Main Belt Comets: ocean-water source closest to Earth?

Water during planet formation and evolution 2018
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Main Belt Comets in the context of Solar System formation

The traditional view of our Solar System is divided it into the inner region, where rocky planets and asteroids were formed, and the outer region where gas giants and icy minor bodies habit. These two regions are separated by the “snow line”, which represents the distance from the Sun where the temperature is appropriate for the formation and survival of icy bodies such as comets. In this context comets are remnants of the early stages of the Solar System and, likely, they are the most pristine bodies.

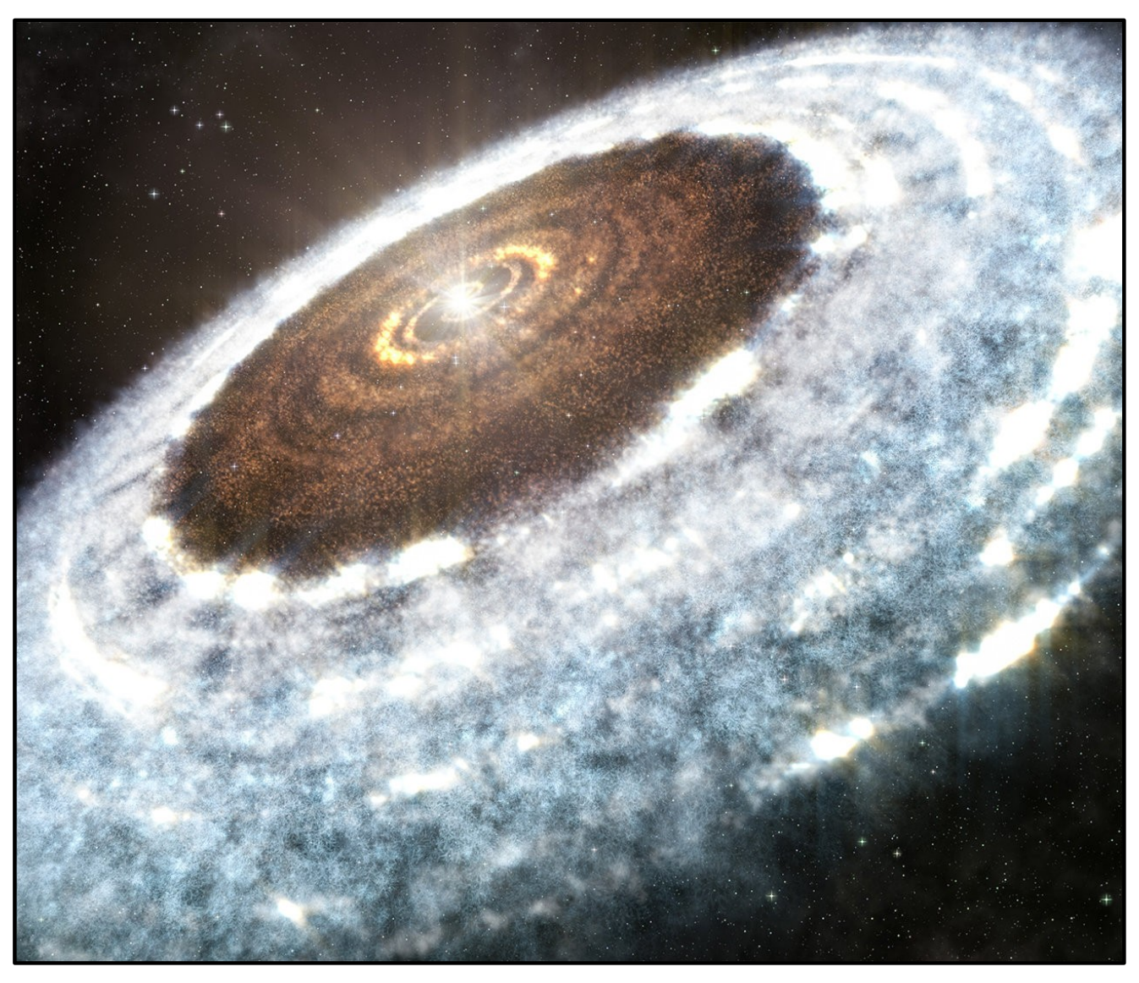


Fig 1: Artist impression of the snow line in a proto-planetary system. Image from NASA.

Understanding their nature and their evolution is a must to understand the history of our Solar System. Comets contain complex organic molecules, and may have played a key role in the transfer of water and organics from the interstellar medium to the early Earth, contributing to the origin of life (Hartogh et al. 2011, Jewitt et al. 2007). This interest is well illustrated by the fact that several space missions have targeted small bodies of the Solar System, and particularly comets like the very successful ESA Rosetta/Philae mission currently returning impressive scientific data that are revolutionizing our knowledge of comets.

The nucleus of a comet, typically a few kilometers in diameter, is essentially composed of water-ice mixed with carbon oxides, methane, ammonia, and dust particles. When the comet approaches the Sun, the ices sublimate, forming a gaseous and dusty coma. Solar radiation and wind blow this material to form spectacular cometary tails. Investigations of the chemical composition of comets are important for a variety of reasons. In addition to revealing the characteristics of comets themselves, the composition of comets holds unique clues to conditions in the early solar nebula and the Solar System’s formation processes, since comets remain the most pristine objects available for detailed studies. In particular, knowledge of the bulk chemical composition of comets and how the composition varies among individuals and/or with exposition to solar radiation can provide strong constraints on the composition and temperature of the proto-planetary nebula at the time solid bodies began to form some 4.6 billion years ago (Mumma et al. 1993). Depending on the region of formation in the proto-solar nebula, comets are currently stored in three main reservoirs: the Oort Cloud, the Kuiper Belt and the Main Asteroid Belt. In general terms, our understanding of comets is high, but some details remain unclear. For example, the injection of comets from the Oort cloud into the inner regions of the Solar System, or the relative proportion of comets formed at different distances from the Sun, are explained using models of planetary evolution, which are sensitive to models for the formation and evolution of the Solar System as a whole, and these are not well constrained. The influence of comets on the terrestrial planets in the early Solar System is also unclear. In early times, Earth was too hot to trap much water, so it is widely accepted that an external source of water was required: did the comets bring water and organics to Earth?.

The measurements of the isotope ratios of deuterium to hydrogen (D/H ratio) found in comets is not the same as in the Earth's oceans, at least for Long Period Comets coming from the Oort cloud. On the other hand, Jupiter Family Comets have shown in only one case the same D/H than on Earth’s oceans, for the comet 103P/Hartley 2. The rest of attempts to find this was unsuccessful, most of the time finding that this ratio is approximately double. In fact, one of the most important discoveries of Rosetta was the lack of Earth-like water in the 67P/Churymov-Gerasimenko (see Fig 2).

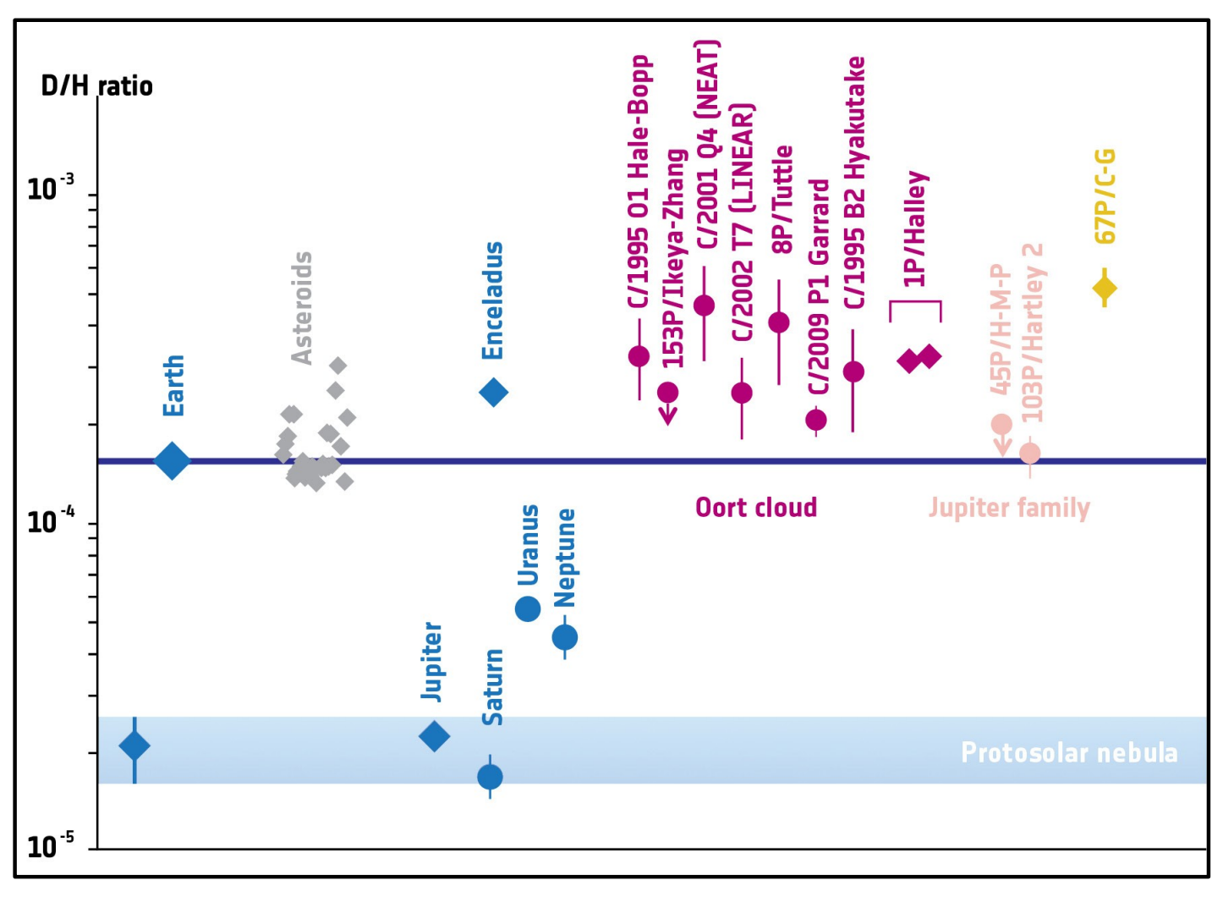
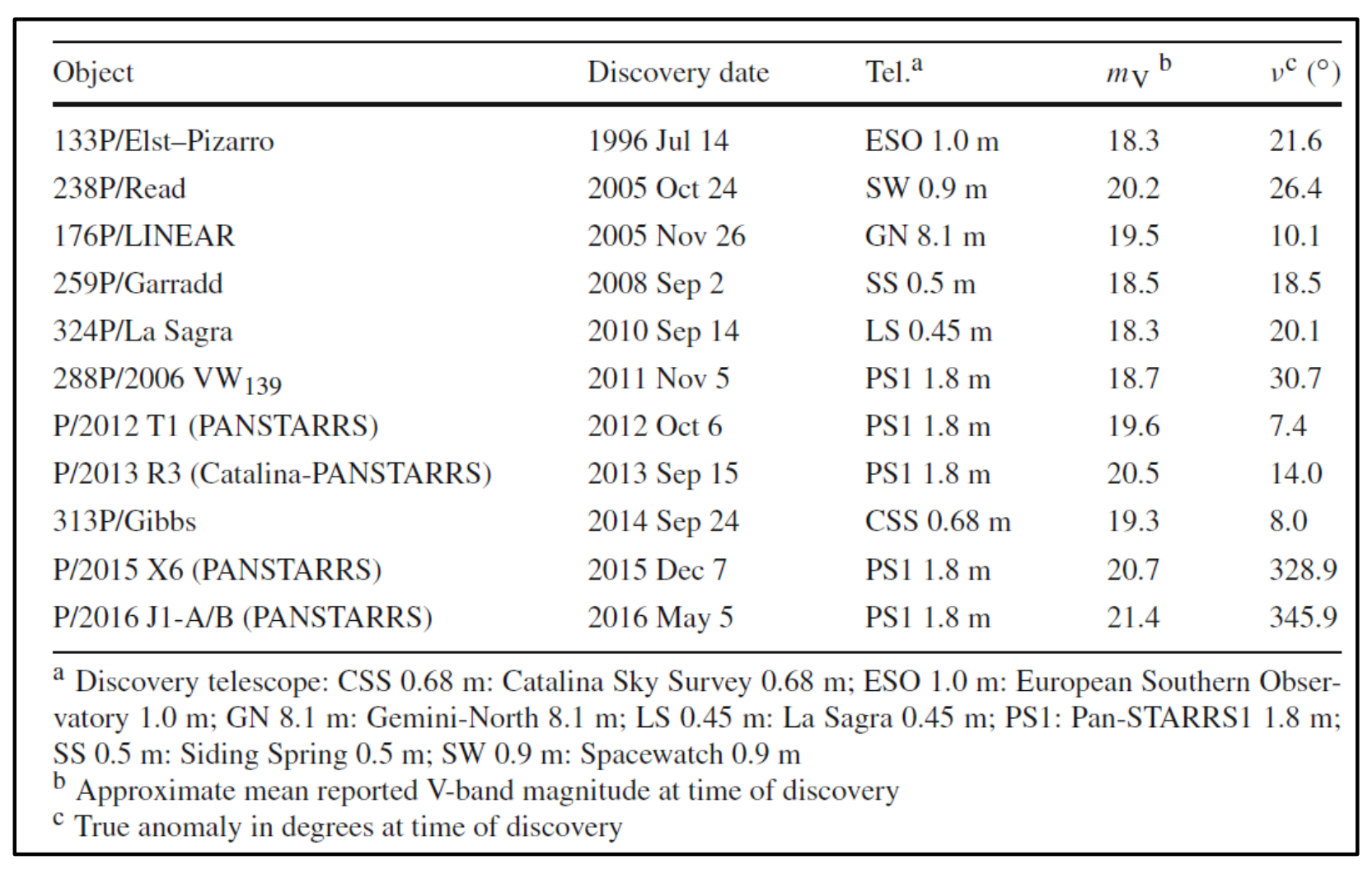


Fig 2: D/H ratios measured in various Solar System objects. Image from ESA.



Object	Discovery date	Tel.[a]	m_V [b]	ν[c] (°)
133P/Elst–Pizarro	1996 Jul 14	ESO 1.0 m	18.3	21.6
238P/Read	2005 Oct 24	SW 0.9 m	20.2	26.4
176P/LINEAR	2005 Nov 26	GN 8.1 m	19.5	10.1
259P/Garradd	2008 Sep 2	SS 0.5 m	18.5	18.5
324P/La Sagra	2010 Sep 14	LS 0.45 m	18.3	20.1
288P/2006 VW_{139}	2011 Nov 5	PS1 1.8 m	18.7	30.7
P/2012 T1 (PANSTARRS)	2012 Oct 6	PS1 1.8 m	19.6	7.4
P/2013 R3 (Catalina-PANSTARRS)	2013 Sep 15	PS1 1.8 m	20.5	14.0
313P/Gibbs	2014 Sep 24	CSS 0.68 m	19.3	8.0
P/2015 X6 (PANSTARRS)	2015 Dec 7	PS1 1.8 m	20.7	328.9
P/2016 J1-A/B (PANSTARRS)	2016 May 5	PS1 1.8 m	21.4	345.9

[a] Discovery telescope: CSS 0.68 m: Catalina Sky Survey 0.68 m; ESO 1.0 m: European Southern Observatory 1.0 m; GN 8.1 m: Gemini-North 8.1 m; LS 0.45 m: La Sagra 0.45 m; PS1: Pan-STARRS1 1.8 m; SS 0.5 m: Siding Spring 0.5 m; SW 0.9 m: Spacewatch 0.9 m
[b] Approximate mean reported V-band magnitude at time of discovery
[c] True anomaly in degrees at time of discovery

Table 1: Main Belt Comets discovered so far (Snodgrass et al. 2017).

Other ideas on the water content of Earth are related to the impact of asteroids containing hydrated minerals, or to a new class of objects known as Main Belt Comets (MBCs) where water-ice sublimation seems to be the driver of their activity. In 1996 was discovered the first MBC, 133P/Elst-Pizarro. Nowadays, ten more members have been detected, for the complete list of them at time of writing see table 1. Due to this possibility of the water-ice sublimation, MBCs provide one of the most debated and open questions in cometary science today. The existence of water in the Main Asteroid Belt should not be a surprise. Actually, some meteorites show evidence of clay minerals and serpentines, proving that they have been bathed in liquid water at temperatures close to triple point. In addition, half of the outer belt asteroids show absorption features, which can be attributed to the presence of hydrated minerals. Therefore, MBCs are of special interest within the broader class of active asteroids as they indicate the possible presence of water in bodies of a size that are very common in the asteroid belt, implying that there is potentially a large population of icy bodies there. Thus, they could be representative of source of terrestrial planets’ volatiles and of the Earth’s oceans in particular, and can therefore be extremely astrobiologically significant. Having said that, it is still unclear as to how this water is still there due to the fact that the dynamical studies on the Main Belt objects reveal that them are native from this region, so the water, in principle should completely disappear. MBCs are therefore interesting bodies to test different scenarios of Solar System formation and evolution, such as the recent “Grand Tack” model (Walsh et al. 2011), as an uniquely accessible population of icy bodies native to their current location.

What does drive the activity of Main Belt Comets?

Some asteroids produce comet-like appearance due to dust ejecta, they are called Active Asteroids. The causes of the activity in these objects are vary and many : impact ejection and disruption, rotational instabilities, electrostatic repulsion, radiation pressure sweeping, dehydration stress and thermal fracture, and the most promising one: water-ice sublimation, for a complete description of these mechanisms see Jewitt et al. (2015). Then, we refer to MBC when an active asteroid exhibits activity determined to likely be due to ice sublimation. In this regard, there are two ways to confirm ice sublimation: 1) from dust modeling, where is possible to distinguish between different activation mechanism (see Figs 4 and 5) or 2) confirmation of recurrent activity near perihelion with intervening periods of inactivity.

The CN radical is used as a proxy of water production, in the case of Jupiter Family Comets this relationship established as $Q(H_2O)/Q(CN) \sim 350$. However, in the case of MBCs this ratio should be much lower. Despite to the large number of attempts, no outgassing has been detected yet in any MBC, and then only upper limits have been established using spectroscopy observations on large telescopes such as the Very Large Telescope, Gemini, Gran Telescopio Canarias and Keck. Among all these attempts, Hsieh et al. (2012) found the upper limits of $Q(CN)=1.3x10^{23}$ mols s^{-1} and $Q(H_2O)=1x10^{26}$ mols s^{-1} using Gemini telescope for the MBC 288P, which are the largest value so far. For a complete list of these attempts and their results see Snodgrass et al. (2017) table 2. Thus, despite to have strong evidences about the water-ice sublimation, this is still an open question.

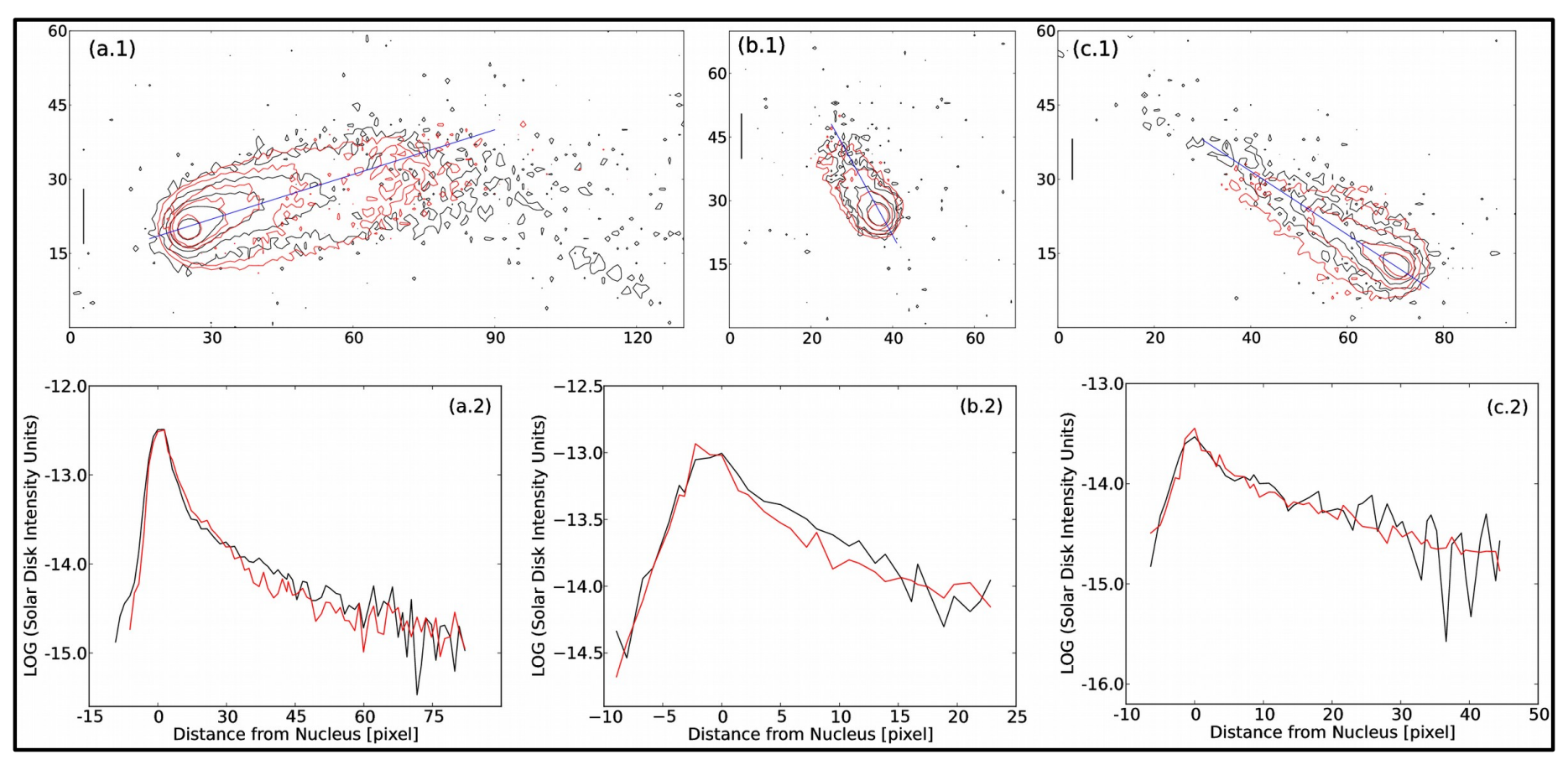


Fig 3: Dust modeling performed by Pozuelos et al. (2015) for the asteroid 313P/Gibbs. The results suggest the water-ice sublimation as the driver mechanism of the activity. Thus, it is considered a MBC.

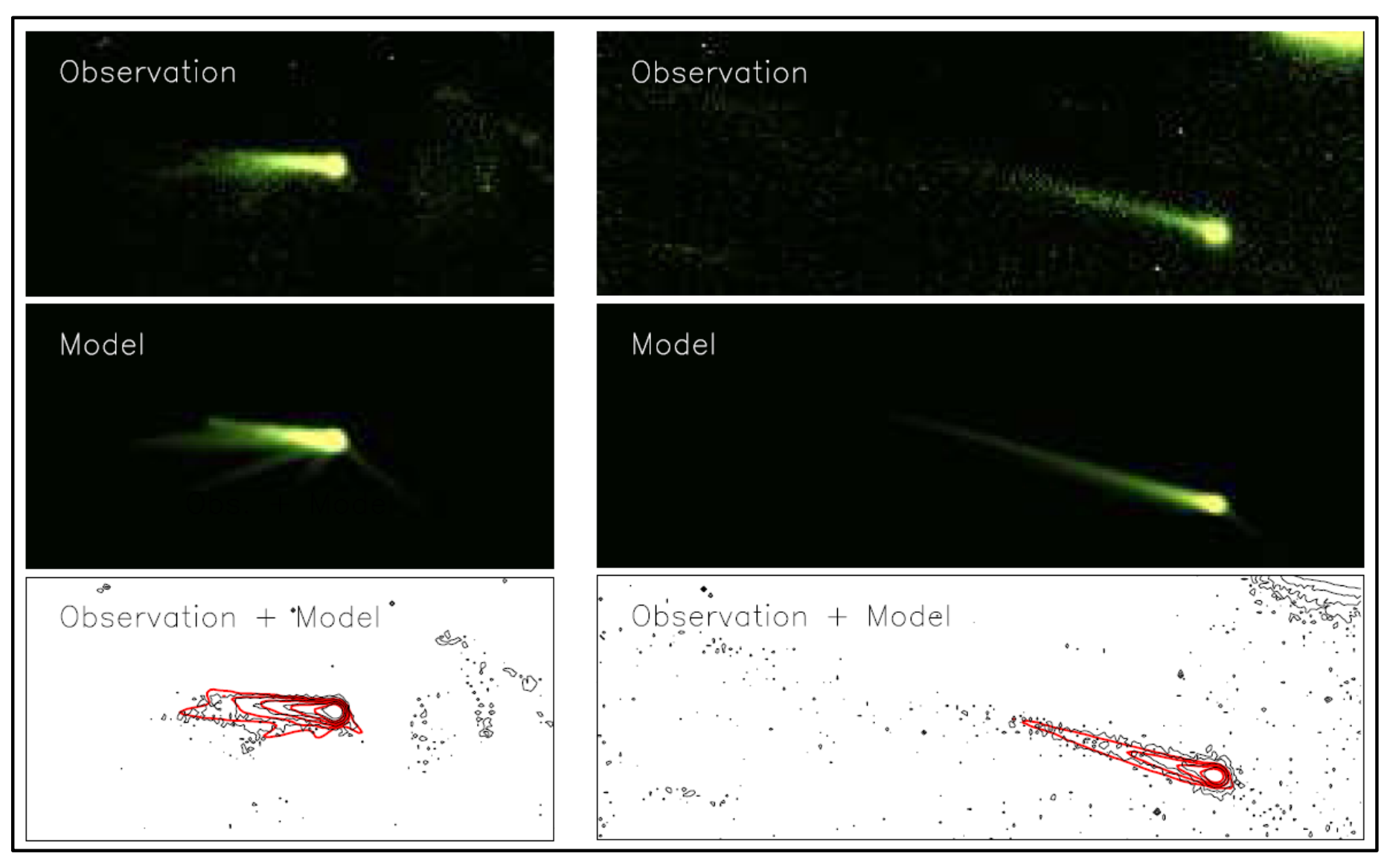


Fig 4: Dust modeling performed by Moreno et al. (2014) for the asteroid P/2013 P5 (PanStarrs). The results suggest the rotational disruption as the cause of the activity. Therefore it was considered Active Asteroid.

Their dynamical nature and controversial origin

In order to understanding whether these objects can be representative of ice-rich asteroids native from the main belt or they have been implanted from outer regions of the Solar System it is particularly important to constrain their origin. However, this task is not easy and different results have been obtained. Studies on the dynamical stability of MBCs have been found to be over 10^8 years or even more (e.g., Haghighipour et al. 2009) suggesting that these objects were formed in situ where we see them today in the asteroid belt. However, some of them are rather unstable on short time scales of 10^7 years implying that they may be recently emplaced (Jewitt et al. 2009). In fact, Hsieh et al. (2016) showed that pathways exits that are capable of temporarily implanting JFCs in the main belt considering only the dynamical influence of major planets and the Sun. On the other hand, recent studies propose that some JFCs could be interlopers from the asteroid belt (Fernandez et al. 2015), suggesting that these pathways appear to work both ways. In addition, in some cases it has been found relationship with known asteroid families, where the members come from the catastrophic disruption of large parent bodies.

The Castalia Mission: rendezvous with a Main Belt Comet

Earth-based observations, including the use of existing and planned space observatories, are insufficient to get even close to address and solve the important planetary science questions related to the MBCs. Therefore, a space mission is the only adequate approach. In this context, *Castalia* is a proposed mission to visit the MBC 133P/Elst-Pizarro (Snodgrass et al. 2017b) . In many ways, *Castalia* is considered a successor to ESA’s *Rosetta* mission, and it will allow direct comparison between very different classes of comet. The scientific goals of this mission are: To characterize a representative member of MBCs, a newly-discovered Solar System family, by in situ investigation; to understand the trigger and the physics of their cometary activity; to directly detect water in the asteroid belt; to measure its D/H ratio to test whether MBCs are a viable source of Earth’s water; and to use MBCs as tracers of our planetary system formation and evolution. To know more about this mission we refer the reader to Snodgrass et al. 2017b.

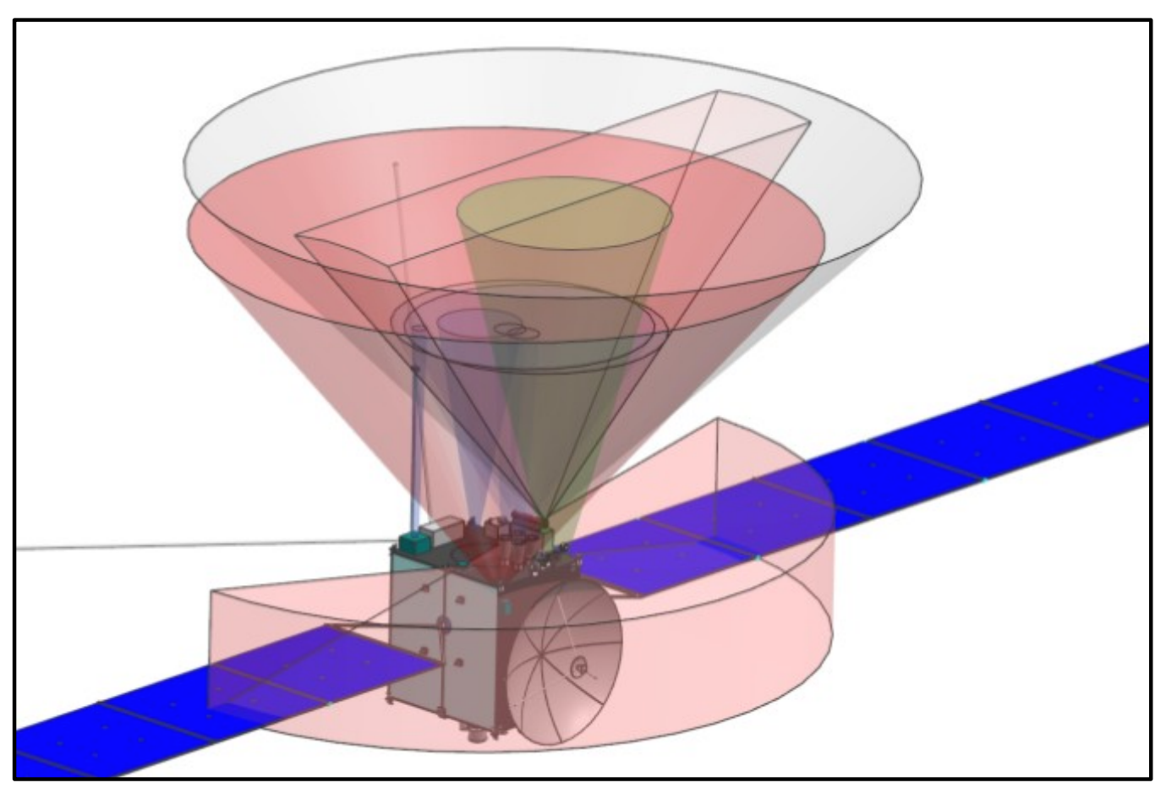


Fig 5: Castalia spacecraft, with the FOV of remote sensing instruments (Snodgrass et al. 2017b).

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