
CK20V020	34	234	147	44	251	0
CK21A010	0	0	0	34	424	346
CK21A090	13	88	0	4	17	0
CK21C050	0	0	0	30	185	0
CK21E030	0	0	0	8	74	40
CK21F010	0	0	0	3	21	7
CK21G020	0	0	0	39	222	0
CK21S030	65	378	197	38	197	0
CK21S040	14	92	0	0	0	0
CK21T040	4	28	0	22	123	0
CK21X010	3	21	0	5	27	0
CK21Y010	7	38	24	19	109	6
CK22A020	30	205	96	32	178	0
CK22A030	8	50	0	13	87	0
CK22E020	12	79	5	10	64	0
CK22E030	33	406	353	50	413	214
CK22P010	5	31	23	21	139	100
CK22Q78E	8	56	0	14	74	0
CK22R060	0	0	0	20	89	0
CK22U020	14	88	73	9	53	22
CK23A030	95	759	245	34	324	0
CK23E010	42	276	185	15	98	0
CK23H020	6	30	26	0	0	0
CK23P010	0	0	0	7	29	0
CK23R010	8	50	0	2	20	0
CK24A010	0	0	0	5	24	0
CK24E010	120	1057	0	0	0	0
CK24G030	0	0	0	8	43	0
CK25K010	15	118	66	0	0	0
CK25R020	6	50	46	6	169	0
CK25T010	4	34	24	0	0	0

Appendix C

Gas production rates and $A(0)f_\rho$

C.1 Comet C/2017 K2 (PanSTARRS)

Table C.1: Gas production rates and $A(0)f\rho$ parameter of comet C/2017 K2 (PanSTARRS) from TRAPPIST data. The $A(0)f\rho$ values are computed within a radius aperture of 5-arcsecond from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	r_Δ (au)	Production rates (molec/s)						$A(0)f\rho$ (cm)		
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc
2017-10-25	15.18	15.31									3773.40±717.30
2018-11-06	12.89	13.08									5986.88±562.23
2018-11-10	12.87	13.06									5123.75±409.26
2019-04-08	11.92	11.85									6809.18±249.87
2019-05-10	11.71	11.56									6739.79±212.81
2019-05-28	11.59	11.41									5911.20±256.14
2019-06-05	11.54	11.35									6225.22±323.87
2019-06-09	11.51	11.33									6903.24±222.92
2019-06-11	11.50	11.31									6693.24±260.36
2019-06-12	11.49	11.31									6121.04±248.04
2019-06-25	11.40	11.22									6826.96±204.70
2019-07-17	11.26	11.11									6489.91±617.77
2019-07-20	11.24	11.10									6881.36±577.68
2019-07-22	11.23	11.09									7358.43±375.48
2019-07-28	11.18	11.06									6669.67±230.02
2019-09-26	10.78	10.89									6730.76±249.43
2019-10-03	10.73	10.87									7157.57±260.69
2019-10-23	10.60	10.81									7109.72±207.93
2019-10-24	10.59	10.81									7260.67±229.85
2019-11-03	10.52	10.77									7110.86±293.56
2020-01-27	9.94	10.18									7385.39±256.92
2020-01-28	9.93	10.17									7304.06±318.19
2020-02-04	9.88	10.10									7118.60±203.10
2020-02-08	9.85	10.05									7101.09±340.09
2020-03-10	9.63	9.69									7832.26±762.57
2020-03-17	9.59	9.61									8064.85±252.32
2020-04-03	9.46	9.40									8108.65±182.73
2020-04-15	9.38	9.25									7519.40±263.56
2020-04-17	9.37	9.23									7946.26±147.37
2020-04-27	9.29	9.12									7994.35±167.97
2020-05-05	9.24	9.03									7308.59±207.45
2020-05-09	9.21	8.98									8162.83±220.96
2020-05-20	9.13	8.88									7793.10±152.64
2020-05-24	9.10	8.84									7740.78±120.90
2020-06-02	9.04	8.76									7714.21±143.66
2020-07-11	8.75	8.49									7550.97±249.67
2020-07-23	8.66	8.44									7506.43±89.91
2020-07-24	8.65	8.43									7793.29±122.18
2020-08-05	8.56	8.39									7863.07±265.63
2020-08-12	8.51	8.38									8013.76±95.72
2020-08-27	8.40	8.35									7692.02±154.72
2020-09-07	8.31	8.33									8771.15±99.06
2020-09-21	8.21	8.32									8503.51±204.74
2020-10-05	8.11	8.30									9216.04±115.88
2020-10-11	8.06	8.29									8868.92±173.21
2020-10-24	7.96	8.26									9022.92±161.57
2020-12-07	7.63	8.08									9439.39±324.59
2021-04-22	6.55	6.31									9637.61±234.19
2021-05-06	6.44	6.11									10034.74±118.95
2021-05-12	6.39	6.04									10363.67±80.99
2021-06-05	6.19	5.73									10333.07±63.64
2021-06-22	6.06	5.58									11414.00±106.92
2021-06-28	6.01	5.54									11205.46±98.23
2021-09-09	5.38	5.40									12457.29±87.67
2021-09-13	5.35	5.40									11995.34±99.31
2022-01-12	4.29	5.00									12140.12±176.53
2022-01-13	4.29	4.98									11988.58±175.16
2022-02-02	4.11	4.69									12096.66±113.28
2022-03-13	3.75	3.94									12256.02±102.55
2022-03-25	3.64	3.67									11632.88±185.45
2022-03-28	3.62	3.60			1.27±0.10e+26	1.49±0.25e+26					
2022-03-29	3.61	3.58									12237.24±268.79
2022-03-31	3.59	3.53			1.35±0.10e+26	1.22±0.51e+26					11261.88±285.32
2022-04-01	3.58	3.51									11879.42±130.81
2022-04-02	3.57	3.48									11398.86±87.10
2022-04-07	3.52	3.37			1.45±0.10e+26	9.69±1.33e+25					11291.50±128.80
2022-04-08	3.52	3.34			1.48±0.11e+26	1.57±0.18e+26					10897.88±218.57
2022-04-09	3.51	3.32			1.43±0.09e+26	1.61±0.26e+26	10399.28±181.51	12016.04±269.77			10996.01±284.99
2022-04-13	3.47	3.23			1.54±0.10e+26	1.05±0.40e+26	9684.19±186.76	11590.88±233.66	10186.83±169.10		10533.13±199.45
2022-04-27	3.34	2.90	1.66±2.67e+28	1.64±0.12e+26	1.17±0.18e+26		9196.37±150.20	11067.33±108.19	9736.40±106.83		10056.05±206.61

UT Date	r_h (au)	r_Δ (au)	Production rates (molec/s)					A(0)f ρ (cm)				
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc	
2022-04-28	3.33	2.88			1.65±0.17e+26	1.61±0.14e+26	4.43±0.42e+25	9538.22±159.89	11321.08±77.96	9914.76±81.62	10297.28±87.87	
2022-05-03	3.29	2.77	1.55±2.75e+28		1.84±0.10e+26	1.25±0.19e+26		9519.65±189.15	10717.32±102.76	9706.76±193.03	10458.82±68.31	
2022-05-10	3.23	2.61						9969.13±225.41	11222.31±75.99	9454.35±153.78	10208.94±64.32	
2022-05-16	3.17	2.49	1.73±1.04e+28		1.78±0.17e+26	1.54±0.17e+26	4.41±0.46e+25	9421.87±273.13	10642.21±250.59	9352.73±263.42	10170.12±80.43	
2022-05-24	3.10	2.33	1.71±2.54e+28				4.27±0.36e+25	9290.15±113.26	10757.36±62.29	9352.46±67.50	9896.96±80.55	
2022-05-25	3.09	2.31	1.73±2.53e+28				2.96±0.23e+25					
2022-05-27	3.07	2.27			2.03±0.11e+26		3.25±0.56e+25	9504.32±144.52	10969.99±52.51	9427.29±98.70	9958.57±82.59	
2022-06-08	2.97	2.08	1.77±0.85e+28				3.62±0.34e+25					
2022-06-09	2.96	2.06	1.82±0.76e+28		2.07±0.11e+26	1.66±0.11e+26	3.94±0.33e+25	8403.57±154.27	9984.15±56.12	8737.93±59.34	9257.98±45.74	
2022-06-11	2.94	2.04									9622.98±55.25	
2022-06-13	2.92	2.01	2.15±2.31e+28		2.09±0.10e+26	1.72±0.17e+26		8353.38±144.28	10330.02±77.70	9062.00±79.13	9644.26±73.33	
2022-06-18	2.88	1.95	2.64±0.58e+28				3.93±0.23e+25					
2022-06-29	2.78	1.85	3.21±2.57e+28		1.98±0.10e+26		4.23±0.28e+25	8160.92±116.02	9976.38±98.02	8800.84±60.67		
2022-06-30	2.77	1.85			2.04±0.09e+26	2.08±0.11e+26	5.65±0.27e+25	8559.22±94.85	10329.01±59.58	8938.91±55.58	9485.21±32.65	
2022-07-04	2.74	1.83			2.08±0.10e+26	2.14±0.10e+26	4.97±0.27e+25	8699.99±110.97	10578.42±42.53	9188.18±51.66	9424.96±37.03	
2022-07-07	2.71	1.82	3.58±2.50e+28		1.99±0.09e+26				9760.89±41.91			
2022-08-17	2.37	2.00	6.70±0.65e+28	6.99±3.12e+25	2.08±0.09e+26	2.12±0.12e+26	4.63±0.35e+25	9354.06±234.69	11412.33±68.11			
2022-08-18	2.36	2.01	7.77±0.79e+28			2.08±0.10e+26	4.42±0.31e+25					
2022-08-19	2.35	2.02	6.39±0.62e+28	1.24±0.30e+26	1.98±0.06e+26	2.24±0.07e+26				9895.09±54.92	10516.60±66.31	
2022-08-21	2.34	2.04	7.28±0.67e+28		1.76±0.05e+26						10293.35±33.15	
2022-08-22	2.34	2.04						8756.62±79.16	11317.90±29.44	9474.49±46.04		
2022-08-23	2.33	2.05	7.76±0.79e+28		1.84±0.06e+26	1.74±0.07e+26	4.08±0.18e+25		11244.40±33.43	9495.22±56.85	10373.68±43.67	
2022-08-24	2.32	2.06	7.72±0.80e+28		1.78±0.06e+26			9093.19±85.92	11494.16±38.14	9694.42±63.94	10489.86±60.71	
2022-08-25	2.32	2.07	6.40±0.68e+28						11055.06±33.76		10541.86±33.13	
2022-08-27	2.30	2.09	7.77±0.94e+28		1.97±0.07e+26	1.84±0.10e+26	4.29±0.22e+25	9108.89±101.31	11525.30±35.50	9624.97±77.85	10390.12±50.79	
2022-08-29	2.29	2.11	7.92±0.89e+28	1.01±0.22e+26	1.94±0.07e+26	1.86±0.10e+26		8788.41±101.57	11209.29±39.64	9398.84±70.91	10404.27±55.99	
2022-08-31	2.26	2.14	8.17±0.79e+28		1.89±0.07e+26						10404.26±40.15	
2022-09-01	2.26	2.14	7.95±1.12e+28						11454.41±37.48	9470.84±56.70	10415.31±40.58	
2022-09-02	2.26	2.15	9.08±1.12e+28		2.04±0.08e+26	1.84±0.12e+26	4.27±0.27e+25	8871.96±146.23	10985.71±72.02		10303.84±63.37	
2022-09-04	2.23	2.18	8.42±0.80e+28		1.88±0.06e+26						10665.87±48.86	
2022-09-05	2.23	2.18					3.68±0.22e+25	9060.62±111.16				
2022-09-06	2.23	2.19		1.64±0.53e+26	2.03±0.12e+26							
2022-09-10	2.20	2.23	9.13±1.08e+28		1.95±0.10e+26	1.55±0.10e+26	4.36±0.27e+25	9129.88±155.01	11443.29±41.76	9874.95±74.51	10462.40±60.76	
2022-09-14	2.17	2.28	8.80±0.91e+28								10537.60±52.00	
2022-09-15	2.17	2.28			1.83±0.07e+26	1.50±0.09e+26		9149.68±104.65	11114.51±49.07			
2022-09-18	2.14	2.32	7.96±0.97e+28	1.13±0.36e+26								
2022-09-19	2.14	2.32			1.74±0.07e+26	1.65±0.09e+26	4.02±0.23e+25	8613.29±137.74				
2022-09-20	2.12	2.33	9.26±1.18e+28	1.36±0.31e+26								
2022-09-21	2.12	2.34	1.03±0.13e+29	1.16±0.35e+26	1.73±0.07e+26	1.81±0.08e+26	3.46±0.23e+25	8778.92±125.11	11023.20±45.71			
2022-09-22	2.12	2.35			1.91±0.12e+26	1.59±0.09e+26	4.01±0.28e+25	9186.00±126.76	11420.02±53.39	9573.12±83.00	10765.38±66.64	
2022-09-23	2.10	2.36	9.43±1.23e+28	1.17±0.30e+26							10721.47±59.64	
2022-09-24	2.10	2.36			1.78±0.07e+26	1.82±0.08e+26	3.98±0.29e+25	9027.18±137.67	11104.90±71.01	9649.48±88.50		
2022-09-26	2.09	2.39	8.06±1.01e+28	3.39±0.26e+26								
2022-09-30	2.06	2.42	1.08±0.15e+29								10977.33±60.48	
2022-10-01	2.06	2.43	1.11±0.16e+29		1.98±0.08e+26	2.23±0.10e+26	4.65±0.32e+25	8952.98±149.53	11829.10±73.71		11104.32±67.78	
2022-10-02	2.06	2.43			1.98±0.08e+26	1.63±0.11e+26	4.34±0.34e+25	9257.92±157.17	11781.13±59.43		10995.86±77.05	
2022-10-06	2.03	2.46	1.14±0.18e+29								11219.20±76.82	
2022-10-07	2.03	2.46			2.04±0.09e+26	2.04±0.11e+26		9065.49±153.03	11713.52±60.41			
2022-10-12	1.99	2.50	1.08±0.18e+29								11120.46±101.29	
2022-10-13	1.99	2.50			1.96±0.10e+26	1.98±0.12e+26		9798.04±194.68	11829.96±81.96			
2022-10-14	1.98	2.51	1.18±0.22e+29									
2022-10-15	1.98	2.52	1.20±0.23e+29		2.14±0.11e+26	2.13±0.13e+26		10377.08±197.29	12643.32±58.22		11639.50±130.00	
2022-10-16	1.98	2.52			2.01±0.10e+26	2.25±0.13e+26		10272.49±197.62	12408.85±102.82		11470.76±96.15	
2022-10-19	1.96	2.54	1.22±0.23e+29									
2022-10-20	1.95	2.54		3.09±0.61e+26	2.01±0.10e+26	2.01±0.11e+26						
2022-10-21	1.95	2.54				2.68±0.12e+26	5.67±0.37e+25					
2022-10-22	1.94	2.55		3.87±0.70e+26								
2022-10-23	1.94	2.56		4.18±0.73e+26		3.06±0.14e+26	6.21±0.41e+25					
2022-10-24	1.94	2.56				3.20±0.15e+26	6.19±0.42e+25					
2023-01-28	1.87	2.26	1.33±0.29e+29		2.84±0.14e+26	2.61±0.17e+26		13528.06±259.55	14924.44±63.84	13337.70±133.27	14127.19±102.92	
2023-01-29	1.87	2.26	1.41±0.30e+29		2.82±0.14e+26		6.82±0.52e+25	13436.79±256.50			13814.90±98.71	
2023-01-30	1.87	2.25	1.37±0.28e+29		2.69±0.13e+26		6.93±0.53e+25	13409.13±243.76			13484.26±95.29	
2023-01-31	1.88	2.25	1.22±0.25e+29		2.60±0.13e+26		7.07±0.50e+25	12725.15±233.41			12759.80±88.69	
2023-02-23	1.98	2.24	9.92±1.45e+28	1.69±0.38e+26	2.22±0.09e+26	2.18±0.10e+26	5.38±0.33e+25	10774.56±169.30	11938.66±40.10	10613.67±97.15	11343.67±70.31	
2023-02-26	2.00	2.25	1.29±0.30e+29	3.57±0.78e+26	2.49±0.18e+26	2.32±0.15e+26					11419.44±67.93	
2023-02-27	2.00	2.25					5.66±0.33e+25	11001.79±144.41	12708.20±46.60	10853.59±77.64	11854.54±66.27	
2023-03-04	2.03	2.27	9.94±1.38e+28	2.43±0.51e+26	2.25±0.10e+26		5.40±0.41e+25	10955.75±186.81	11938.53±79.65	10635.30±116.84	11488.29±85.20	
2023-03-13	2.09	2.34	7.16±0.99e+28									
2023-03-14	2.09	2.34		2.04±0.47e+26	2.22±0.09e+26	2.11±0.08e+26	5.58±0.33e+25	9935.40±159.32			11085.31±75.40	
2023-03-20	2.13	2.40	7.10±0.96e+28	1.26±0.59e+26								
2023-03-21	2.13	2.40			2.06±0.09e+26	1.74±0.08e+26	4.89±0.30e+25	9539.89±176.97	10538.70±48.97	9343.81±84.38		
2023-03-23	2.15	2.43			2.19±0.10e+26							
2023-03-24	2.15	2.43				1.73±0.09e+26	5.55±0.33e+25	9418.33±122.62			10562.88±55.61	
2023-03-26	2.18	2.46	7.83±1.11e+28									
2023-03-27	2.18	2.46			2.27±0.09e+26	1.74±0.10e+26	5.96±0.37e+25	9463.55±152.08		9645.06±89.73		

UT Date	r_h (au)	r_Δ (au)	Production rates (molec/s)					A(0)f ρ (cm)			
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc
2023-03-30	2.20	2.51	8.11±1.40e+28								
2023-03-31	2.20	2.51		2.33±0.71e+26	2.30±0.10e+26	1.53±0.10e+26	5.49±0.44e+25				
2023-04-10	2.28	2.65	3.87±0.73e+28		2.17±0.10e+26						
2023-04-11	2.28	2.65				1.56±0.10e+26		9781.91±176.84			
2023-04-18	2.34	2.76			2.08±0.08e+26	1.32±0.10e+26	4.88±0.37e+25				9480.55±67.10
2023-04-19	2.35	2.77	5.33±1.21e+28					10010.17±172.54	10451.85±54.06		10070.73±50.00
2023-04-26	2.41	2.88									9537.65±56.30
2023-04-28	2.42	2.91									10318.65±65.31
2023-04-29	2.43	2.92									9696.57±67.18
2023-05-03	2.46	2.98									9338.61±63.24
2023-05-07	2.49	3.04									9433.18±61.48
2023-08-25	3.46	3.92									9724.36±50.56
2023-09-16	3.65	3.84									9228.83±61.84
2023-09-20	3.69	3.82	3.51±53.70e+26		2.02±0.25e+25			6664.21±163.02	7101.00±83.87		7387.04±118.02
2023-09-24	3.73	3.80									8428.02±56.18
2023-09-25	3.73	3.80				1.02±0.15e+26		6782.46±262.86	7289.63±75.36		8787.31±45.49
2023-09-29	3.77	3.77									8617.09±68.03
2023-10-05	3.83	3.74			2.04±0.68e+25	8.78±1.94e+25	7.73±2.41e+24				7403.56±65.80
2023-10-06	3.84	3.73									7364.98±63.78
2023-10-08	3.85	3.72									7378.67±44.75
2023-10-10	3.87	3.71									7505.57±65.87
2023-10-11	3.88	3.70			2.97±0.37e+25						7077.14±77.66
2023-10-15	3.92	3.67									7178.48±41.37
2023-10-20	3.96	3.65									7523.33±36.77
2023-10-26	4.01	3.61						6313.46±150.46	6873.33±97.94		7180.85±76.53
2023-11-08	4.13	3.55									7308.62±52.94
2023-11-12	4.17	3.54									6716.60±64.68
2023-11-14	4.19	3.53									6694.86±53.90
2023-11-16	4.20	3.52									7426.78±85.88
2023-11-18	4.22	3.52									7480.30±69.18
2023-11-22	4.26	3.52									6906.71±50.66
2023-12-06	4.38	3.53									6947.59±36.70
2023-12-07	4.39	3.54									6187.96±49.97
2023-12-09	4.42	3.55									6828.59±55.06
2023-12-10	4.43	3.55									6934.24±62.69
2023-12-11	4.43	3.56									6101.98±89.04
2023-12-14	4.46	3.58									6812.69±66.66
2023-12-18	4.50	3.61									6726.98±60.82
2023-12-21	4.52	3.63									5994.54±55.49
2024-01-02	4.63	3.76									6460.88±51.61
2024-01-06	4.66	3.81									6656.26±31.48
2024-01-23	4.82	4.11									6503.41±73.57
2024-01-24	4.82	4.13									6291.64±77.35
2024-01-27	4.85	4.19									5967.72±59.84
2024-02-03	4.91	4.34									6087.57±51.16
2024-02-11	4.98	4.52									6413.08±93.37
2024-02-12	4.99	4.54									6198.75±54.54
2024-02-21	5.07	4.75									6251.93±117.50
2024-02-29	5.14	4.95									6261.90±73.92
2024-03-04	5.17	5.05									5418.19±66.65
2024-03-10	5.22	5.18									6076.09±40.21
2024-04-03	5.42	5.77									5622.44±51.66
2024-04-09	5.47	5.91									5344.47±67.99
2024-04-11	5.50	5.97									5408.12±103.88
2024-09-12	6.76	6.98									4619.09±156.38
2024-09-14	6.78	6.96									4548.82±178.25
2024-09-26	6.88	6.86									4648.64±189.65
2024-09-27	6.88	6.85									4745.24±197.46
2024-10-04	6.94	6.79									4517.08±81.08
2024-10-30	7.15	6.57									3865.80±56.82
2024-11-04	7.18	6.54									3705.50±143.13
2024-11-11	7.24	6.50									3125.83±130.47
2024-11-23	7.33	6.47									3807.00±95.94
2024-11-27	7.37	6.47									3051.94±107.26
2024-12-03	7.42	6.48									3737.69±112.79
2024-12-11	7.47	6.50									4024.36±201.05
2024-12-19	7.54	6.55									2846.36±237.66
2025-01-04	7.66	6.72									2718.69±127.23
2025-01-20	7.78	6.96									4196.35±114.38
2025-01-25	7.82	7.05									3892.18±190.63
2025-02-01	7.88	7.21									3880.53±219.32
2025-02-17	8.00	7.57									3693.66±117.04
2025-03-26	8.28	8.47									3475.26±262.88
2025-04-20	8.46	9.04									2680.62±329.86

C.2 Comet C/2009 P1 (Garradd)

Table C.2: Gas production rates and $A(0)f\rho$ parameter of comet C/2009 P1 (Garradd). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					$A(0)f\rho$ (cm)	
			OH	CN	C ₂	C ₃	BC	GC	Rc
2010-12-09	4.70	5.04						7044.40±110.85	6097.58±42.60
2010-12-10	4.70	5.05						7709.33±177.13	6249.53±42.06
2010-12-12	4.68	5.06						7839.96±164.39	
2010-12-13	4.67	5.07						7005.58±158.51	
2010-12-20	4.60	5.10						6738.16±226.34	5966.50±79.56
2010-12-29	4.52	5.14						7671.19±142.84	6124.30±59.88
2011-01-04	4.46	5.15							5982.36±64.07
2011-01-06	4.45	5.16							5825.31±73.69
2011-04-30	3.35	3.78							9039.24±31.58
2011-05-02	3.33	3.73		1.44±0.10e+26		1.17±0.42e+25	10960.44±106.00	11777.63±65.76	9452.44±38.65
2011-05-03	3.32	3.71		1.08±0.09e+26				11691.31±70.23	9618.10±38.39
2011-05-04	3.31	3.68		1.17±0.10e+26			11575.96±127.56	11672.98±78.89	9218.58±44.60
2011-05-05	3.30	3.65		1.40±0.09e+26		1.28±0.50e+25	10967.72±134.89	11875.83±85.60	9889.78±47.58
2011-05-12	3.24	3.48		1.35±0.10e+26	4.49±0.74e+25	1.06±0.33e+25	11596.10±184.75	12050.12±109.74	10239.94±56.27
2011-05-13	3.23	3.45		1.36±0.08e+26	3.52±0.85e+25	8.61±2.65e+24	11451.93±216.01	12132.54±103.18	10226.36±59.88
2011-05-15	3.21	3.40		1.40±0.08e+26	3.87±0.43e+25	1.09±0.30e+25	11769.32±202.14	12272.80±112.99	10214.15±61.56
2011-05-18	3.18	3.32		1.39±0.11e+26	4.98±0.88e+25	1.20±0.40e+25		12290.79±168.84	10378.42±75.25
2011-06-04	3.01	2.87		1.77±0.08e+26		2.20±0.31e+25	11941.58±55.84	12445.74±31.76	10193.40±16.84
2011-06-09	2.96	2.73	2.20±0.91e+28	1.81±0.10e+26	9.44±0.90e+25	2.01±0.28e+25	12066.69±103.18	12313.06±61.07	
2011-06-11	2.94	2.68	2.28±0.71e+28	1.74±0.08e+26	1.65±0.10e+26	2.11±0.23e+25	11812.10±114.94	12585.28±72.90	10533.98±39.33
2011-06-12	2.93	2.65	2.06±0.84e+28	1.79±0.08e+26	1.14±0.09e+26	2.30±0.28e+25	11748.83±132.80	12529.70±79.89	10159.65±43.74
2011-06-14	2.91	2.60	1.72±0.78e+28	1.78±0.09e+26	1.37±0.12e+26	2.19±0.38e+25	12171.82±176.06	12445.30±109.70	10476.67±52.67
2011-06-15	2.90	2.57	1.71±0.59e+28	1.71±0.10e+26	1.06±0.11e+26	3.17±0.34e+25			
2011-08-28	2.20	1.40							10032.11±11.19
2011-08-29	2.19	1.40	8.46±1.56e+28	2.40±0.13e+26	3.01±0.16e+26	4.08±0.44e+25	11122.28±21.69	11698.78±14.24	
2011-08-30	2.19	1.41			2.74±0.15e+26		11373.95±12.72	11636.60±9.00	9898.85±6.06
2011-08-31	2.18	1.41	7.89±2.08e+28	2.52±0.16e+26	2.69±0.17e+26	4.11±0.49e+25	11713.41±3.40	11915.59±1.85	10024.12±1.27
2011-09-01	2.17	1.41	9.19±3.08e+28	2.63±0.18e+26	2.87±0.20e+26	5.27±0.65e+25	11741.76±604.95	11916.77±361.24	9941.52±166.38
2011-09-03	2.15	1.42	1.03±0.16e+29	2.59±0.11e+26	3.17±0.12e+26	5.78±0.36e+25	11667.57±307.77		
2011-09-04	2.13	1.44							9822.10±114.24
2011-09-05	2.13	1.44	9.09±1.45e+28	2.76±0.11e+26	3.32±0.13e+26	5.94±0.37e+25	11278.94±262.53	11846.82±175.31	
2011-09-08	2.11	1.46	7.73±1.27e+28	2.67±0.11e+26	3.12±0.18e+26	5.77±0.40e+25	11136.72±319.01	11560.88±225.16	9541.63±144.23
2011-09-09	2.10	1.47	8.15±1.25e+28	2.54±0.10e+26	3.06±0.16e+26	5.08±0.40e+25	11068.02±312.05	11350.60±202.63	
2011-09-10	2.08	1.48					11140.97±228.37	11787.76±169.64	9654.69±96.44
2011-09-11	2.08	1.48	9.33±1.53e+28	2.77±0.13e+26	3.22±0.15e+26	5.82±0.48e+25	11188.11±237.96	11637.50±138.14	9741.08±88.68
2011-09-12	2.07	1.49	9.00±1.84e+28	2.76±0.17e+26	3.23±0.18e+26	5.85±0.58e+25	11343.90±291.37	11728.48±202.25	9598.39±109.00
2011-09-18	2.02	1.56			3.64±0.12e+26	6.29±0.38e+25		11586.85±57.01	9593.13±43.98
2011-09-19	2.02	1.56	9.14±1.65e+28	2.94±0.13e+26			11339.61±115.87	11578.00±66.66	
2011-09-22	1.98	1.60						11267.50±20.53	9502.14±10.40
2011-09-23	1.98	1.60	8.70±1.55e+28	2.58±0.11e+26	3.33±0.10e+26	5.47±0.31e+25	10690.55±37.83	10955.92±20.63	
2011-09-25	1.96	1.64						11265.70±197.13	9613.66±131.85
2011-09-26	1.96	1.64	9.95±1.72e+28	2.81±0.12e+26	3.37±0.11e+26	5.75±0.35e+25	11039.37±397.81	11420.50±246.04	
2011-09-27	1.94	1.66				5.56±0.33e+25		11340.52±186.66	9511.05±101.68
2011-09-28	1.94	1.66	9.85±1.62e+28	2.72±0.11e+26	3.17±0.10e+26		11190.70±313.09	11365.58±169.75	9526.46±98.03
2011-09-29	1.93	1.69			3.44±0.10e+26		11110.28±295.42	11190.20±166.59	9464.36±83.46
2011-09-30	1.93	1.69	1.03±0.20e+29	2.82±0.13e+26	3.35±0.11e+26	6.07±0.36e+25	10978.40±309.85	10952.26±160.02	9474.43±90.47
2011-10-01	1.92	1.70	8.93±1.79e+28	2.72±0.12e+26		5.67±0.36e+25	10581.51±275.74	11052.59±230.12	
2011-10-02	1.91	1.72						11396.64±161.10	9575.03±85.50
2011-10-03	1.91	1.72	1.02±0.21e+29	2.91±0.13e+26	3.70±0.12e+26	6.11±0.42e+25	11057.68±337.16	11236.14±242.28	
2011-10-04	1.89	1.74			4.05±0.12e+26			11515.99±141.45	9716.98±78.07
2011-10-05	1.89	1.74	1.11±0.19e+29	3.11±0.13e+26					
2011-10-06	1.88	1.75	9.38±1.97e+28	2.64±0.13e+26	3.53±0.13e+26	5.43±0.41e+25		11242.74±148.40	9370.32±86.10
2011-10-07	1.88	1.77					10460.47±194.20	11207.17±148.54	9529.63±84.91
2011-10-08	1.86	1.79	8.34±1.60e+28						9486.00±96.55
2011-10-09	1.85	1.80		2.40±0.12e+26	3.11±0.12e+26	5.20±0.37e+25		10421.40±101.44	9039.18±50.38
2011-10-10	1.85	1.80	9.32±1.82e+28		2.99±0.13e+26	4.80±0.39e+25	10430.88±152.88	10417.50±102.67	9232.31±50.91
2011-10-11	1.84	1.82	7.14±1.37e+28					10901.07±97.43	
2011-10-12	1.84	1.82		2.28±0.12e+26	3.12±0.13e+26	5.07±0.40e+25			
2011-10-18	1.79	1.90	7.49±1.99e+28				10606.29±37.59		9572.05±15.21
2011-10-19	1.79	1.90		2.71±0.16e+26	3.58±0.15e+26	5.63±0.50e+25			

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)				A(0)f ρ (cm)		Rc
			OH	CN	C ₂	C ₃	BC	GC	
2011-10-21	1.77	1.93	8.06±2.28e+28				9935.37±527.19		
2011-10-22	1.77	1.93		2.43±0.16e+26	3.23±0.16e+26	4.99±0.52e+25		10040.82±331.13	
2012-05-01	2.32	2.21		9.90±0.79e+25		1.53±0.38e+25	6562.38±109.62	6617.85±59.38	5514.75±29.68
2012-05-02	2.32	2.21			1.21±0.12e+26				
2012-05-05	2.36	2.32			1.23±0.12e+26		6234.04±26.34	6507.87±14.70	5246.08±7.92
2012-05-06	2.36	2.32		9.65±0.88e+25		1.86±0.43e+25			
2012-05-07	2.38	2.37		7.84±0.64e+25	1.02±0.09e+26	1.01±0.24e+25	5815.60±253.94	5672.21±191.76	4804.49±79.63
2012-05-09	2.40	2.42		9.27±0.68e+25				5446.96±148.52	
2012-05-11	2.41	2.47				1.51±0.24e+25	5313.33±185.96		5062.41±62.16
2012-05-12	2.42	2.50		9.57±0.63e+25	9.81±0.92e+25	1.14±0.27e+25	6062.26±188.14		5113.20±61.19
2012-05-13	2.42	2.50						6198.75±119.78	
2012-05-14	2.44	2.55		9.44±0.61e+25	1.32±0.09e+26	1.40±0.26e+25	5765.41±160.72		4924.74±57.09
2012-05-15	2.44	2.55						6025.58±104.19	
2012-05-16	2.46	2.60		9.75±0.69e+25	1.16±0.09e+26	1.59±0.28e+25	5387.74±137.07		4950.15±45.04
2012-05-17	2.46	2.60						6000.70±96.51	
2012-05-18	2.48	2.65		9.28±0.61e+25	8.25±0.87e+25	1.38±0.28e+25	5927.65±120.81		4876.84±41.46
2012-05-19	2.48	2.65						5190.57±67.70	
2012-05-21	2.51	2.73					3488.24±82.37		3249.67±19.43
2012-05-31	2.60	2.98							2589.27±2.93
2012-11-10	4.17	4.34							1433.02±34.85
2012-11-17	4.24	4.29							1642.48±35.85
2012-11-20	4.27	4.27							1474.15±26.82
2012-11-23	4.29	4.24							1441.27±30.23
2012-12-02	4.38	4.17							1345.81±1.32
2012-12-05	4.41	4.15							1374.88±4.95
2012-12-06	4.42	4.14							1359.52±6.21
2012-12-07	4.43	4.13							1311.80±4.03
2012-12-20	4.55	4.05							1176.23±4.25
2012-12-24	4.58	4.03							1201.88±4.40
2012-12-28	4.62	4.01							1136.39±8.28
2013-01-13	4.77	3.98							1073.35±5.81
2013-03-13	5.30	4.59							725.86±31.76
2013-03-29	5.44	4.93							625.78±30.70
2013-04-05	5.50	5.09							612.06±15.34
2013-05-03	5.75	5.78							525.71±12.97
2013-05-09	5.81	5.92							465.86±17.45

C.3 Comet C/2012 F6 (Lemmon)

Table C.3: Gas production rates and $A(0)f\rho$ parameter of comet C/2012 F6 (Lemmon). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					$A(0)f\rho$ (cm)				
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc	
2012-11-18	2.26	2.59									1433.47±8.03	
2012-11-23	2.19	2.46									1514.34±8.63	
2012-12-05	2.03	2.13									1854.28±8.49	
2012-12-06	2.02	2.11									1806.32±8.36	
2012-12-07	2.00	2.08									1885.67±9.37	
2012-12-08	1.99	2.05									1907.97±8.94	
2012-12-11	1.95	1.97			8.31±0.23e+25	9.35±0.32e+25	1.98±0.07e+25	1736.23±26.02		1861.59±14.65		
2012-12-15	1.89	1.87			8.67±0.28e+25	9.77±0.22e+25	2.07±0.09e+25	1852.23±24.68				
2012-12-19	1.84	1.76	3.77±0.39e+28		9.58±0.25e+25	1.14±0.03e+26	2.27±0.07e+25	1952.98±19.39		2084.51±13.60		
2012-12-20	1.82	1.74						1973.16±28.62		1977.49±17.23		
2012-12-22	1.80	1.69	3.96±0.41e+28		1.06±0.03e+26	1.22±0.02e+26	2.50±0.06e+25		2733.84±21.68	2140.70±12.08		
2012-12-24	1.77	1.64	4.20±0.46e+28	9.11±0.82e+25	1.07±0.03e+26	1.28±0.03e+26	2.63±0.09e+25	2157.95±26.30	2772.74±0.27	2136.70±22.28	2400.48±8.45	
2012-12-28	1.71	1.54	4.87±0.44e+28	1.45±0.10e+26	1.18±0.03e+26	1.52±0.04e+26	3.10±0.15e+25	2250.97±27.07	2786.45±0.40	2233.86±19.08	2591.88±12.31	
2013-01-05	1.60	1.36	5.34±0.52e+28	3.75±0.24e+26	1.36±0.04e+26	1.81±0.04e+26	3.64±0.10e+25	2473.22±23.57	3167.72±10.83	2552.94±13.84	3050.75±10.34	
2013-01-07	1.57	1.32	5.95±0.69e+28	4.46±0.31e+26	1.55±0.04e+26	2.10±0.03e+26	4.32±0.09e+25	2456.58±21.08	3362.72±12.62	2696.91±17.58		
2013-01-13	1.49	1.20	6.15±0.76e+28	5.03±0.34e+26	1.62±0.04e+26	2.40±0.04e+26	4.34±0.11e+25	2714.34±21.64	3571.58±13.97	2840.38±18.19	3479.28±16.96	
2013-02-07	1.14	0.99	8.83±1.76e+28	8.24±0.72e+26	2.85±0.13e+26	5.49±0.10e+26	8.20±0.35e+25	5081.20±80.71	6510.15±21.73	5479.11±49.46	5951.72±25.10	
2013-02-09	1.11	0.99	1.21±0.27e+29	9.85±0.98e+26	3.25±0.17e+26	5.98±0.13e+26	9.19±0.44e+25	5825.64±104.47		5822.21±59.16	7697.45±53.44	
2013-02-12	1.07	1.00	1.47±0.28e+29	1.12±0.09e+27	3.70±0.18e+26	6.93±0.13e+26	1.04±0.04e+26	6692.62±103.12	8205.02±27.45	6883.14±59.40	8109.39±34.80	
2013-02-13	1.06	1.01	1.51±0.26e+29	1.19±0.09e+27	3.88±0.18e+26	7.22±0.13e+26	1.12±0.04e+26	7105.62±103.43	8674.46±28.71	7097.15±59.29	8173.84±33.87	
2013-02-14	1.04	1.01	1.53±0.28e+29	1.22±0.10e+27	4.00±0.18e+26	7.48±0.13e+26	1.13±0.05e+26	7679.34±119.27	8959.87±31.61	7530.62±67.85	8275.77±33.74	
2013-02-17	1.01	1.04	1.93±0.38e+29	1.52±0.20e+27	4.77±0.24e+26	9.18±0.30e+26	1.35±0.09e+26	9443.49±260.35	10515.18±60.31	8798.55±135.79		
2013-02-18	0.99	1.04	1.85±0.36e+29	1.40±0.12e+27	4.70±0.23e+26	8.60±0.17e+26	1.38±0.07e+26	8954.99±137.05	10923.42±34.60	9280.97±73.44		
2013-02-19	0.98	1.05	1.94±0.40e+29	1.46±0.13e+27	4.90±0.25e+26	8.87±0.17e+26	1.39±0.06e+26	9659.11±166.44	11255.74±39.83	9405.82±90.74		
2013-02-21	0.96	1.07	1.95±0.39e+29	1.50±0.13e+27	5.18±0.26e+26	9.44±0.19e+26	1.41±0.06e+26	10647.41±183.75	13016.92±48.93	10912.50±107.26		
2013-02-23	0.93	1.09	1.85±0.38e+29	1.37±0.13e+27	5.21±0.27e+26	9.53±0.22e+26	1.40±0.07e+26	10986.79±209.12	12688.81±47.89	11446.60±124.71		
2013-02-25	0.91	1.12	2.20±0.47e+29	1.73±0.16e+27	6.29±0.30e+26	1.14±0.02e+27	1.68±0.08e+26	13164.91±236.12	15197.84±54.66	12792.40±130.47		
2013-02-26	0.90	1.13	2.13±0.47e+29	1.65±0.16e+27	6.24±0.29e+26	1.15±0.03e+27	1.67±0.09e+26	13692.63±258.46	15361.35±59.08	13917.77±150.37	10586.24±87.55	
2013-02-27	0.89	1.14	2.07±0.45e+29	1.65±0.15e+27	6.13±0.31e+26	1.11±0.02e+27	1.53±0.08e+26	14104.43±255.48	16184.34±59.17	13770.97±140.53	10602.20±82.51	
2013-02-28	0.88	1.15	2.13±0.48e+29	1.76±0.22e+27	6.66±0.35e+26	1.19±0.03e+27	1.63±0.09e+26	15703.54±296.48	18364.80±71.08	15330.53±164.74	10954.58±89.50	
2013-03-01	0.87	1.17	2.11±0.50e+29	1.88±0.19e+27	7.04±0.39e+26	1.25±0.03e+27	1.78±0.10e+26	16308.58±322.33	19137.51±75.90	16363.49±181.53	11202.28±96.68	
2013-03-02	0.86	1.18	1.85±0.46e+29	1.65±0.17e+27	6.70±0.38e+26	1.17±0.03e+27	1.65±0.10e+26	17627.54±365.21	20042.48±86.77	17457.09±202.47		
2013-03-03	0.85	1.19	1.97±0.51e+29	1.92±0.21e+27	7.58±0.52e+26	1.30±0.03e+27	1.76±0.11e+26	18955.92±408.09	22280.65±96.86	19234.23±233.26	11106.76±106.12	
2013-03-04	0.84	1.21	1.63±0.45e+29	1.79±0.21e+27	7.47±0.44e+26	1.33±0.04e+27	1.83±0.12e+26	19727.11±452.48	22553.91±104.38	19307.83±251.36	11018.10±112.73	
2013-03-05	0.83	1.22	1.62±0.48e+29	1.83±0.23e+27	7.66±0.44e+26	1.29±0.04e+27	1.81±0.13e+26	21017.21±506.31	23688.77±115.43	20290.63±276.76		
2013-03-06	0.82	1.23	1.78±0.57e+29	2.02±0.28e+27	8.37±0.63e+26	1.40±0.05e+27	1.96±0.17e+26	21451.19±569.46	23635.44±127.18	21771.87±326.37	11679.13±135.40	
2013-04-29	1.01	1.70	9.30±2.42e+28		3.64±0.21e+26	6.87±0.20e+26	1.03±0.06e+26	9920.72±221.70		9718.60±124.72		
2013-05-03	1.06	1.71	9.15±2.15e+28	1.13±0.12e+27	3.54±0.18e+26	6.51±0.17e+26		9298.45±192.96	10648.65±47.92		11633.99±89.10	
2013-05-05	1.09	1.71	9.32±2.18e+28		3.33±0.18e+26	5.92±0.16e+26	8.00±0.52e+25		10587.40±45.76	9282.55±103.32	11406.33±95.27	
2013-05-06	1.10	1.71	8.90±2.00e+28	1.12±0.11e+27	3.32±0.17e+26	6.21±0.16e+26	8.75±0.50e+25	8486.95±165.84	10397.75±45.32	8676.91±95.29	11229.22±92.32	
2013-05-07	1.12	1.71									11112.13±77.07	
2013-05-08	1.13	1.72	8.90±1.85e+28		3.25±0.16e+26	5.99±0.14e+26	8.99±0.47e+25	8601.80±161.07	10325.32±43.92	8644.26±87.62	10938.38±75.34	
2013-05-09	1.14	1.72									10482.35±66.70	
2013-05-10	1.16	1.72	6.87±1.55e+28	9.22±1.01e+26	2.73±0.15e+26	5.14±0.14e+26	7.01±0.41e+25	7968.07±117.29	9766.82±35.78	8442.27±77.55		
2013-05-11	1.17	1.72	7.99±1.82e+28	1.08±0.12e+27	3.26±0.17e+26	5.90±0.15e+26	8.64±0.49e+25	7912.36±151.79	9661.54±40.99	8311.15±92.26		
2013-05-14	1.21	1.72	9.87±2.05e+28	1.05±0.11e+27	3.09±0.15e+26	5.49±0.13e+26	8.30±0.44e+25	7559.18±138.08	9172.16±37.69	8033.46±82.30	9986.90±74.97	
2013-05-16	1.24	1.73	8.49±1.87e+28	8.73±0.99e+26	2.59±0.14e+26	4.65±0.12e+26	7.52±0.42e+25	6615.52±126.47	8615.57±37.80	6949.37±77.05	8893.91±65.69	
2013-05-20	1.30	1.73	8.98±1.81e+28	8.90±0.91e+26	2.62±0.13e+26	4.50±0.11e+26	7.20±0.38e+25	6732.41±120.53	8338.65±33.75	6906.53±69.67	8477.87±61.33	
2013-05-22	1.32	1.73	8.20±1.74e+28	7.99±0.89e+26	2.46±0.12e+26	4.21±0.11e+26	6.57±0.36e+25	6430.98±119.96	8123.03±36.85	6825.82±75.28	8223.34±66.69	
2013-05-23	1.34	1.74	8.51±1.83e+28	7.85±0.88e+26	2.47±0.12e+26	4.06±0.10e+26	6.64±0.36e+25	6699.72±128.91	8000.75±33.02	6759.81±75.22	8230.08±61.96	
2013-05-24	1.35	1.74				4.31±0.10e+26			7872.61±41.24	6630.62±84.76	7935.44±55.03	
2013-05-25	1.37	1.74	7.26±1.63e+28	7.04±0.88e+26	2.33±0.12e+26	3.84±0.11e+26	6.24±0.37e+25	6397.36±133.80	7466.59±58.78	6258.37±77.83	7643.59±62.13	
2013-05-26	1.38	1.74	6.28±1.43e+28	6.32±0.82e+26		3.68±0.10e+26	5.82±0.34e+25	5355.25±110.91	7134.69±38.22	5610.04±82.69	7291.20±52.66	
2013-05-29	1.42	1.74	5.47±1.36e+28	6.03±0.73e+26	2.27±0.11e+26	3.54±0.09e+26	5.75±0.34e+25	5666.27±97.24	7196.72±33.37	4985.51±64.32	7168.71±43.67	
2013-05-30	1.44	1.74	6.84±1.71e+28	5.14±1.00e+26	2.23±0.13e+26	3.48±0.10e+26	5.83±0.38e+25	5776.99±123.68	7364.34±39.10	6048.66±73.96	7286.85±61.82	
2013-06-02	1.48	1.75	5.47±1.47e+28	5.07±0.89e+26	1.91±0.11e+26	2.94±0.10e+26	4.72±0.34e+25	5888.41±123.90	6962.87±36.28	5925.16±69.35	6884.41±57.24	
2013-06-03	1.50	1.75	6.00±1.44e+28		1.98±0.10e+26	3.12±0.09e+26			6986.48±38.78	5912.05±68.34	6934.18±54.17	
2013-06-04	1.51	1.75	5.47±1.69e+28	4.94±0.92e+26	1.95±0.11e+26	2.98±0.09e+26	5.03±0.35e+25	5714.59±127.30	6820.20±38.04	5787.28±72.85	6737.96±57.18	
2013-06-05	1.52	1.75	6.07±1.55e+28	4.84±0.75e+26	1.92±0.11e+26	2.77±0.09e+26	4.77±0.31e+25	5761.24±123.12	7084.08±33.98	5841.79±74.58	6904.19±58.31	
2013-06-06	1.54	1.75	5.83±1.59e+28	4.62±0.91e+26	1.86±0.12e+26	2.65±0.09e+26	4.52±0.34e+25	5310.27±124.63	6281.75±38.72	5477.25±71.59	6313.10±57.84	
2013-06-11	1.61	1.76		3.94±0.81e+26	1.62±0.11e+26	2.31±0.09e+26	4.11±0.36e+25	5238.21±130.71	6334.63±42.02	5305.53±74.98		

C.4 Comet C/2013 R1 (Lovejoy)

Table C.4: Gas production rates and $A(0)f\rho$ parameter of comet C/2013 R1 (Lovejoy). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					A(0) $f\rho$ (cm)			
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc
2013-09-11	1.92	1.83			2.51±0.08e+25						887.76±16.02
2013-09-12	1.91	1.81	6.20±1.07e+27			2.14±0.11e+25	4.37±0.29e+24		440.88±4.71	364.54±7.28	390.77±4.66
2013-09-16	1.85	1.71			2.86±0.09e+25	2.48±0.18e+25		348.35±17.42			408.10±7.80
2013-09-20	1.80	1.62	5.37±0.77e+27								938.02±14.39
2013-09-21	1.79	1.59	8.38±1.01e+27	3.57±1.43e+25	2.89±0.13e+25	2.73±0.20e+25	5.26±0.56e+24	693.92±10.96	492.94±3.10		995.91±7.61
2013-09-24	1.75	1.52			3.26±0.11e+25						541.08±6.89
2013-09-25	1.73	1.50			3.34±0.12e+25	3.51±0.14e+25		396.92±30.62			594.01±13.80
2013-09-26	1.72	1.47	1.18±0.13e+28	5.87±1.03e+25							625.93±10.09
2013-09-29	1.68	1.40	1.17±0.15e+28	5.49±1.08e+25	3.59±0.16e+25	3.96±0.20e+25	6.66±0.32e+24	976.83±23.03	1353.28±7.12	868.48±5.88	1235.94±7.86
2013-10-03	1.63	1.30	1.17±0.15e+28		3.73±0.12e+25	4.17±0.11e+25	8.07±0.31e+24	449.68±16.49			951.78±12.29
2013-10-04	1.61	1.27		7.61±0.88e+25	3.91±0.11e+25						770.74±14.40
2013-10-05	1.60	1.25	1.15±0.16e+28		4.03±0.12e+25		7.97±0.33e+24	594.28±23.70		566.44±18.20	759.44±24.56
2013-10-06	1.58	1.23			3.66±0.11e+25				552.35±4.01		765.21±2.34
2013-10-08	1.56	1.18	1.24±0.16e+28		3.35±0.11e+25	3.85±0.15e+25		665.32±16.50			737.82±11.48
2013-10-10	1.53	1.13	1.33±0.19e+28		4.52±0.15e+25	4.96±0.31e+25		1398.70±20.92			
2013-10-20	1.40	0.89	2.06±0.32e+28		5.00±0.18e+25	6.47±0.32e+25		943.24±17.44			1199.27±8.75
2013-10-21	1.38	0.87	2.20±0.23e+28	1.24±0.14e+26	5.73±0.20e+25	6.78±0.19e+25	8.04±0.38e+24		1348.22±21.39	1080.47±34.54	1111.64±23.46
2013-10-24	1.34	0.80	2.50±0.27e+28	1.47±0.14e+26	6.39±0.18e+25	8.23±0.22e+25	1.39±0.07e+25	1214.19±28.54			1469.72±24.85
2013-10-26	1.32	0.75	2.57±0.30e+28	1.55±0.14e+26	6.56±0.29e+25	8.49±0.35e+25	1.38±0.06e+25	1328.22±29.64	1641.47±24.51	1341.38±29.23	1579.52±26.95
2013-11-02	1.23	0.60			7.75±0.25e+25	1.14±0.02e+26	1.81±0.06e+25		2033.60±30.89	1708.62±37.20	1992.31±35.86
2013-11-03	1.21	0.58	2.83±0.34e+28	2.06±0.16e+26							2048.87±13.83
2013-11-16	1.06	0.41		2.56±0.56e+26	1.15±0.11e+26	1.79±0.09e+26	2.31±0.27e+25	2651.31±156.31	3038.35±36.12	2696.44±109.80	3432.34±63.92
2014-02-13	1.26	1.56	1.83±0.41e+28		7.42±0.39e+25	1.21±0.04e+26		3350.32±62.97			4241.88±34.83
2014-02-14	1.27	1.56			6.15±0.32e+25		1.32±0.11e+25		4241.75±30.34	3617.70±37.53	4146.28±30.29
2014-02-15	1.28	1.56	1.43±0.28e+28	1.25±0.25e+26		9.54±0.34e+25		3363.66±52.33			3964.69±27.23
2014-02-16	1.29	1.57			5.19±0.28e+25						3771.28±28.56
2014-02-21	1.36	1.58	1.19±0.21e+28	1.07±0.19e+26	5.06±0.23e+25	7.31±0.28e+25	1.03±0.09e+25	2717.67±23.45			3254.37±17.58
2014-02-22	1.37	1.58				8.27±0.25e+25		2775.82±21.46	3478.12±9.70	2907.59±13.69	3348.43±10.02
2014-02-28	1.45	1.59				6.34±0.19e+25		2091.68±12.72			2781.72±5.99
2014-03-01	1.47	1.59						2279.60±18.05	2863.74±8.04	2394.68±8.36	2775.78±6.09
2014-03-06	1.53	1.59	1.12±0.15e+28	9.66±1.37e+25	4.43±0.16e+25	6.04±0.16e+25	8.87±0.52e+24				2431.06±6.10
2014-03-13	1.63	1.58	1.02±0.12e+28	8.15±1.29e+25	3.86±0.14e+25	4.95±0.16e+25	7.88±0.63e+24	1710.72±17.87			
2014-03-18	1.70	1.57	8.09±1.07e+27	5.30±1.56e+25	3.37±0.15e+25	3.29±0.20e+25	6.86±0.77e+24	1131.49±21.34	1833.17±13.92	1540.60±14.75	1712.84±10.72
2014-03-20	1.72	1.56			3.36±0.12e+25						
2014-03-25	1.79	1.55			3.26±0.13e+25	3.86±0.19e+25					
2014-03-26	1.80	1.55	7.60±0.75e+27	5.69±0.89e+25	3.41±0.11e+25	3.60±0.15e+25	6.52±0.35e+24	1252.93±22.88	1518.23±37.71	1312.10±12.39	
2014-04-04	1.92	1.52		2.50±1.05e+25	2.74±0.09e+25	3.04±0.14e+25	4.75±0.30e+24	754.76±19.78	1112.37±18.71	932.55±14.46	
2014-04-10	2.00	1.50	5.97±0.58e+27		2.91±0.11e+25	2.58±0.17e+25	4.87±0.40e+24	871.79±28.48	1077.39±31.51	877.10±20.42	1086.06±16.93
2014-04-14	2.06	1.49			2.32±0.17e+25	2.25±0.21e+25		853.76±43.45			965.25±16.67
2014-04-15	2.07	1.48	4.84±0.61e+27				4.60±0.55e+24		1009.19±39.32	799.06±30.52	942.59±39.38
2014-04-16	2.08	1.48									892.98±19.24
2014-04-18	2.11	1.48	4.53±0.54e+27		2.34±0.15e+25	2.37±0.22e+25		687.99±43.96	899.79±55.51	751.26±29.69	816.32±25.03
2014-04-19	2.12	1.47		2.03±1.59e+25			3.60±0.79e+24				792.39±37.35
2014-04-22	2.16	1.47	4.43±0.52e+27		2.56±0.12e+25	2.43±0.29e+25		673.03±38.83			768.75±27.84
2014-04-25	2.20	1.47	3.89±0.52e+27		2.17±0.10e+25	1.43±0.27e+25	1.95±0.47e+24	615.54±25.20	841.28±40.75	612.68±26.54	830.34±47.00
2014-05-06	2.34	1.47									422.94±49.83
2014-05-08	2.37	1.48			1.90±0.18e+25	1.90±0.49e+25		374.97±32.58			553.99±31.40
2014-05-14	2.44	1.50			1.89±0.21e+25	1.25±1.14e+25		409.48±53.22			
2014-05-20	2.52	1.54			7.30±1.55e+24	5.11±2.44e+24		346.95±12.26	376.98±15.49	338.64±17.12	588.82±8.79
2014-05-24	2.57	1.57			1.52±0.19e+25	2.62±0.43e+25		375.20±14.73			433.64±11.73
2014-05-27	2.61	1.60			1.41±0.18e+25	4.89±2.72e+24	2.67±0.44e+24	373.60±5.96	502.14±5.10	369.17±2.66	455.22±2.04
2014-05-31	2.66	1.64			1.39±0.12e+25	1.16±0.19e+25	2.07±0.58e+24	392.70±15.17	495.00±12.20	374.01±17.15	435.85±9.86
2014-06-22	2.93	1.99			6.23±1.40e+24			309.59±19.92	301.61±17.16		281.45±17.07
2014-06-24	2.95	2.03			6.01±2.13e+24	1.72±1.92e+24		282.02±26.74	194.94±16.64		409.16±8.65
2014-06-30	3.02	2.15			9.03±1.89e+24			281.92±23.44			289.42±11.93
2014-07-04	3.07	2.23			7.42±1.87e+24	7.39±2.37e+24		290.85±11.72		286.19±15.93	327.66±4.58
2014-07-06	3.10	2.30			6.52±1.53e+24			291.01±7.31			325.63±2.28
2014-07-07	3.10	2.30				5.55±10.70e+23					
2014-07-13	3.18	2.45									320.24±36.96
2014-07-18	3.23	2.57									301.14±11.35
2014-08-04	3.43	3.00									166.39±1.04
2014-08-09	3.50	3.16									243.44±16.84
2014-08-20	3.61	3.43									196.56±12.43
2014-09-06	3.80	3.88									324.98±13.31
2014-10-06	4.14	4.65									668.88±47.65
2014-10-14	4.21	4.81									403.24±36.09

C.5 Comet C/2020 M3 (Atlas)

Table C.5: Gas production rates and $A(0)f\rho$ parameter of comet C/2020 M3 (Atlas). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					$A(0)f\rho$ (cm)	
			OH	NH	CN	C ₂	C ₃	BC	Rc
2020-09-11	1.43	0.68			6.99±0.64e+24	1.91±0.42e+24		80.18±11.00	88.99±5.42
2020-09-29	1.33	0.55			9.93±0.61e+24	1.32±0.08e+25			
2020-09-30	1.32	0.54			1.13±0.07e+25	1.33±0.14e+25			
2020-10-01	1.32	0.54		2.30±0.75e+25	1.07±0.09e+25		3.62±0.41e+24	120.39±17.70	143.95±21.12
2020-10-06	1.30	0.51			1.23±0.09e+25	1.71±0.16e+25	4.41±0.44e+24		
2020-10-11	1.29	0.48	5.60±1.42e+27		1.40±0.09e+25	1.83±0.11e+25			
2020-10-13	1.28	0.47	6.09±1.64e+27	3.79±0.75e+25	1.46±0.09e+25	1.95±0.10e+25	5.17±0.33e+24	166.57±1.09	205.31±0.52
2020-10-14	1.28	0.46	7.20±1.51e+27		1.41±0.08e+25	1.96±0.10e+25	5.20±0.26e+24		
2020-10-16	1.28	0.45	6.72±0.98e+27	3.80±0.58e+25	1.36±0.07e+25	1.89±0.08e+25	4.64±0.41e+24	183.41±19.79	224.20±11.30
2020-10-21	1.27	0.42	7.71±1.13e+27	4.02±0.64e+25	1.44±0.09e+25	2.01±0.09e+25	4.97±0.28e+24	187.94±10.93	237.24±7.65
2020-10-24	1.27	0.41	7.11±1.49e+27	3.99±0.73e+25	1.52±0.09e+25	2.32±0.11e+25	5.19±0.21e+24	185.75±5.93	231.09±4.87
2020-10-30	1.27	0.39	8.25±1.25e+27	4.16±0.69e+25	1.63±0.12e+25	2.03±0.14e+25	5.16±0.33e+24	212.88±13.63	256.19±15.20
2020-11-07	1.28	0.37	6.85±1.01e+27	3.52±0.64e+25	1.54±0.12e+25	1.91±0.16e+25	4.92±0.28e+24	210.35±20.67	249.06±15.54
2020-11-11	1.29	0.36			1.53±0.12e+25				
2020-11-16	1.31	0.36	6.43±0.95e+27	3.10±0.61e+25	1.33±0.12e+25	1.80±0.19e+25	4.62±0.36e+24	206.76±9.04	236.32±4.11
2020-11-18	1.31	0.36			1.29±0.10e+25				
2020-11-19	1.32	0.36			1.31±0.11e+25				
2020-11-20	1.32	0.36							226.67±5.99
2020-11-21	1.33	0.36	7.03±1.09e+27	2.96±0.56e+25	1.34±0.11e+25	1.65±0.15e+25	3.98±0.35e+24	195.78±26.22	
2020-11-22	1.33	0.37			1.30±0.12e+25				
2020-12-08	1.42	0.44	4.03±0.54e+27	1.23±0.55e+25	1.01±0.09e+25	1.23±0.14e+25	2.77±0.38e+24	147.04±10.19	181.90±8.92
2020-12-16	1.48	0.50	3.06±0.42e+27	8.47±4.40e+24	9.04±0.68e+24	1.10±0.14e+25	2.46±0.22e+24	141.53±3.25	157.38±3.56
2021-01-02	1.62	0.70	1.07±0.39e+27						
2021-01-03	1.62	0.70			5.06±0.59e+24	4.04±1.67e+24	1.69±0.19e+24	52.17±40.46	70.79±30.13
2021-01-14	1.73	0.85	1.27±0.33e+27		5.53±0.43e+24	5.75±0.71e+24	1.25±0.25e+24	70.02±24.16	110.81±10.63
2021-01-29	1.87	1.08			2.93±0.43e+24	3.65±0.82e+24	1.11±0.35e+24	62.74±19.22	73.43±2.42
2021-02-12	2.01	1.32			3.49±0.43e+24	3.56±0.95e+24			
2021-03-13	2.31	1.88							
2021-04-03	2.53	2.33							

C.6 Comet C/2012 K1 (PanSTARRS)

Table C.6: Gas production rates and $A(0)f\rho$ parameter of comet C/2012 K1 (PanSTARRS). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					$A(0)f\rho$ (cm)			
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc
2013-03-28	6.21	5.91									4151.81±34.01
2013-03-30	6.19	5.86									4226.10±36.21
2013-04-13	6.07	5.56									3952.98±25.62
2013-04-20	6.00	5.42									3966.84±22.98
2013-05-03	5.88	5.19									4043.24±38.25
2013-05-07	5.85	5.13									4315.84±39.14
2013-05-16	5.77	5.00									3894.78±34.08
2013-05-21	5.72	4.95									3993.45±39.06
2013-05-22	5.71	4.93									3952.76±44.50
2013-06-07	5.56	4.79									4141.98±32.92
2013-06-22	5.42	4.73							4548.44±259.27		4537.33±113.66
2013-07-08	5.28	4.73									4146.65±38.35
2013-07-12	5.24	4.73						4100.92±176.29	4512.80±48.39	4495.34±82.71	4238.64±37.37
2013-07-16	5.20	4.74									4607.51±38.77
2013-07-19	5.17	4.75									4454.32±73.75
2013-08-01	5.04	4.80									4479.38±41.88
2013-08-13	4.92	4.87						3904.03±153.48			
2013-08-14	4.92	4.87							4313.00±51.09	3934.05±66.81	4796.80±57.21
2013-08-18	4.88	4.89									4612.19±50.22
2013-08-19	4.87	4.89						4131.15±241.68	4184.42±82.12	3946.27±137.31	
2013-09-12	4.62	5.00									4835.66±51.29
2014-02-03	3.11	3.24			5.06±0.55e+25					4958.94±96.59	5190.05±69.81
2014-02-05	3.09	3.19						4518.67±262.60	5465.31±46.27		5274.31±78.50
2014-02-06	3.08	3.16			4.72±0.43e+25					4933.64±219.64	5294.58±80.06
2014-02-07	3.07	3.13				4.11±0.44e+25	1.12±0.21e+25		5772.02±60.41		5391.61±83.45
2014-02-08	3.06	3.11						4539.27±277.70	5386.59±63.48	4865.21±149.39	5324.08±82.78
2014-02-09	3.04	3.08			4.58±0.41e+25	4.48±0.70e+25		4625.30±201.91		4842.66±127.44	5063.68±78.97
2014-02-10	3.03	3.05						4749.16±208.45	5524.60±58.24		5282.02±80.67
2014-02-11	3.02	3.03			4.92±0.36e+25	4.77±0.76e+25	8.96±1.93e+24	4445.48±171.63			5495.21±105.52
2014-02-14	2.99	2.95			4.87±0.42e+25	5.32±0.95e+25				4782.45±12.19	5210.53±8.40
2014-02-15	2.98	2.92									5084.27±11.84
2014-02-16	2.97	2.89						4661.96±54.70	5475.84±12.44	4803.07±44.01	5209.56±16.07
2014-02-17	2.96	2.87									5260.50±35.77
2014-02-19	2.93	2.81			4.81±0.40e+25			4628.23±66.66			5304.41±19.47
2014-02-20	2.92	2.78								4692.86±31.43	5125.88±27.09
2014-02-21	2.91	2.76					1.16±0.22e+25	4248.18±84.95			5263.25±32.55
2014-02-23	2.89	2.70						4492.10±79.02	5325.48±27.53		5437.82±39.99
2014-02-26	2.85	2.62			5.81±0.39e+25	6.28±0.60e+25		4323.59±107.74			5393.32±38.88
2014-03-01	2.82	2.54						4426.84±147.10	5529.70±50.27	4749.31±61.95	5523.95±57.50
2014-03-04	2.78	2.46			6.47±0.36e+25			4452.61±155.35			5311.66±60.53
2014-03-13	2.68	2.23			5.99±0.38e+25	6.36±0.59e+25		4704.03±35.18			5179.40±15.56
2014-03-16	2.65	2.16	2.27±0.67e+28					4522.82±82.30			5258.33±30.75
2014-03-17	2.63	2.13								4750.17±53.90	5092.06±35.85
2014-03-23	2.56	1.99	2.76±0.82e+28		6.93±0.42e+25		1.96±0.17e+25	4381.44±145.93	5437.87±63.48	4613.38±85.52	5021.19±59.84
2014-03-24	2.55	1.97									5119.26±61.60
2014-04-01	2.46	1.81			7.28±0.58e+25	6.01±0.64e+25	1.50±0.19e+25	4763.50±84.14	5463.86±23.81	4754.33±43.24	5083.92±27.31
2014-04-08	2.38	1.68			8.09±0.65e+25	7.23±0.74e+25	1.56±0.26e+25	4999.09±272.70	5682.63±51.66	4823.60±112.15	5298.91±71.32
2014-04-16	2.28	1.57			7.72±0.93e+25	8.77±0.97e+25		4691.86±127.51	5378.22±24.50	4829.49±42.88	5285.46±30.65
2014-04-22	2.21	1.52						4816.59±177.77	5672.18±47.39	4834.65±101.45	5359.83±67.07
2014-04-23	2.20	1.51			7.76±0.78e+25	8.40±1.01e+25		4467.51±172.06			5273.63±80.62
2014-05-01	2.11	1.48			9.00±1.02e+25			4851.44±294.85		4717.99±146.37	5576.65±123.49
2014-05-06	2.05	1.47				8.75±0.83e+25					
2014-05-09	2.01	1.48			8.25±0.98e+25	9.23±1.12e+25		4657.51±294.11		4469.42±147.50	
2014-05-18	1.91	1.52			7.59±0.73e+25	1.07±0.09e+26		4818.82±161.42	5702.45±45.83	4841.08±93.96	
2014-05-20	1.88	1.54			9.04±0.79e+25	1.19±0.08e+26					
2014-05-30	1.76	1.64	4.97±1.91e+28		8.42±0.60e+25		1.55±0.21e+25				5090.30±105.36
2014-05-31	1.75	1.64				1.27±0.07e+26		4333.59±256.86	5540.66±79.08	4545.30±167.53	5413.72±149.23
2014-06-07	1.66	1.73			9.44±0.56e+25	1.40±0.06e+26	1.89±0.18e+25	4392.96±144.34	5464.55±39.28	4527.32±89.80	5295.09±71.46
2014-06-08	1.65	1.74			8.35±0.49e+25	1.21±0.05e+26	1.53±0.16e+25				
2014-06-09	1.64	1.75			7.74±0.48e+25	1.26±0.05e+26	1.67±0.16e+25	4334.27±123.75			5196.91±59.60
2014-06-14	1.58	1.81	5.11±1.49e+28			1.15±0.05e+26					
2014-06-23	1.49	1.91			9.43±0.60e+25	1.57±0.07e+26		4423.00±6.09	5651.28±1.96		5576.00±3.84
2014-06-29	1.42	1.98	6.72±2.19e+28		1.12±0.08e+26			4803.13±308.27			5651.36±147.23
2014-07-03	1.38	2.01			1.22±0.09e+26	1.88±0.10e+26		4627.66±247.33			5720.15±131.69
2014-09-06	1.07	1.82		3.23±0.53e+26	1.35±0.10e+26	2.47±0.09e+26	3.33±0.32e+25	4437.03±127.70	5722.22±35.90	4857.05±68.04	6198.83±76.61
2014-09-07	1.07	1.80			1.16±0.09e+26	2.14±0.09e+26					
2014-09-20	1.13	1.56			9.69±0.49e+25	1.74±0.05e+26	2.41±0.18e+25	3849.74±56.11	5278.94±31.82	4334.86±34.61	5420.26±33.58
2014-09-27	1.17	1.42		2.29±0.19e+26	9.64±0.36e+25	1.74±0.04e+26	2.52±0.12e+25	3438.98±121.88	4828.38±53.38	3939.51±87.15	4925.88±82.14
2014-09-28	1.18	1.40		2.52±0.19e+26	1.06±0.03e+26	1.81±0.03e+26		3465.79±4.39	4842.31±1.93	3963.55±3.28	4881.52±2.55
2014-10-06	1.24	1.25		1.90±0.13e+26	9.48±0.25e+25	1.63±0.03e+26	2.32±0.09e+25	3343.94±84.78	4639.19±66.48	3686.66±71.07	4516.06±50.70
2014-10-07	1.25	1.23		1.95±0.18e+26	1.06±0.04e+26	1.82±0.04e+26		3376.41±17.48	4577.07±7.41	3705.71±12.62	4528.31±9.97
2014-10-11	1.29	1.15	4.82±0.44e+28	1.49±0.11e+26		1.50±0.03e+26	2.32±0.12e+25	2916.15±63.72	4400.56±44.12	3533.78±58.29	4250.99±54.78
2014-10-13	1.30	1.12	4.36±0.45e+28	1.25±0.18e+26	7.87±0.20e+25	1.39±0.04e+26	1.87±0.13e+25	3210.37±149.67	4287.39±155.36	3423.41±102.04	4161.68±100.99
2014-10-14	1.31	1.10	3.95±0.35e+28	1.52±0.10e+26	7.47±0.20e+25	1.47±0.03e+26	2.17±0.07e+25				
2014-10-23	1.40	0.99	3.59±0.30e+28	1.01±0.09e+26	7.02±0.18e+25	1.20±0.03e+26	1.77±0.06e+25		3757.95±11.68	2959.35±11.19	3484.60±27.82
2014-10-27	1.44	0.96	3.98±0.33e+28	9.39±0.96e+25	7.63±0.20e+25	1.12±0.03e+26	1.89±0.07e+25	2707.59±54.12	3750.79±40.53	2999.61±51.66	3592.39±68.59
2014-10-29	1.47	0.95									3513.85±37.48
2014-11-04	1.53	0.96						2739.03±66.46			3433.20±27.49

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C.7 Comet C/2017 T2 (PanSTARRS)

Table C.7: Gas production rates and $A(0)f\rho$ parameter of comet C/2017 T2 (PanSTARRS). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus and corrected for the phase angle effect.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)						$A(0)f\rho$ (cm)			
			OH	NH	CN	C ₂	C ₃	BC	RC	GC	Rc	
2019-08-04	3.70	4.17									4364.42±33.95	
2019-08-06	3.68	4.12									4528.82±29.38	
2019-08-07	3.67	4.10									4440.08±28.03	
2019-09-03	3.42	3.46									4523.34±22.81	
2019-09-05	3.40	3.42									4440.88±17.78	
2019-09-19	3.27	3.07									4442.00±19.63	
2019-09-24	3.22	2.94									4495.57±24.35	
2019-09-25	3.21	2.92									4373.47±34.16	
2019-09-29	3.17	2.82									4499.22±25.46	
2019-10-04	3.12	2.70									4298.83±28.05	
2019-10-28	2.89	2.17									4525.44±27.43	
2019-10-29	2.88	2.15									4507.08±41.08	
2019-11-06	2.81	2.00			5.37±0.26e+25			4043.56±28.76			4295.58±14.70	
2019-11-08	2.79	1.97	1.25±0.41e+28		4.34±0.38e+25	3.63±0.45e+25	1.35±0.14e+25	4099.73±43.65	4801.81±16.89	4571.09±26.79	4345.25±18.17	
2019-11-22	2.65	1.74						4119.58±36.44				
2019-11-23	2.64	1.73	1.63±0.26e+28		5.92±0.31e+25	5.23±0.54e+25	2.07±0.13e+25	4316.48±41.11	4347.34±11.06	4553.92±27.29	4269.74±33.26	
2019-11-24	2.64	1.73								4469.10±20.47		
2019-11-27	2.60	1.68	1.72±0.46e+28		5.82±0.25e+25	5.45±0.45e+25	1.82±0.10e+25					
2019-11-30	2.58	1.65	1.52±0.35e+28		4.85±0.30e+25	4.85±0.47e+25	1.58±0.16e+25	3451.49±36.56	4209.19±21.97		3968.33±19.38	
2019-12-08	2.50	1.58	1.53±0.43e+28		5.21±0.42e+25	5.01±0.57e+25	1.49±0.14e+25	3690.81±52.22	4487.60±16.79		4130.35±16.06	
2019-12-13	2.46	1.55	1.84±0.38e+28	1.14±2.97e+25	5.48±0.31e+25	5.70±0.56e+25	1.52±0.13e+25	3875.00±45.70	4419.11±19.33		4222.34±22.12	
2019-12-18	2.41	1.53	1.98±0.28e+28	9.27±14.00e+24	6.02±0.27e+25	5.84±0.35e+25	1.63±0.09e+25	3785.38±29.90	4661.20±13.97		4282.70±14.72	
2019-12-22	2.38	1.52	2.39±0.34e+28		6.24±0.26e+25	6.20±0.32e+25	1.93±0.10e+25	3825.30±31.65	4779.44±11.66		4429.79±14.49	
2019-12-25	2.35	1.52	2.39±0.36e+28	9.17±11.40e+24	6.16±0.26e+25	6.13±0.34e+25	1.77±0.09e+25		4579.54±20.01		4315.33±15.67	
2019-12-29	2.31	1.52	2.57±0.34e+28	5.54±9.76e+24	6.55±0.26e+25	7.04±0.36e+25	1.77±0.10e+25	3764.87±32.03	4688.40±10.69		4546.64±16.81	
2020-01-04	2.26	1.53	3.07±0.39e+28		6.71±0.26e+25	5.98±0.40e+25	1.70±0.11e+25	3954.97±34.99	4962.98±23.05		4532.25±14.99	
2020-01-10	2.21	1.54	3.03±0.35e+28		6.92±0.29e+25	6.19±0.46e+25	1.89±0.14e+25	4051.41±40.74	4943.47±19.41		4590.58±17.42	
2020-01-12	2.19	1.55		2.80±1.64e+25							4772.48±14.15	
2020-01-13	2.19	1.55	2.14±0.31e+28						4897.24±11.17			
2020-01-18	2.14	1.57	3.47±0.46e+28	2.10±1.50e+25	7.48±0.26e+25	7.64±0.34e+25	2.14±0.08e+25	4067.34±32.38			4725.42±20.30	
2020-01-24	2.09	1.59		1.59±1.92e+25			1.55±0.13e+25					
2020-01-26	2.08	1.60	3.52±0.50e+28	4.01±1.82e+25	7.73±0.35e+25	8.23±0.39e+25	2.03±0.10e+25	4099.99±54.32			4922.40±18.75	
2020-01-27	2.07	1.61	3.10±0.52e+28		7.84±0.29e+25	9.17±0.34e+25					4733.56±23.02	
2020-01-30	2.05	1.62			7.96±0.24e+25						4836.90±20.43	
2020-02-03	2.02	1.64	4.44±0.47e+28	4.46±2.10e+25	7.95±0.28e+25	8.56±0.73e+25	2.21±0.12e+25	4113.79±45.57	5016.20±28.95		4891.72±25.91	
2020-02-10	1.96	1.67	3.80±0.46e+28	3.44±2.71e+25	7.31±0.33e+25	8.21±0.60e+25	2.03±0.17e+25	4160.69±60.66	5243.41±25.28	4329.04±34.34		
2020-02-17	1.91	1.70	4.72±0.63e+28	5.13±1.69e+25	7.78±0.36e+25	8.29±0.44e+25	2.22±0.13e+25	4323.22±53.40	5558.76±38.60	4349.36±31.46	4913.15±21.23	
2020-02-21	1.89	1.72	4.36±0.66e+28	6.84±1.87e+25	7.58±0.34e+25			4202.25±55.96			4905.03±23.04	
2020-02-26	1.85	1.73	6.08±0.80e+28		9.13±0.38e+25	1.00±0.04e+26	2.71±0.14e+25	4834.45±58.93	5869.38±19.77			
2020-02-27	1.85	1.74		8.52±3.99e+25						4447.23±62.85	5124.40±39.32	
2020-03-02	1.82	1.75	6.52±0.87e+28	8.86±2.08e+25	8.81±0.35e+25	1.03±0.04e+26	2.53±0.13e+25	4689.08±58.74	5520.32±23.63	4875.25±37.29	5518.39±22.88	
2020-03-10	1.78	1.76	5.56±0.81e+28	1.01±0.20e+26	7.33±0.37e+25			4279.49±67.60			5175.94±27.28	
2020-03-11	1.77	1.76				7.23±0.41e+25	2.03±0.11e+25		5188.91±24.51	4275.92±34.11		
2020-04-01	1.68	1.77				8.28±0.41e+25	2.21±0.15e+25		4936.30±20.87	4409.30±37.50	4911.77±29.02	
2020-04-02	1.67	1.77	3.30±0.72e+28	1.08±0.22e+26	6.94±0.32e+25			3641.24±56.95			4838.88±25.33	
2020-04-20	1.63	1.73	2.73±0.51e+28	1.05±0.18e+26	6.64±0.29e+25	7.92±0.30e+25	1.37±0.09e+25	3292.16±46.86			3749.04±19.25	
2020-05-03	1.61	1.70	2.83±0.53e+28	7.55±2.01e+25	5.18±0.27e+25	5.19±0.27e+25	9.75±0.93e+24	2512.33±36.21			3358.02±18.47	
2020-05-19	1.63	1.66	2.19±0.35e+28	4.88±1.22e+25	5.24±0.19e+25	5.37±0.18e+25	1.48±0.07e+25	2533.73±31.20	3282.03±11.49		3059.46±13.25	
2020-05-25	1.64	1.66	1.96±0.33e+28	5.30±1.00e+25	4.78±0.18e+25	5.31±0.19e+25		2292.58±32.96			2950.48±17.01	
2020-05-26	1.64	1.66					1.29±0.08e+25		2906.33±10.61			
2020-05-31	1.66	1.66	2.10±0.33e+28	5.40±1.37e+25	5.38±0.20e+25		1.54±0.08e+25	2551.49±36.18			3112.64±13.75	
2020-06-01	1.66	1.66				5.51±0.22e+25			3277.67±11.94		3130.54±18.24	
2020-06-03	1.67	1.66			5.35±0.16e+25						3025.84±11.30	
2020-06-04	1.67	1.67									3031.60±13.19	
2020-06-05	1.67	1.67			5.19±0.24e+25							
2020-06-11	1.70	1.68									2813.39±14.82	
2020-06-12	1.70	1.68			5.12±0.23e+25	5.13±0.25e+25	1.35±0.09e+25	2573.48±45.56	2802.92±11.46		2721.24±19.17	
2020-06-13	1.70	1.69									2527.52±9.67	
2020-06-19	1.73	1.72	1.71±0.27e+28	2.87±0.94e+25	4.60±0.18e+25	4.59±0.20e+25	1.25±0.06e+25	2092.39±30.12	2293.12±10.69		2381.04±12.26	
2020-06-25	1.76	1.76			3.41±0.13e+25							
2020-06-26	1.76	1.76		2.20±0.57e+25			7.04±0.00e+20	1235.72±14.60	1260.49±7.85	1306.80±10.18	1431.78±8.55	
2020-07-01	1.79	1.80									1205.39±11.71	
2020-07-03	1.80	1.82			2.00±0.13e+25	1.82±0.24e+25		879.33±41.94	927.25±17.39		834.33±13.97	
2020-07-04	1.81	1.83	9.51±1.36e+27		2.98±0.11e+25	3.62±0.24e+25	1.00±0.07e+25	537.04±44.97	1215.71±16.46		749.91±12.70	
2020-07-08	1.83	1.87	6.57±2.02e+27		1.98±0.13e+25	2.07±0.19e+25		888.38±30.31			1182.40±6.33	
2020-07-09	1.84	1.88	8.73±1.95e+27		2.87±0.13e+25	2.59±0.19e+25		1250.05±28.19	1406.96±11.09		1300.54±11.54	
2020-07-18	1.90	1.99			2.88±0.12e+25	2.68±0.14e+25	7.04±0.48e+24	1383.91±24.06	1643.93±10.72		1525.38±7.62	
2020-07-24	1.94	2.07			3.05±0.16e+25	2.20±0.19e+25		1467.28±27.87	1654.44±8.94		1458.77±11.90	
2020-08-15	2.11	2.42			2.44±0.13e+25	2.14±0.18e+25		1357.90±22.78	1569.71±8.54		1434.06±11.83	

Table C.9: Gas production rates and $A(0)f\rho$ parameter of comet C/2021 S3 (PanSTARRS). The $A(0)f\rho$ values are computed within a radius aperture of 10 000 Km from the nucleus.

UT Date	r_h (au)	Δ (au)	Production rates (molec/s)					A(0)f ρ (cm)			Rc
			OH	CN	C ₂	C ₃	BC	RC	GC		
2023-02-20	4.60	4.39									3069.33±28.82
2023-03-20	4.33	4.37									3268.78±37.21
2023-04-20	4.03	4.32									3075.80±41.07
2023-04-25	3.97	4.30									3005.95±38.95
2023-04-28	3.94	4.29									3242.00±38.93
2023-05-17	3.75	4.21									3026.94±0.62
2023-05-23	3.69	4.18									2777.56±1.38
2023-05-29	3.63	4.14									2738.38±3.23
2023-09-29	2.35	2.95									2464.97±4.61
2023-11-07	1.95	2.50									2556.68±24.30
2023-11-08	1.94	2.49									2611.85±27.52
2023-11-20	1.82	2.36									2676.16±34.91
2023-11-23	1.79	2.32									2660.58±1.81
2023-11-25	1.77	2.30									2704.88±3.66
2023-11-26	1.76	2.29									2652.27±4.42
2023-11-27	1.75	2.28									2706.52±6.24
2023-12-01	1.72	2.23									2748.68±10.15
2023-12-03	1.70	2.21									2693.46±10.10
2023-12-15	1.60	2.07									2621.82±23.16
2023-12-17	1.58	2.05									2660.08±31.41
2023-12-20	1.56	2.01									2953.01±29.71
2024-01-09	1.43	1.78									3084.95±18.00
2024-01-13	1.41	1.74									3105.04±21.83
2024-01-14	1.40	1.73									2990.41±24.02
2024-01-16	1.39	1.70									3153.00±26.91
2024-01-27	1.35	1.58									2867.47±6.49
2024-01-31	1.34	1.54									3019.41±15.35
2024-02-02	1.33	1.52		3.22±0.17e+25	2.48±0.15e+25		2205.88±25.11	3066.57±20.54			2905.00±12.18
2024-02-03	1.33	1.51		2.62±0.15e+25							
2024-02-07	1.32	1.48	8.62±2.18e+27	2.71±0.13e+25	2.62±0.13e+25		2195.62±67.46	3137.13±94.54			2881.59±86.09
2024-02-11	1.32	1.44	1.08±0.24e+28	2.94±0.14e+25	2.24±0.18e+25						
2024-02-12	1.32	1.44	1.38±0.23e+28	3.55±0.17e+25	2.82±0.18e+25						
2024-02-13	1.32	1.43			3.17±0.14e+25						
2024-02-18	1.32	1.39			2.60±0.12e+25						
2024-02-19	1.32	1.38	1.27±0.20e+28	3.99±0.16e+25							
2024-02-24	1.33	1.35	6.67±1.11e+27	2.67±0.10e+25	2.28±0.12e+25						
2024-03-01	1.34	1.32			2.07±0.09e+25			2740.95±41.72			
2024-03-03	1.35	1.32	5.48±0.79e+27	2.16±0.07e+25	1.95±0.09e+25		1825.29±30.92	2722.57±33.16			
2024-03-06	1.35	1.31	6.42±0.94e+27	2.04±0.06e+25	1.86±0.07e+25						
2024-03-09	1.37	1.30	7.16±0.95e+27	2.52±0.08e+25	2.30±0.08e+25		1794.21±14.41	2695.22±7.57			2414.57±11.57
2024-03-14	1.39	1.30	8.30±0.93e+27	2.58±0.09e+25	2.18±0.10e+25		1807.02±23.32				2442.22±17.14
2024-03-15	1.39	1.30		3.06±0.09e+25	2.48±0.08e+25	4.88±0.26e+24		2758.30±16.03			
2024-03-17	1.40	1.30	8.50±0.98e+27	2.34±0.07e+25	2.57±0.12e+25	4.25±0.26e+24	1503.35±15.57	2593.20±19.65			2329.88±12.70
2024-04-02	1.50	1.34			1.90±0.13e+25	2.16±1.03e+24		2307.02±3.80			2062.77±1.44
2024-04-03	1.50	1.35	5.18±0.54e+27	2.20±0.08e+25	1.79±0.14e+25	1.16±0.21e+24	1540.94±0.31				
2024-04-05	1.52	1.36	3.95±0.41e+27	2.05±0.06e+25	1.59±0.12e+25		1428.06±41.82	2067.14±139.76			1816.06±141.49
2024-04-10	1.55	1.39	2.77±0.34e+27	1.59±0.06e+25	1.58±0.15e+25		1292.26±29.92				1754.83±89.54
2024-04-15	1.59	1.42	4.29±0.50e+27	2.05±0.09e+25	2.20±0.14e+25		1051.67±38.70	2074.75±100.68			1900.58±64.86
2024-04-17	1.61	1.43	3.68±0.41e+27	1.69±0.06e+25	1.29±0.14e+25		1270.95±28.00	1859.45±45.32			1684.95±23.42
2024-04-24	1.67	1.49	3.78±0.44e+27	1.63±0.08e+25	9.86±1.81e+24		1123.41±16.52	1603.04±9.13			1454.52±15.17
2024-05-01	1.73	1.54	3.15±0.43e+27	1.47±0.07e+25	1.22±0.14e+25		1290.69±37.36	1875.99±53.34			1717.64±33.19
2024-05-07	1.78	1.59		1.37±0.34e+25	1.67±0.10e+25		1023.74±42.74	1713.05±49.58			1553.68±27.98
2024-05-09	1.80	1.61	3.31±0.50e+27	1.35±0.06e+25	1.17±0.23e+25		1229.67±42.68	1683.86±56.66			1596.40±42.86
2024-05-15	1.86	1.67									1531.28±12.48
2024-05-17	1.88	1.68	2.48±0.39e+27	1.26±0.06e+25	1.10±0.08e+25		1119.74±15.98	1657.15±15.06			1520.20±11.38
2024-05-21	1.92	1.72	2.62±0.47e+27	1.19±0.09e+25	9.81±2.04e+24		1132.30±16.14	1714.27±14.32			1207.02±11.04
2024-05-29	2.00	1.79									1079.57±18.47
2024-06-04	2.06	1.84		6.07±0.52e+24	5.70±0.76e+24		731.82±22.13	992.48±26.17			892.55±9.72
2024-06-06	2.08	1.86		8.29±0.52e+24		2.02±1.72e+23	795.38±20.26	1116.42±32.39			1173.84±18.06
2024-06-14	2.16	1.92			5.42±1.26e+24		966.31±27.12	1481.62±17.86	1158.35±15.34		
2024-06-16	2.19	1.95			7.98±1.19e+24			1468.75±10.41	1088.11±11.44		1330.21±9.74
2024-06-17	2.19	1.95		6.41±0.74e+24			968.32±43.01				
2024-06-18	2.21	1.96			5.51±1.63e+24			1242.44±13.72			1168.15±12.70
2024-06-19	2.21	1.96		5.37±0.59e+24			871.10±21.04				
2024-06-23	2.26	2.00									1031.97±5.43
2024-06-24	2.27	2.01		4.86±0.71e+24	4.42±1.71e+24		766.00±13.57	1045.51±10.80			946.62±4.99
2024-06-26	2.29	2.03					902.94±6.03	1320.64±8.21			
2024-06-28	2.31	2.04					984.72±5.78	1333.07±7.93			1237.24±5.88
2024-07-02	2.35	2.07		4.76±0.51e+24	4.37±0.78e+24	2.43±1.74e+23	891.17±1.24	1300.60±1.14			1209.54±0.62
2024-07-05	2.39	2.10					795.69±57.32	1307.27±40.30			1135.12±38.40
2024-07-06	2.40	2.10		4.82±0.59e+24	3.20±1.91e+24						1184.82±26.13
2024-07-09	2.43	2.13									924.84±20.18
2024-07-10	2.44	2.13									823.08±27.74
2024-07-13	2.47	2.16									765.42±11.39

Appendix D

List of publications

Papers in referee journals (7 in total, 1 as first author):

1. **S. Hmiddouch**, E. Jehin, M. Lippi, M. Vander Donckt, K. Aravind, D. Hutsemékers, J. Manfroid, A. Jabiri, Y. Moulane, and Z. Benkhaldoun. “Variations in the volatile-driven activity of comet C/2017 K2 (PanSTARRS) revealed by long-term multiwavelength observations”, [A&A](#), **701**, A61.
2. K. Aravind, E. Jehin, **S. Hmiddouch**, et al. “Ionic emission from and activity evolution in comet C/2020 F3 (NEOWISE): Insights from long-slit spectroscopy and photometry”, [A&A](#), **701**, A161.
3. E. Hemmen, M. Vander Donckt, E. Jehin, **S. Hmiddouch**, et al. “Activity and composition of the periodic comets 67P/Churyumov-Gerasimenko and 103P/Hartley 2 at two different perihelion passages”, [A&A](#), **710**, A172.
4. G. Ahuja, K. Aravind, S. Ganesh, **S. Hmiddouch**, et al. “Long-term monitoring of a dynamically new comet C/2020 V2 (ZTF)”, [MNRAS](#), **Volume 543**, Issue 2.
5. M. Vander Donckt, E. Jehin, K. Aravind, C. Adami, **S. Hmiddouch**, et al. “Photometric and spectroscopic monitoring of the outbursting Halley-type comet 12P/Pons-Brooks”, [A&A](#), **705**, A89.
6. C. Opitom, C. Snodgrass, E. Jehin, M. Bannister, E. Bufanda, S. Deam, R. Dorsey, M. Ferrais, **S. Hmiddouch**, et al. “Snapshot of a new interstellar comet: 3I/ATLAS has a red and featureless spectrum”, [MNRAS](#), **Volume 544**, Issue 1.
7. Y. Moulane, E. Jehin, J. Manfroid, D. Hutsemékers, C. Opitom, Y. Shinnaka, D. Bode-wits, Z. Benkhaldoun, A. Jabiri, **S. Hmiddouch**, et al. “Activity and composition of the hyperactive comet 46P/Wirtanen during its 2018 close approach”, [A&A](#), **670**, A159.

Papers in preparation (3 in total, 1 as first author)

1. **S. Hmiddouch**, et al. “Comparative Analysis of Light Curves, Dust–Gas Activity, and Dynamical Evolution of Dynamically New and Returning Long Period Comets”. *In preparation*.
2. K. Aravind, **S. Hmiddouch**, et al. “Optical narrow band photometric and spectroscopic study of comet C/2022 E3”. *In preparation*.

3. Y. Moulane, **S. Hmiddouch**, et al. “Photometry and dynamical evolution of comets 252P/LINEAR and P/2016 BA14 (PanSTARRS)”. *In preparation*.

Communications in conferences (19 in total, as first author)

1. **S. Hmiddouch**, E. Jehin, S. Anderson, Y . Moulane, M. Vander Donckt, k. Aravind, A. Jabiri, D. Hutsemékers, J. Manfroid, and Z. Benkhaldoun. “Comparative Analysis of Light Curves, Dust–Gas Activity, and Dynamical Evolution in Long-Period and Dynamically New Comets”, 06 - 10 Jul, 2026. [Two posters at the Asteroids, Comets, Meteors Conference \(ACM26\), Poznan, Poland](#)
2. **S. Hmiddouch**, E. Jehin, M.Lippi, M. Vander Donckt, k. Aravind, A. Jabiri, D. Hutsemékers, Y . Moulane, J. Manfroid, and Z. Benkhaldoun. “Variations in the volatile-driven activity of comet C/2017 K2 (PanSTARRS) revealed by long-term multiwavelength observations”, 22 - 27 March, 2026. [E-poster at The 6th Annual conference of the African Astronomical Society\(AfAS26\), Kasane, Botswana](#)
3. **S. Hmiddouch**, E. Jehin, M. Lippi, M. Vander Donckt, A. Jabiri, Y. Moulane, J. Manfroid, D. Hutsemekers, and Z. Benkhaldoun. “Long-Term Activity and Compositional Evolution of Comet C/2017 K2(PanSTARRS) from Photometric and High-Resolution Spectroscopic Observations”, 7 - 12 Sep, 2025. [Talk at the EPSC-DPS Joint Meeting 2025, Helsinki, Finland](#)
4. **S. Hmiddouch**, E. Jehin, M. Vander Donckt, A. Jabiri, Y. Moulane, J. Manfroid, D. Hutsemekers, and Z. Benkhaldoun. “Composition and activity of comets with TRAPPIST telescopes”, 23 - 27 Jun, 2025. [E-poster at the European Astronomical Society Annual Meeting \(EASC25\), Cork, Ireland](#)
5. **S. Hmiddouch**, E. Jehin, A. Jabiri, Y. Moulane, K. Aravind, M. Vander Donckt, G. Ahuja, Z. Benkhaldoun, and S. Ganesh. “Long-term TRAPPIST monitoring of a few Long Period and Dynamically New Comets”, 8 - 13 Sep, 2024. [Talk at the Europlanet Science Congress \(EPSC24\), Berlin, Germany](#)
6. **S. Hmiddouch**, E. Jehin, M. Vander Donckt, A. Jabiri, Y. Moulane, and Z. Benkhaldoun. “The dust and gas production rates: monitoring of Long-period comets (LPC) and Dynamically new comets (DNC) with TRAPPIST telescopes”, 6 - 15 Aug. 2024. [Talk at the General Assembly of the International Astronomical Union \(IAUGA24\), Cape Town, South Africa](#)
7. **S. Hmiddouch**, E. Jehin, Y. Moulane, M. Vander Donckt, A. Jabiri, k. Aravind, Z. Benkhaldoun, and S. Ganesh. “Activity and composition of five bright long-period comets from photometry and long-slit spectroscopy”, 15 - 20 Apr. 2024 [Talk at the 4th Annual Conference of the African Astronomical Society\(AfAS24\), Marrakech, Morocco](#)
8. **S. Hmiddouch**, E. Jehin, M. Lippi, M. Vander Donckt, A. Jabiri, Y. Moulane, J. Manfroid, and Z. Benkhaldoun. “Monitoring the activity and composition of Comet C/2017 K2 (PanSTARRS)”, 31 Jan - 04 Feb, 2024 [Poster at the 42nd meeting of the Astronomical Society of India \(ASI24\), Bengaluru, India](#)
9. **S. Hmiddouch**, E. Jehin, M. Vander Donckt, A. Jabiri, Y. Moulane, M. Lippi, D. Hutsemekers, Z. Benkhaldoun, and J. Manfroid. “Monitoring the activity and composition of Comet C/2017 K2 (PanSTARRS)”, 5 - 8 Sept. 2023 [Talk at the Active small bodies in the Solar System over a wide range of heliocentric distances workshop, Stara Lesna, Slovakia](#)

10. **S. Hmiddouch.** “The rotational period of near-Earth objects (NEOs)”, 7 - 14 Jul, 2023
[Talk at the Oukaimden International School for Astrophysics, Marrakech, Morocco](#)
11. **S. Hmiddouch,** E. Jehin, M. Vander Donckt, Y. Moulane, J. Manfroid, A. Jabiri, and Z. Benkhaldoun. “TRAPPIST Narrow Band Survey of Bright Long-Period Comets in 2022-2023.” 18 - 23 Jun, 2023 [Poster at the Asteroids, Comets, Meteors Conference \(ACM23\), Flagstaff, Arizona, USA](#)
12. **S. Hmiddouch,** 25 - 28 Apr, 2023 [Participated in the Europlanet Workshop Series, Casablanca, Morocco](#)
13. **S. Hmiddouch,** 8 Dec, 2022 [Participated in the ESO Belgian Day, Brussels, Belgium](#)
14. **S. Hmiddouch,** E. Jehin, Y. Moulane, A. Jabiri, M. Vander Donckt, and Z. Benkhaldoun. “Monitoring the activity and composition of comet C/2017K2 (PanSTARRS) with TRAPPIST telescopes” 18 - 23 Sep, 2022 [Poster at the Europlanet Science Congress \(EPSC22\), Granada, Spain](#)
15. **S. Hmiddouch,** E. Jehin, Y. Moulane, A. Jabiri, M. Vander Donckt, and Z. Benkhaldoun. “Composition and activity of comets with TRAPPIST telescopes” 2 - 11 Aug. 2022. [Talk at the General Assembly of the International Astronomical Union \(IAUGA22\), Busan, Republic of Korea](#)
16. **S. Hmiddouch,** “Study of the chemical composition and analysis of the comet’s light curves with TRAPPIST telescopes”, 1 - 7 Jul, 2022. [Talk at the Oukaimden International School for Astrophysics, Marrakech, Morocco](#)
17. **S. Hmiddouch,** Y. Moulane, M. Vander Donckt, E. Jehin, A. Jabiri, Z. Benkhaldoun, and H. Sriba. “Composition and activity of comet C/2020 M3 (ATLAS) with the TRAPPIST-North telescope”, 18 - 19 Mar. 2022. [Poster at the Second National Congress of Fundamental and Applied Physics, Safi, Morocco](#)
18. **S. Hmiddouch,** Y. Moulane, M. Vander Donckt, E. Jehin, A. Jabiri, Z. Benkhaldoun, and H. Sriba. “Composition and activity of comet C/2020 M3 (ATLAS) with the TRAPPIST-North telescope”, 14 - 18 Mar. 2022. [Poster at the second annual conference of the African Astronomical Society](#)
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