



IFU Observations of Comet 3I/ATLAS = C/2025 N1 (ATLAS) Using the Hobby–Eberly Telescope with the VIRUS Instrument*

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Abstract

We observed interstellar object 3I/ATLAS = C/2025 N1 (ATLAS) on 2025 December 9 UT with the VIRUS spectrograph on the Hobby–Eberly Telescope. VIRUS is a low spectral resolving power, multi-integral field unit (IFU), optical spectrograph. We used a single IFU for the observations and were able to obtain spectra spaced every 1'' (1327 km) from the optocenter out to about 85,000 km in the sunward direction. The spectra include molecular features normally seen in the optical for spectra of solar system comets, with the addition of many very strong lines of Fe I and Ni I. We modeled these observations using the Haser (1957) model framework and find that the data can only be fit if we assume that the outflow velocity of the gas is half that of comets in our solar system observed at the same heliocentric distance. We derived Haser model scale lengths for three Ni I and four Fe I lines. We discuss the implication of the similarities and differences between this object and normal solar system comets. The excellent spatial resolution of VIRUS, coupled with a field of view (FOV) of 50'' × 50'' and a geocentric distance of 1.83 au, allowed us to probe the coma of 3I in great detail. An accidental offset of the optocenter of the comet to the edge of the FOV meant that we probed to a large distance (>85,000 km) in the sunward direction from the optocenter, adding new information to the extensive literature on 3I, even with a single epoch of observations.

Unified Astronomy Thesaurus concepts: [Interstellar objects \(52\)](#)

1. Introduction

We study comets in our solar system as windows on conditions in the early stages of planet formation. Comets are the least altered bodies that remain from that time (M. J. Mumma & S. B. Charnley 2011; K. Altwegg et al. 2019). Our current understanding is that some comet precursors formed in the region beyond Neptune; those leftovers include the population of Jupiter-Family Comets (low-inclination objects with orbital periods of less than 20 yr) and the scattered disk population (L. Dones et al. 2004; D. Nesvorný 2018). Other comet precursors were also formed in the giant planet region. Some of these were incorporated into the growing giant planets, but, for those not included in building the giant planets, 5%–10% were gravitationally perturbed into the Oort Cloud, and 90%–95% of them were ejected completely from the nascent solar system (J. A. Fernández & A. Brunini 2000; N. A. Kaib & K. Volk 2024).

It is logical to assume that other planetary systems went through similar formation and sorting processes, leaving some small objects in these other planetary systems but ejecting

other “comets” out into the Galaxy (A. Morbidelli 2008). Some of those ejected comets are on trajectories crossing the solar system. Such extrasolar comets can be identified by hyperbolic orbits and high excess velocity (v_∞).

At present, there are three small objects that have been discovered and classified as interstellar objects. The first such object, C/2017 U1 = 1I/‘Oumuamua, was discovered with the Pan-STARRS telescope by Robert Weryk on 2017 October 19 (K. J. Meech et al. 2017). The nucleus was quite small and elongated. It did not have any obvious gas emissions or coma, but it did exhibit nongravitational motions to its orbit (M. Micheli et al. 2018).

The second interstellar body was discovered on 2019 August 30 by amateur astronomer Gennadiy Borisov and is designated C/2019 Q4 = 2I/Borisov. Borisov showed a gaseous coma whose composition exhibited high CO relative to H₂O compared with solar system comets (D. Jewitt & J. Luu 2019).

The last discovery, on 2025 July 1, was 3I/ATLAS = C/2025 N1 (ATLAS) (hereafter, we will designate this object as 3I). By studying 3I, we hope to learn about conditions in the natal planetary system of this target and/or its long interstellar journey.

Observations of interstellar objects are important to our understanding of the formation of our solar system. This is true regardless of whether they look compositionally just like typical solar system comets, or look very different, because it speaks to the universality of the processes by which comets are formed. However, it must be remembered that we do not know the conditions under which the interstellar objects we have discovered were formed, how old the objects are, what type of

* Based on observations obtained with the Hobby–Eberly Telescope (HET), which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Ludwig-Maximilians-Universität München, and Georg-August Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly.



stellar system they formed with, and how the structure of the nucleus has been altered as the object wanders around the Galaxy. Indeed, M. J. Hopkins et al. (2025) concluded that 3I must be at least 7.6 Gyr, based on the velocity and radiant of its orbit. They argued for a different origin for 3I than for either of the previous two interstellar objects. Based on kinematic calculations, A. G. Taylor & D. Z. Seligman (2025) figured that the age is somewhere between 3 and 11 Gyr. From isotopic considerations, M. Cordiner et al. (2026) figured that 3I was formed 10–12 Gyr ago. Thus, while it is quite possible that 3I is older than our solar system, its age is not definitively known.

M. Cordiner et al. (2026) and C. Opitom et al. (2026) examined the isotopic ratios for carbon and nitrogen in 3I and compared them with bodies in our solar system. $^{14}\text{N}/^{15}\text{N}$ is 2 times higher in 3I than in solar system comets, while $^{12}\text{C}/^{13}\text{C}$ is moderately higher. D/H in 3I is substantially higher than normal comets, with the D/H in H_2O and CH_4 being measured as 10–40 times higher than Earth or comets (M. Cordiner et al. 2026; N. X. Roth et al. 2026a; L. E. Salazar Manzano et al. 2026).

Observations of 3I show that it is very enriched in CO and CO_2 , with a $\text{CO}_2/\text{H}_2\text{O}$ mixing ratio higher than previously measured comets (M. A. Cordiner et al. 2025; C. M. Lisse et al. 2026a, 2026b). M. A. Cordiner et al. (2025) concluded that 3I is either intrinsically CO_2 rich or is H_2O ice depleted. This has implications for the formation temperature of the body.

R. Maggiolo et al. (2026) concluded that substantial Galactic cosmic rays (GCRs) impinged on its surface, altering the structure. They argued that these objects have heavily processed surfaces, rather than pristine ones. Whether by GCRs or by differences in insolation, the structure of the surface ices might be quite different from bodies in our solar system, accounting for observed spectral differences such as those presented in this paper.

2. Observations

We used the Hobby–Eberly Telescope (HET) and its wide-field, low resolving power spectrograph, the Visible Integral-Field Replicable Unit Spectrograph (VIRUS; G. J. Hill et al. 2021), to obtain a set of data on 3I.⁶ The data were obtained on 2025 December 9 UT. At the time of the observations, 3I was at a heliocentric distance of 2.03 au and a geocentric distance of 1.83 au and was moving away from the Sun.

It is named VIRUS because it contains 78 pairs of spectrographs that are identical in order to save costs and gain field of view (FOV). Together, the integral field units (IFUs) cover an FOV that is $18'$ on a side. VIRUS spectrographs cover 3500–5500 Å, with $R = \lambda/\Delta\lambda = 700$. The fibers are $1.5''$ in diameter, and each IFU covers $50''$ by $50''$ of the sky. There are spaces between adjacent fibers. Those spaces are filled, and a field is fully imaged, using three separate pointings (dithers; G. J. Hill et al. 2021, see their Figures 7 and 8).

The HET is an unusual telescope (L. W. Ramsey et al. 1998) because it is fixed in altitude. Its azimuth can be changed, but once at the desired azimuth, the telescope structure does not move during observations. Instead, a tracker at the prime focus

is used to trace the path of the target across the sky. Two guide cameras offset from the VIRUS FOV can lock onto stars to ensure that the telescope stays pointed at the target. However, for objects moving at nonsidereal rates, the guide stars do not stay fixed with respect to the prime target. Thus, the nonsidereal motion must be compensated for, and the guide star(s) must be handed off from one guide camera to the other.

There was some interval of time between when the target was sent to the IFU and when the guide stars were set up and ready to follow 3I with appropriate tracking. As it turned out, the interval for the handoff was not properly accounted for, so 3I ended up on the edge, and not the center, of an IFU. However, once on its guiding location, the telescope tracked the moving target well, venturing off tracking 3I correctly by $1''$ or less over the three dither observations (just under 20 minutes). The errors in tracking were checked by comparing the three dither subframes.

Since the comet optocenter ended up on the edge of the IFU, we ran several tests to confirm that the optocenter was on the detector, and we knew on which pixel it was imaged. One test was to fit contour plots that showed the peak was near, but not off, the edge of the detector. Another test was to derive column densities assuming different optocenter pixels and determine if the data were symmetric around the selected pixel and which pixel had the maximum counts for all features. We were able to convince ourselves that we knew the location of the optocenter to within 1 pixel, and the optocenter was just on the IFU, but at the edge.

The data reduction was performed with the package “Remedy” (see G. R. Zeimann et al. 2024 for complete details on the data reduction). Basically, typical IFU handling procedures are followed including bias and dark removal, removal of bad pixels, gain correction, sky removal and extraction, and appropriate combinations of fibers. All of the data are formed into cubes, accounting for differential atmospheric refraction, with X and Y on the sky and wavelength defining the slices.

The wavelength scale for each spaxel was defined with observations of a HgCd lamp. All of the spectra were wavelength rectified onto a common linear grid of 3470–5540 Å with 2 Å per slice. There are 1036 slices (wavelength intervals) per output target cube.

Flux calibration was performed using a fixed empirical instrument response curve derived from spectrophotometric standard-star observations obtained over an extended period. For each exposure, this response curve is scaled using the measured mirror illumination and guider throughput to account for variations in telescope throughput and observing conditions. This procedure provides an absolute flux calibration that is typically accurate to about 15%. The relative flux calibration, referring to the accuracy of the spectral shape across wavelength rather than the overall normalization, is more precise, with an accuracy of approximately 5% above 3900 Å and 10% below 3900 Å. During cube construction, fiber flux densities are divided by the fiber area and resampled onto a regular spatial grid using a flux-conserving reconstruction. Because the pixel area is explicitly accounted for, the resulting values correspond to flux density per square arcsecond for a $1'' \times 1''$ grid.

The solar spectrum was constructed from the HETDEX Continuum Catalog (version 5.0.1; E. Mentuch Cooper et al. 2023). We selected G-type stars and computed a biweight

⁶ HET is a 10 m telescope sited on Mount Fowlkes as part of the McDonald Observatory complex outside of Ft. Davis, TX.

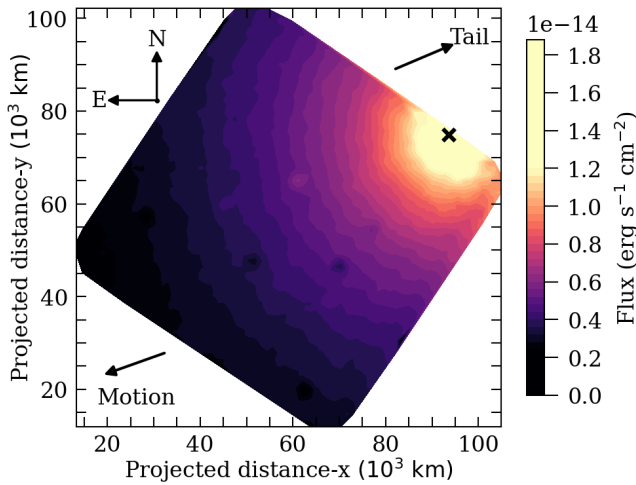


Figure 1. The spatial distribution of the CN fluxes on the IFU FOV is shown. The position of the optocenter of 3I, on the edge of the IFU, is denoted by an X. The CN fluxes are determined every 1", or 1327 km. The tail direction marked is just the extended heliocentric radius vector as we did not actually see a tail. We mark the direction of motion.

average spectrum on a fixed 3470–5540 Å grid, normalizing by the g-band AB flux.

Figure 1 shows the spatial distribution of the summed fluxes in the CN bandpass (3865–3905 Å) for the three combined dithers. The comet optocenter is on the right edge of the IFU. Although the placement on the edge of the array was unfortunate, the reasonably accurate tracking meant that we could still use these spectra to determine what gases were present in the spectra and how they behaved with cometo-centric distance.

Only one IFU out of the VIRUS array of 78 pairs of spectrographs contained an appreciable signal from 3I. However, that one IFU imaged a 50" × 50" patch of the sky with thousands of data points, making these data a very rich, and unique, look at the gas in the inner ~85,000 km of the coma. Figure 2 shows the observed spectrum from 1 spaxel near the optocenter. Various molecular and atomic features are identified. The region of the spectrum redward of 3850 Å shows the usual molecules at the same relative strengths that we normally detect in the spectra of comets observed in the inner solar system. In 3I, we detected CN, C₃, CH, and two bands of C₂. These species result from the dissociation of various ices that are in the nucleus, as well as chemistry in the inner coma.

3. The Spatial Distribution of Gas in the Coma

At the end of the data reduction, we have spectra at every wavelength and spaxel. We want to determine what the gas is doing as it flows away from the nucleus, so we need to convert these spectra into useful information at each position.

The spectra after reduction are a mixture of cometary emission features and a continuum generated by solar photons reflecting off the dust. Since we wish to measure the gas distribution, we need to remove the solar/continuum spectrum first. We defined seven continuum regions, marked underneath the spectra in Figure 2, and computed the sum of the flux in each of the continuum regions in both the comet spectra and a solar spectrum. The ratio of those two sums then yields a factor that we used to scale the solar spectrum to the continuum of the comet spectrum. With only seven continuum

regions, we needed to fit a cubic polynomial to these ratios in order to define a factor at each wavelength to scale the solar spectrum to the comet. Then, we just subtracted the scaled solar spectrum from the comet plus dust spectrum. That yielded a spectrum that contained only cometary gas features. It was these comet gas spectra that we used to determine the quantity of each gas species at each position on the detector.

3.1. Molecules

In order to place the data on a scale that could be compared with solar system comets, we need to convert from the flux at each wavelength to the column density for a particular gas species. First, we sum the flux within bandpasses that encompass the whole band for a given molecule. Then, we convert this integrated flux to a column density using standard efficiency factors. We used the efficiency factor values listed in Table 1 of A. L. Cochran et al. (2012).

The distribution of the column densities for the CN molecule is shown in Figure 3. Inspection of this figure shows that we have abundant column density points to define the distribution of CN. With the comet optocenter at the edge of the FOV, we preferentially were looking on the sunward side of the nucleus. The placement of the optocenter on the edge of the field meant that our observations measured intensities at large distances from the nucleus. For all of the common molecular species, we traced the gas out to ~85,000 km. The profiles include points offset at different angles from the nucleus. We see no real difference in the gas distribution with angle.

To convert the observed column densities to production rates for comparison with solar system comets, we used the Haser model (L. Haser 1957). This approach is widely used in the comet literature and provides a common framework for reporting production rates (for example, M. F. A'Hearn et al. 1995; U. Fink 2009; L. E. Langland-Shula & G. H. Smith 2011; A. L. Cochran et al. 2012). The model assumes a steady, spherically symmetric coma with gas expanding radially outward at a constant velocity and with photodissociation scale lengths that are fixed for the observing geometry. Our data show that the coma morphology is reasonably symmetric, making these assumptions a pragmatic approximation for the present analysis. From an inference standpoint, the Haser model could be viewed as a simplified forward model that encodes a particular set of assumptions about the structure of the coma and the photochemistry. However, these assumptions are not expected to hold exactly for real comae, which can exhibit anisotropic outflow, time variability, and more complex chemical pathways. For this reason, the derived production rates should be interpreted cautiously as model-dependent quantities, rather than direct physical measurements.

The Haser model can be expressed as

$$n = Q[4\pi r^2 v]^{-1} [\beta_0 / (\beta_1 - \beta_0)] [e^{-\beta_0 r} - e^{-\beta_1 r}] \quad (1)$$

where n is the number density of the daughter species, β_0 and β_1 are the reciprocal scale lengths of the parent and daughter species, respectively, v is the outflow velocity, Q is the production rate of the parent, and r is the radial position within the coma. The scale lengths for the Haser model are generally reported in the literature at 1 au. When running the models discussed here, the scale lengths were scaled to the heliocentric

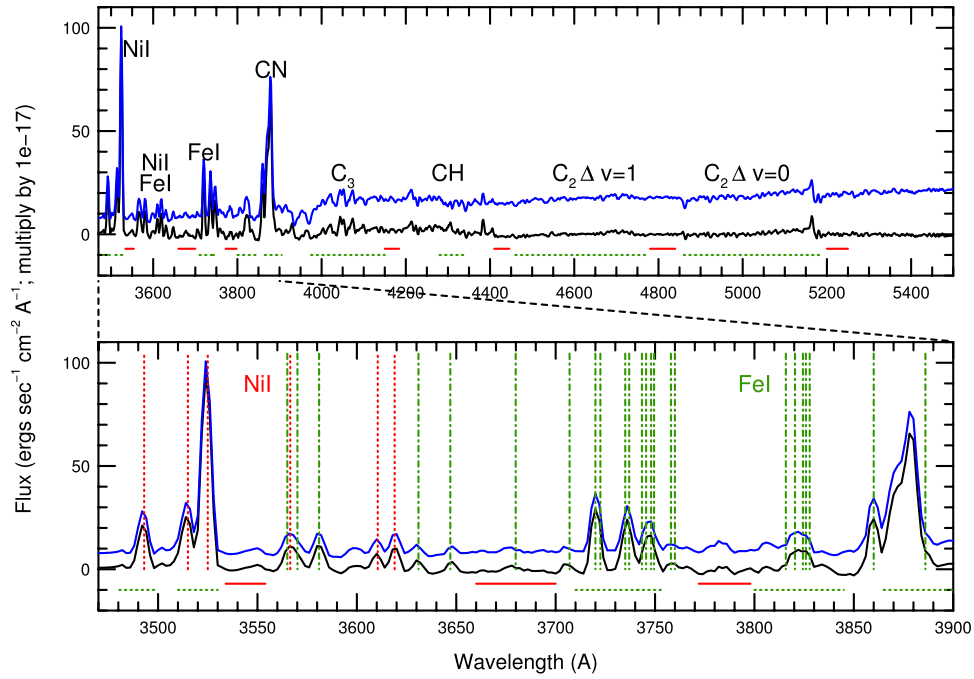


Figure 2. A spectrum from a spaxel near the optocenter is shown. The complete spectrum is displayed in the upper panel, with features identified. The blue spectrum is the comet spectrum with the solar continuum spectrum reflected off cometary dust imposed on the comet spectrum. The black spectrum is the same spectrum but with the dust removed (see Section 3). The lower panel is an expanded view of the bluer end of the spectrum. There are many atomic Ni I and Fe I features identified in the lower panel with the Ni I lines as red-dotted lines and the strongest Fe I lines as green-dashed-dotted lines. On both panels, the horizontal green-dotted lines under the spectra delineate the feature bandpasses used, while the horizontal solid red lines under the spectra delineate the continuum regions used.

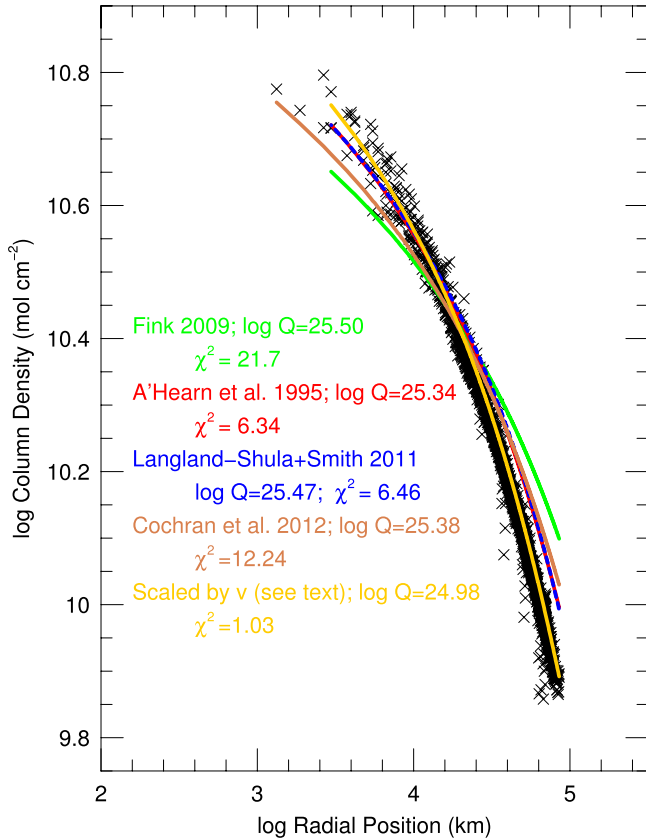


Figure 3. The column densities for CN are shown as a function of distance to the optocenter. We computed Haser model production rates (see text) for each molecule's distribution. As discussed in the text, there are several widely used scale lengths to convert from column densities to production rate. Fits for several scale lengths from the literature are shown, along with a set of scale lengths that were scaled from a standard set (see text).

distance of the comet observations using a factor of R_h^2 (where R_h is the comet's heliocentric distance in au) for most molecules and scale lengths in the literature. The exception is that the C_2 parent scale lengths are scaled by $R_h^{2.5}$ for the scale lengths of A. L. Cochran et al. (2012). The outflow velocity used for our modeling was $v = 0.85 R_h^{-0.5}$ (A. L. Cochran & D. G. Schleicher 1993). At the heliocentric distance of 31I, this relation yields $v = 0.597 \text{ km s}^{-1}$. Inspection of Equation (1) shows that the scale lengths define the shape of the gas distribution with distance to the optocenter. Q and v control the overall total number densities and are dependent on one another. Thus, changing v changes the derived Q .

Figure 3 shows the CN data with model fits from four common sets of scale lengths in the literature (M. F. A'Hearn et al. 1995; U. Fink 2009; L. E. Langland-Shula & G. H. Smith 2011; A. L. Cochran et al. 2012), identified by color (since the M. F. A'Hearn et al. 1995; and L. E. Langland-Shula & G. H. Smith 2011 models completely overlap, their lines are dashed). The fits are normalized at a log column density of 10.4. The narrowness of the distribution of the CN column density with cometocentric distance is indicative that the error bars on each data point are small. The analysis shows that, for CN, the error bar on the log column densities would be much less than ± 0.1 at each point. The error bars are computed from 1σ per-sample errors that are propagated through the imaging and Gaussian smoothing.

Inspection of this figure shows that none of the models using published scale lengths are good fits to the data. As noted above, the scale lengths control the shape of the distribution. The scale lengths depend on the gas being studied and the target's distance to the Sun. The scale length expresses the distance a molecule will travel in the coma in some unit of time. Thus, if the velocity of the outflowing gas changes, not

only will v change in Equation (1) but also the scale lengths will change.

It was not possible to determine the outflow velocity of the gas from our data owing to the low spectral resolving power of VIRUS. N. Biver et al. (2026) used the IRAM radio telescope and observations of HCN and CH₃OH to determine that the outflow velocity was 0.37 km s^{-1} when the comet was at a heliocentric distance of 1.36 au. The velocity equation above would have predicted $v = 0.73 \text{ km s}^{-1}$ at the heliocentric distance of their observations. Scaling their velocity by the square root of R_h to our observation's distance of 2.03 au would predict a velocity of 0.31 km s^{-1} , not the canonical 0.597 km s^{-1} .

M. Cordiner et al. (2026) used Atacama Large Millimeter/submillimeter Array observations to measure the velocity when they observed 3I at $R_h = 2.4 \text{ au}$. They found that the outflow velocity of the CO gas was 0.345 km s^{-1} and of the HCN gas was 0.276 km s^{-1} . At the heliocentric distance of their observations, we would have expected $v = 0.55 \text{ km s}^{-1}$. Scaling their velocities to our heliocentric distance would yield $v = 0.38 \text{ km s}^{-1}$ with the CO velocity value or 0.30 km s^{-1} with the HCN velocity.

In all three cases, the gas was flowing away from the nucleus at about half the expected speed. If we assume that these slow velocities change the scale lengths of both the parent and daughter species, we can run the Haser model with scale lengths that are adapted to the more slowly outflowing gas. Since the scale length is a function of the velocity and the molecular lifetime, if the molecule being studied remains the same as in our typical comets, then so will its lifetime. Thus, the scale lengths will change by the ratio of the velocities. With a velocity of 0.30 km s^{-1} (as predicted based on scaling the radio telescope velocities) and assuming the same molecular lifetimes, the scale lengths should change by a factor of ~ 2 .

We computed the model with this slower velocity and the resultant different scale lengths. The derived curve is shown in Figure 3. This is a much better fit than any of the models with the published scale lengths. If we assume that only the parent outflow velocity (and therefore the parent scale length) changed by a factor of 2, but that the outflow velocity for the daughter was the normal value for gas flowing away from a comet in our solar system, we find that the fit is not as good as when we change the outflow velocities for both the parent and daughter. The reduced χ^2 goes from 1.03 for changing both scale lengths to 1.75 for changing just the parent.

The distribution of gas with distance to the nucleus is shown in Figure 4 for the other species that are commonly seen in optical spectra of solar system comets. The data are shown with Haser models using the canonical scale lengths of A. L. Cochran et al. (2012). The models are shown in orange.

There is no reason to assume that only the CN gas is moving slowly (especially since the slow gas was measured in the radio in several molecular species). Thus, we reran the models with scale lengths that were half of the A. L. Cochran et al. (2012) ones due to the ratio of normal to slower velocity. These models are shown in red in Figure 4.

The reduced χ^2 values for the fits indicate that C₂ modeled with the scale lengths that we show in Table 1 is only slightly better than models with the scale lengths of A. L. Cochran et al. (2012) (less than 10%). On the other hand, the CH and C₃ fits with the scaled velocity and, therefore, scale lengths show

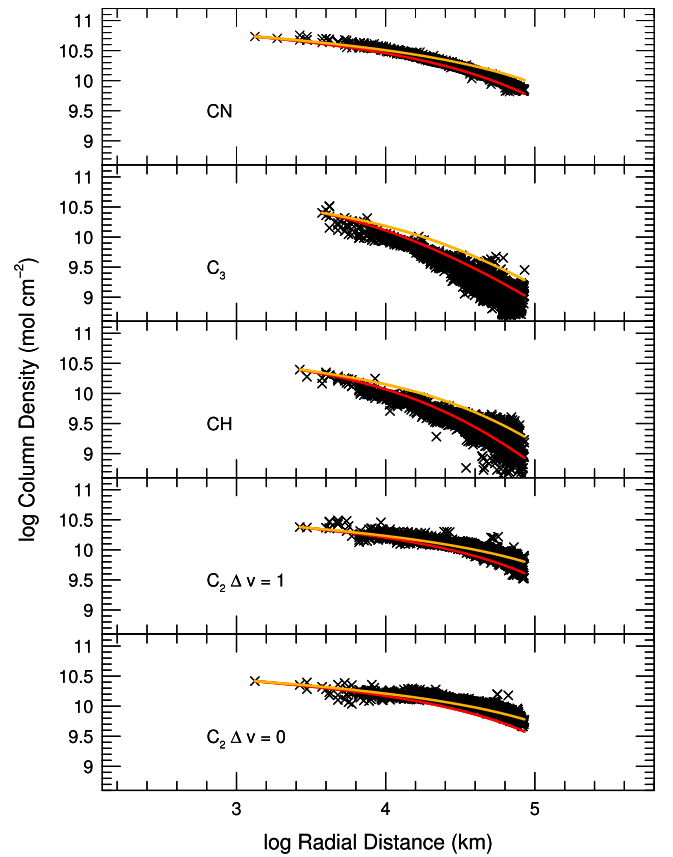


Figure 4. The column densities for CN, C₃, CH, and C₂ (two bands) are shown as a function of distance to the optocenter. Models using the scale lengths of A. L. Cochran et al. (2012) are shown with orange lines. Models using scale lengths that are scaled by the low velocity of 3I (0.3 km s^{-1}) are shown with red lines. The error bars in the inner coma are smaller than the point markers. Even the least reliable column densities, those for C₃ and CH, have log column density error bars less than ± 0.1 for the data at the largest distances from the optocenter.

Table 1
Haser Model Scale Lengths Used

Molecule	Parent (km)	Daughter (km)	$\log Q$ (mol s^{-1})
CN	$3.5\text{e}4$	$6.2\text{e}5$	24.98 ± 0.02
C ₃	$6.5\text{e}3$	$3.0\text{e}5$	24.15 ± 0.06
CH	$1.6\text{e}5$	$1.0\text{e}4$	25.59 ± 0.07
C ₂ $\Delta v = 1$	$7.4\text{e}4$	$2.5\text{e}5$	25.04 ± 0.04
C ₂ $\Delta v = 0$	$7.4\text{e}4$	$2.5\text{e}5$	25.05 ± 0.04

considerable improvement. The CH fit is improved by almost a factor of 2 in χ^2 , while the χ^2 value for the C₃ fit is 25% lower for the scaled parameters than for the literature values. The CN data are less noisy than other species. That makes the fits more sensitive to shape differences. The scaled fit has a reduced χ^2 value 10 times lower than the fit with the normal A. L. Cochran et al. (2012) parameters, as can be seen in Figure 3.

Table 1 gives the values for the scale lengths we used (at the distance of 3I from the Sun and with the outflow velocity of 0.3 km s^{-1}). We also show the derived production rates.

Other authors observed some of the same species (W. B. Hoggendorn et al. 2025, 2026a, 2026b; R. Rahatgaonkar et al. 2025; K. Medler et al. 2026; R. Zhao et al. 2026) but just used literature scale lengths to derive production rates. Most do not include

spatial information in their publications, so it is difficult to assess the quality of the fits of their models to their data. W. B. Hoogendarm et al. (2025, 2026b) used a similar instrument to us (KCWI on Keck), but their FOV was limited to $<10,000$ km (log radial distance = 4). They would not be sensitive to deviations of the model from the data with observations only this close to the optocenter.

We can use the production rates measured to compare 3I to solar system comets. The production rates that were reported in the cited papers are not entirely consistent with one another, generally because of the use of different scale lengths. There seems to be some consensus that C_2/CN looks somewhat depleted relative to “typical” comets in our solar system. A caveat is that one must use the definitions of “typical” and “depleted” that go with the scale lengths that are used for the interpretation of the data. R. Zhao et al. (2026) and E. Jehin et al. (2025) found that 3I started off depleted in C_2/CN but became less depleted (or even not depleted) after perihelion. Our observations were during their postperihelion observations, when the comet was not depleted in C_2 .

A. L. Cochran et al. (2012) defined “depleted” values for solar system comets as $\log(Q(C_3)/Q(CN)) < -0.86$ and $\log(Q(C_2)/Q(CN)) < 0.02$. We found values for these two quantities of -1.0 (C_3) and 0.15 (C_2) using the scale lengths of A. L. Cochran et al. (2012) and -0.83 (C_3) and 0.07 (C_2) with the scale lengths we derive in this paper. Our observations do not show the C_2/CN being depleted, although it is at the low end of the “typical” regime. Our C_3/CN does look somewhat depleted.

Inspection of Figure 4 shows that the distributions of the usual molecules with cometocentric distance look fairly symmetric. With the placement of the comet on the array, many of our data points are more or less sunward. However, toward the edge that the comet was placed on, those data are along lines that are perpendicular to the Sun-tail line. These perpendicular vectors cannot be differentiated from the purely solar vector points, confirming that the coma looks symmetric in our data. However, with the comet’s placement on the edge of the IFU, we cannot determine if the comet is also symmetric in the tailward direction.

The molecules that we detected are daughter species and not the ices making up the nucleus. Observations with JWST were used to study the coma formed from parent species. M. A. Cordiner et al. (2025) found that CO_2 was enhanced in the sunward direction. N. X. Roth et al. (2026b) showed that some species were symmetric, and some were not (anisotropic for apolar species and isotropic for polar species; see their Figure 2).

3.2. Ni I and Fe I

The spectrum blueward of $3850 \text{ \AA}$, shown in the lower panel of Figure 2, does not look like a typical solar system comet because we observe obvious features, identified as Ni I and Fe I, which are not seen as strong lines in similar spectra of solar system comets. Until this century, the only comets for which Fe I and Ni I were observed were the Great Comet of 1882 and comet C/1965 S1 (Ikeya-Seki), both sungrazing comets (see J. Manfroid & D. E. J. Hutsemékers 2021 and references therein). With the advent of better detectors and larger telescopes, J. Manfroid & D. E. J. Hutsemékers (2021) showed that Fe I and Ni I are present in the spectra of many comets at a wide range of heliocentric distances. However, the

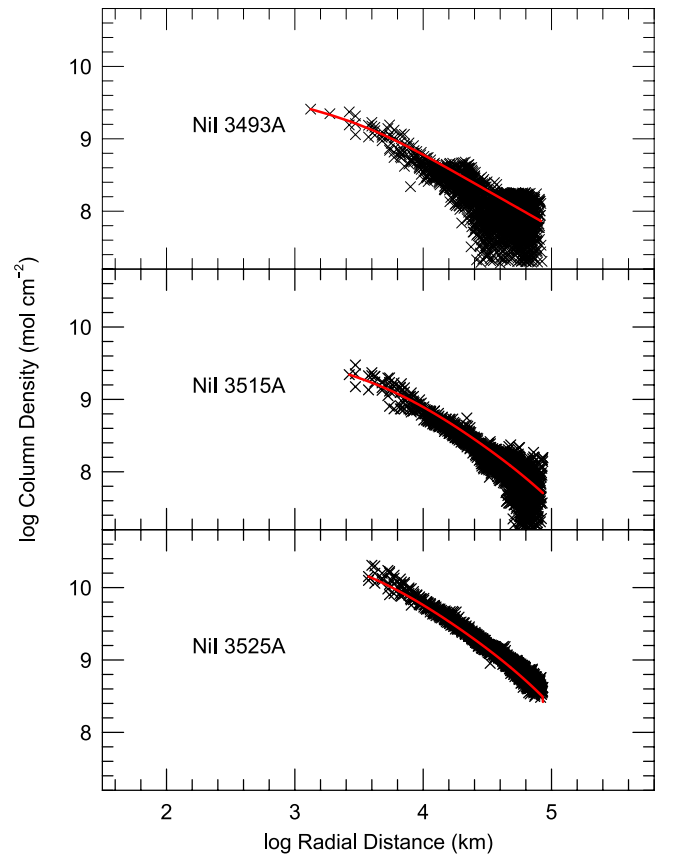


Figure 5. The column densities of three of the Ni I lines are shown as a function of cometocentric distance. The model fits are marked with a red line. Again, the error bars for most of these data are smaller than the data points in the plot for the inner coma. The largest error bars are ± 0.375 far from the optocenter for Ni 3493 Å.

detected lines are relatively weak and can only be seen at high spectral resolving power (very weak lines that are observable at high spectral resolving power cannot be detected at low spectral resolving power since the small line flux gets spread over a wider resolution element and disappears below the continuum). Inspection of a very large number of low spectral resolving power spectra of comets (those of A. L. Cochran et al. 2012) showed no detections of these lines. However, in Figure 2, these lines are very obvious in the spectrum of 3I. Indeed, the Ni I line at $3525 \text{ \AA}$ appears brighter than the CN feature in this spectrum.

Since Fe I and Ni I were not typically detected at low resolving power, there were no computations of the fluorescence efficiencies needed to compute the column densities until 2021, when S. J. Bromley et al. (2021) published calculations for many Ni I and Fe I lines. These calculations included the effect of the heliocentric radial velocity of the comet shifting the emission lines from the comet into and out of alignment with the solar absorption lines of the continuum. When solar absorption features and a cometary emission line are at similar wavelengths, the cometary line sees less solar exciting flux.

We measured the strength of each line above the continuum for Ni I lines and groups of lines for strong Fe I lines to determine the integrated flux for each line or groups of lines. We then used the S. J. Bromley et al. (2021) fluorescence efficiencies (using the updated version of the code archived on Zenodo; S. Bromley 2026; Bromley personal communications)

Table 2
The Derived Fe I and Ni I Scale Lengths (at 2.03 au)

Wavelength (Å)	Parent (km)	Daughter (km)	Log Q (mol s ⁻¹)	Wavelength (Å)	Parent (km)	Daughter (km)	Log Q (mol s ⁻¹)
Fe I				Ni I			
3719.7, 3722.5	4.12e3	2.06e5	23.10 ± 0.05	3493.0	2.97e3	3.30e7	22.76 ± 0.08
3734.9, 3737.1	2.97e3	4.12e4	23.41 ± 0.15	3515.1	4.12e3	2.06e5	22.98 ± 0.06
3746 ^a	3.13e3	1.65e5	22.87 ± 0.05	3524.5	3.05e3	1.56e5	23.96 ± 0.03
3823 ^b	1.69e3	4.12e4	23.37 ± 0.15				

Notes. $v = 0.3 \text{ km s}^{-1}$ used to set all scale lengths.

^a The Fe I line designated 3746 includes lines at 3743.4, 3745.6, 3745.9, 3748.3, and 3749.5 Å.

^b The Fe I line designated 3823 includes lines at 3815.8, 3820.4, 3824.4, 3825.9, and 3827.8 Å.

to convert the fluxes we measured for three Ni I lines and four Fe I line groups to column densities at each spaxel. For the Fe I line groups, we summed the fluorescence efficiencies of the stronger lines to convert fluxes to column densities. The column densities are shown in Figures 5 and 6.

Note in these figures that the column densities of individual lines of a species at different wavelengths do not all have the same maximum. Differences in fluorescence efficiencies result in different strengths for lines of the same molecule (see Figure 2). In addition, depending on the heliocentric radial velocity of the comet, some lines will experience different amounts of fluorescence energy from the solar spectrum (the so-called Swings effect). Also, for the Fe lines, all of these column densities include multiple lines from different transitions (see the notes to Table 2; this is a complication caused by our low spectral resolving power). To the extent that the fluorescence efficiencies of the different transitions are correct, the different lines might contribute more or less to the combined line fluxes. Fe lines that might not have been included, or were added at a wrong assumed strength, will make some of the Fe line column densities less accurate. However, the spatial distribution of the photons of a particular line will be accurate for that one line, and, thus, the scale lengths we derive should be considered more correct than the overall production rates for Ni and, especially, Fe.

As these species are not seen in low resolving power observations of solar system comets, there are no published scale lengths for Haser models of these species. We computed grids of models with our Haser code to determine a set of scale lengths for the data in Figures 5 and 6. Best fits were defined as those with the smallest χ^2 values. The scale lengths are listed in Table 2. Inspection of Table 2 shows that the parent scale lengths are short relative to the scale lengths for the molecular species. Indeed, the parent scale lengths are all similar, at $\sim 3 \times 10^3 \text{ km s}^{-1}$. This short parent scale length is comparable to the size of a pixel. We do not have any information below this size. It would be possible for the parent scale length to be even shorter, possibly just above the surface of the nucleus.

We assumed an outflow velocity of the gas of 0.3 km s^{-1} to fit the data and derive the daughter scale lengths. We could not find daughter scale lengths that produced a model curve of a proper shape to fit the data points farther from the optocenter using the nominal solar system comet outflow velocities instead of these seemingly slow outflow velocities. The velocity is the same as was found with the radio observations above. We were only able to constrain the daughter scale lengths because of the relatively large FOV of the VIRUS IFU. However, inspection of Table 2 shows that there are

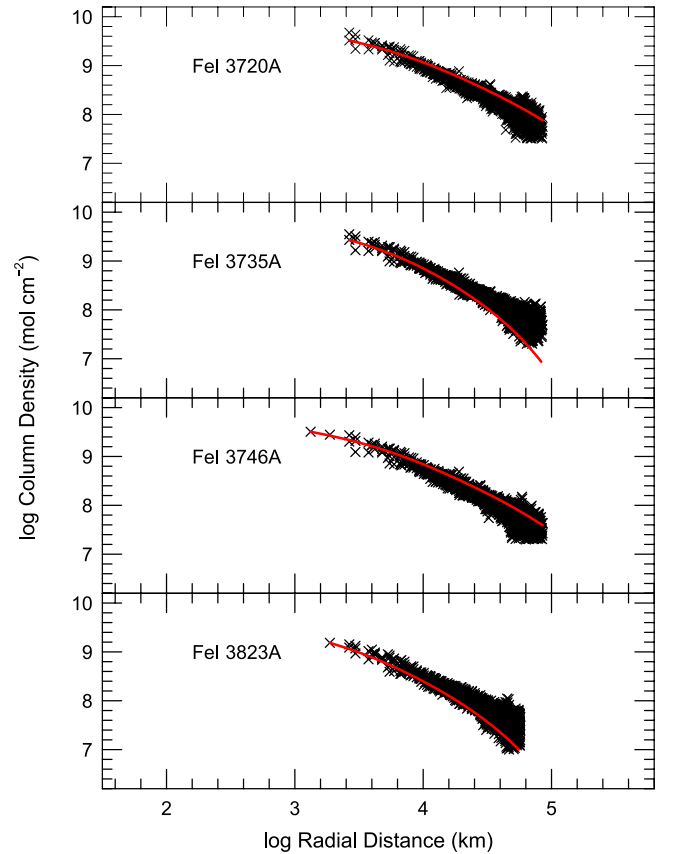


Figure 6. The column densities of four groups of Fe I lines are shown as a function of cometocentric distance. The model fits are marked with a red line. The error bars are again quite small, with the largest error bars being that in the outer regions of the Fe 3746 Å line, which is ± 0.15 .

discrepancies in the daughter scale lengths derived for different examples of each species. This is the result of even our large FOV being smaller than the needed daughter scale lengths. UVES and KCWI both had too small FOVs to determine these scale lengths. (The FOV of KCWI was $8'' \times 20''$ and for UVES was $1.8'' \times 7.5''$, whereas our FOV was $50'' \times 50''$.)

D. Hutsemékers et al. (2026) observed 3I at high spectral resolving power as it approached perihelion. They first observed Ni I at 3.78 au inbound. However, they did not observe any Fe I until the comet reached 2.64 au. R. Rahatganonkar et al. (2025) and W. B. Hoogendam et al. (2025) also detected Ni I at larger heliocentric distances before Fe I was detected perihelion.

Averaging our Fe I and Ni I observations for all lines included in our Table 2, we find a value for $\log(Q(\text{Ni})/Q(\text{Fe})) = 0.19$, similar to the values reported in D. Hutsemékers et al. (2026) for heliocentric distances comparable to our observations.

4. Conclusions

The excellent spatial resolution of VIRUS, coupled with an FOV of $50'' \times 50''$ and a geocentric distance of 1.83 au, allowed us to probe the coma of 3I in great detail. The accidental offset of the optocenter of the comet to the edge of the FOV meant that we probed to a large distance ($>85,000$ km) from the optocenter. This added new information to the extensive literature on 3I, even with a single epoch of observations. With the spatial information that we were able to obtain, we could trace the outflow of the gas, including molecular species and Fe and Ni. Assuming the molecular lifetimes are normal in the vicinity of the Sun, we concluded that the gas must be flowing outwards from the optocenter much more slowly than in the comae of typical comets, in agreement with radio telescope measurements of parent species' outflow velocities.

The presence of very strong Ni I and Fe I lines in spectra of 3I is an important difference from solar system comets. 3I was exceptional even compared to the other interstellar objects, 1I and 2I, due to its exceptionally high Ni I and Fe I (D. Hutsemékers et al. 2026). Wandering around in the interstellar medium should result in the body having high material strength, with Fe I and Ni I metal on its surface (J. M. Trigo-Rodríguez et al. 2025). However, the surface temperatures at the heliocentric distances that 3I was observed are too low to vaporize Fe or Ni in metallic form (J. Manfroid & D. E. J. Hutsemékers 2021). The very short parent scale lengths that we measure must indicate that Fe and Ni are coming directly off the nucleus in their metallic form or must have a very short-lived parent. This was also the conclusion about the origin of the Fe I and Ni I observed at high spectral resolving power (J. Manfroid & D. E. J. Hutsemékers 2021; D. Hutsemékers et al. 2026). Indeed, J. M. Trigo-Rodríguez et al. (2025) suggested that 3I has a composition that is a close match to a carbonaceous chondrite and might be the result of its elevated metallic abundance and abundant water ice.

If comets are leftovers from the formation of most planetary systems, and a high fraction are ejected from their formation nebula, there should be many such objects wandering around the Galaxy that can potentially cross through our solar system. Our Sun, like most planetary systems, probably formed in a cluster of infant stellar systems. The leftover debris of all those stars can, therefore, be influenced by nearby passing stellar systems. As the young stars orbit around the center of the Galaxy, the debris they have ejected will sometimes continue wandering in space, devoid of a star to which they are attached. Thus, unlike a comet in our solar system that can be influenced by the gravity and radiation of our Sun, these other interstellar comet-like objects may be going into and out of insolation from stars they pass.

The low outflow velocities, and therefore the short scale lengths, that we found for the typical cometary gas molecules also indicate something is different for 3I compared with normal comets. Once the ices have sublimed to the gas form, they should respond to sunlight in the same manner as for our solar system comets if the parents are identical. However, with

a very different parent star, it is possible that there are differences in the composition of the ices. As noted above, 3I is rich in CO_2 . N. Biver et al. (2026) suggested that a heavy molecular gas, such as CO_2 -rich gas, is what is slowing the outflow velocity, since CO_2 is much heavier than the predominant gas in the coma of solar system comets.

As new telescopes come online (e.g., the Rubin telescope D. Clery 2025) with large surveys, we should expect that the number of interstellar objects detected passing through our solar system will increase. Observations of these objects will yield important comparative information about how planetary systems form and potentially lose or gain material. Observations of 3I demonstrate the need for a wide variety of types of observations to try to understand similarities or differences with our solar nebula. Ultimately, not being sure where or when these objects formed will be our biggest impediment to using interstellar objects to constrain the formation of our solar system.

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