Main Belt Comets and other “Interlopers” in the Solar System

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Abstract: According to traditional ideas about the formation of the Solar System starting from a protoplanetary disk of gas and dust, a well-defined distribution of planets and minor bodies is expected: (a) volatile-poor rocky bodies (terrestrial planets and asteroids) in the inner part of the Solar System and (b) volatile-rich objects (gaseous giant planets, comets, Centaurs, and trans-Neptunian objects) in the outer part. All these bodies are expected to orbit near a plane (the ecliptic) coinciding with that of the protoplanetary disk. However, in the modern Solar System many bodies are present that do not respect this simplistic expectation. First of all, there are the so-called Main Belt Comets, apparently asteroidal objects that show an activity similar to that of comets. In addition, there is an object (and several others very probably exist), which, despite its S-type spectrum characteristic of rocky bodies, is found on a cometary orbit. Finally, there are many asteroids on very inclined orbits with respect to the ecliptic. These very interesting groups of objects, which, according to the traditional point of view, could be collectively seen as some sort of “interlopers” of the Solar System, will be discussed in this review, which offers descriptions of their properties and their likely origin. In this respect, the possibility is discussed that many active asteroids (such as those belonging to the Taurid Complex) are the result of the fragmentation of large comets that occurred in the relatively recent past.

Keywords: minor planets; comets: general; asteroids: general; Oort cloud; astrophysics—Earth and planetary astrophysics

1. Introduction

Comets are minor bodies of the Solar System, formed in the external parts of our system and consisting mainly of ices, which at least once in their life enter the internal parts of the Solar System, assuming a typical morphology (characterized by the presence of a coma and one or more tails) that distinguishes them. In this dynamic property they differ from other icy members of the Solar System (such as several satellites of the outer planets, the Centaurs and the trans-Neptunian objects or TNOs) whose orbits, in the absence of perturbations, never bring them close to the Sun. Comets also differ from asteroids, which are other minor bodies of the Solar System made up of mainly rocky materials, as they formed in the region between the orbits of Mars and Jupiter.

Despite this simple definition, since the internal composition of a body is rarely known, in many cases it is practically impossible to establish whether a body is actually a comet (or more precisely a cometary nucleus) or an asteroid.

Until a few decades ago, it was believed that comet nuclei were no larger than 60 km (as in the case of comet Hale–Bopp [1]), so a body larger than this threshold most likely had to be an asteroid. Today we know, instead, that at least two cometary nuclei exist, namely C/2002 VQ94 LINEAR (with a diameter close to 100 km [2]) and the recent C/2014 UN271 (also known as Bernardinelli–Bernstein, with a likely diameter of 150 km [3]), that greatly exceed this threshold. On the other hand, even in the past, the inner Solar System could have been visited by comets of much larger dimensions than those known so far, such as in
the case of the giant comet Sarabat (C/1729 P1), with a size between 100 and 300 km [4]. On the other hand, according to various authors (see for example [5]), some TNOs that currently orbit beyond the orbit of Neptune (in particular those in the scattered disk of the Edgeworth–Kuiper Belt), following orbital resonances with this planet could in the future be pushed towards the internal regions of the Solar System; since the largest TNOs can exceed 1000 km, if such objects experienced this fate, they would become gigantic comets. In addition, Centaurs are intermediate stage objects on the path for dynamical transfer from the scattered disk to the Jupiter family group, and some of these (e.g., Chiron) are very large. Therefore, size does not represent a valid parameter to discriminate between comets and asteroids.

Until a little while ago it was believed that cometary nuclei were the only bodies in the Solar System capable of leaving a dust trail along their orbit. This therefore represented a useful method for identifying extinct or quiescent cometary nuclei, distinguishing them from asteroids [6]. Today, however, we know that dust grains can be ejected or simply lifted off from the surface of an asteroid by various processes [7–9]. Once detached from the surface, these grains, pushed by the pressure of solar radiation, can then escape the weak gravitational attraction of the asteroid, forming a trail of dust similar to those of comets [8].

Unfortunately, even the determination of the axial rotation period of a body is not useful for determining whether that body is an asteroid or a cometary nucleus [6].

The determination of the visual geometric albedo \( p_V \) is also of little use. In fact, the albedo of cometary nuclei is generally very low, ranging between 0.02 and 0.06 for almost all comets [10]. The problem is that a large percentage of all asteroids have comparable values of the visual albedo [11]. Thus, a low \( p_V \) value is not indicative of a cometary origin; on the other hand, a high albedo does not provide a sure indication of an asteroidal origin, since (see Section 2) there is a small but non-zero number of high-albedo objects that meet the definition of a comet given above.

The analysis of the reflection spectrum of a body certainly has greater diagnostic power in this regard. In fact, although a spectrum of classes C, P, T, and D, typical of cometary nuclei (see [12] and references therein), does not provide certainty regarding a cometary origin (due to the large number of dark asteroids belonging to these spectral classes), a spectrum of taxonomic type S was until recently considered as a sure indication that the body under examination was an asteroid coming from the innermost zone of the asteroid Main Belt (MB). Unfortunately, however, as discussed in Sections 2 and 3, even this rule is not without exceptions, and it must also be remembered that observations do not provide many reliable spectra useful for a taxonomic classification; therefore, again, it is not possible to obtain certain indications about the origin and nature of the bodies under study.

From a dynamic point of view, a parameter that is often used to identify the asteroidal or cometary nature of an object is the Tisserand parameter with respect to Jupiter. The Tisserand parameter with respect to a given planet (see [13] for the exact definition) is a parameter that characterizes the motion of a third body interacting gravitationally with the planet and the Sun. Assuming that the planet has a circular orbit and that the third body has a negligible mass compared to the other two bodies, then neglecting the interaction with the other planets, the parameter remains constant over time, regardless of the perturbations in the orbit of the third body induced by the second body. In practice, the Tisserand parameter, while not remaining constant, is however subject to very limited variations, so it can be used to evaluate whether two different observations can refer to the same body.

It can be shown [14] that the relative velocity \( u \) of the body with respect to the planet, when the former crosses the orbit of the latter, is related to the Tisserand parameter \( T_p \) and to the orbital velocity \( v_p \) of the planet by Equation:

\[
    u = \sqrt{3 - T_p v_p}.
\]

Therefore, the Tisserand parameter determines the relative velocity of encounter between the body and the planet.
In the case of the Solar System, since the most important perturbing body of solar gravity is Jupiter, the Tisserand parameter with respect to Jupiter as perturbing body (\(T_J\)) is of particular importance for the dynamic description of the system; it allows, for example, to distinguish asteroids (usually characterized by \(T_J > 3\)) from Jupiter-family comets (which, in general, have \(2 < T_J < 3\)) and from Halley-like and Oort cloud comets (typically with \(T_J < 2\)). As shown by Equation (1), objects with \(T_J > 3\) never intersect the orbit of Jupiter, always remaining inside (as in the case of the vast majority of asteroids) or outside (as in the case of Centaurs and TNOs). On the contrary, bodies with \(T_J < 3\) intersect Jupiter’s orbit with various relative speeds and correspond to short- and long-period comets.

However, it should be remembered that this dynamic subdivision between comets and asteroids is only indicative, as there are bodies with a cometary appearance that are found on typically asteroidal orbits with \(T_J > 3\) (see Section 2), as well as objects with an asteroidal appearance located on orbits with \(T_J < 3\) and therefore typically cometary [15].

In light of the above discussion, it is clear that there is no sharp boundary between comets and asteroids. In fact, most comets, which we could define as “typical comets” (or “classical comets”), are characterized by well-defined characteristics that distinguish them, in particular: (a) the emission of gas and dust from the nucleus due to the sublimation of ice; (b) a low albedo accompanied by a spectral class indicative of a surface composition rich in organic material in the form of a very dark crust; (c) sizes typically smaller than a few tens of kilometers; and (d) an orbit with fairly high orbital eccentricity characterized by \(T_J < 3\).

These are the characteristics of the comet model that up to twenty years ago was believed to be able to describe without exception all the comets of the Solar System. However, today we know that, in addition to these typical comets, there are also objects that we could define as “atypical comets”, as they show a certain cometary activity, but have dynamic (\(T_J > 3\)) and superficial characteristics (high albedo and S-type spectra) that assimilate them to asteroids. Beyond their differences, these two types of comets are both composed of ices mixed with refractory (rocky and/or carbonaceous) materials in the form of objects that probably range in size from dust grains to boulders.

In the next two sections, I will describe these atypical comets, which evidently represent interesting exceptions, some sort of interlopers, in the context of the simple comet model reported above. In particular, Section 2 will treat the active objects characterized by \(T_J > 3\) and in some cases also by a high albedo (Oljato), as well as objects of this type that have probably become extinct (Ryugu); Section 3 will deal with active objects, such as C/2014 S3 (PANSTARRS), which have \(T_J < 2\) (and therefore typically cometary dynamic properties) but a high albedo and a rocky spectrum. In Section 4, I will describe bodies with completely asteroidal characteristics but with very inclined orbits with respect to the ecliptic. The existence of these objects, taken individually, does not present any problems; their peculiarity, however, lies in the fact that their relatively large number does not seem to be the result of either gravitational perturbations of the planets in their current configuration or of collisions between asteroids. In Section 5, I will discuss a possible evolutionary scheme capable of providing a unitary explanation of the existence of all these interlopers in the Solar System. Finally, in Section 6, the conclusions and possible future developments of this study will be drawn.

2. Main Belt Comets and Atypical Comets

As already mentioned in the Introduction, there are objects which, despite having orbital and surface characteristics of a typical asteroid, show a relatively weak activity, like that of comets, characterized by episodes of dust particle ejection which give rise to the formation of a coma and/or tails or simply dust trails. These bodies are called active asteroids (see for example [16]). In these cases, the activity may be due to various causes: collisions, rotational mass loss, thermal disintegration, the electrostatic effect, or ice sublimation [16]. When the activity is due to ice sublimation, these objects are called Main Belt Comets (MBCs) [17]. In fact, as shown in Table 1, all these objects have values of the
semi-major axis—between 2.0 au and 3.2 au—typical of the bodies of the MB; moreover, in most cases the perihelion and the aphelion distance from the Sun also fall within the MB.

Table 1. Physical properties of the currently known MBCs. The table reports the name of the object as well as the eccentricity (e), the semi-major axis (a), the perihelion (q) and aphelion (Q) distances from the Sun, the Tisserand parameter with respect to Jupiter (T_J), the geometric albedo (p_v), and the spectral type (ST). In this last column, (S) indicates a SMASSII spectral type [18], while (T) stands for a Tholen spectral type [19]. Apart from P/2020 O1 (studied by Kim et al. [20]), all the remaining objects were reported by Jewitt and Hsieh [21], which the reader should consult for references to the studies of the various objects. Note that practically all of these objects have an aphelia beyond 3 au and in most cases even beyond 3.5 au, while the average eccentricity of these MBCs is 0.28. The data reported in this table were taken from the NASA/JPL Small-Body Database site (https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/).

| Name                                      | e      | a (au) | q (au) | Q (au) | T_J | p_v  | ST  |
|-------------------------------------------|--------|--------|--------|--------|-----|------|-----|
| 2201 Oljato (1947 XC)                     | 0.71278| 2.17550| 0.62484| 3.72615| 3.298| 0.4328| Sq (S) |
| 4015 Wilson–Harrington (1979 VA)          | 0.63175| 2.62498| 0.96664| 4.28332| 3.082| 0.05  | CF (T) |
| 7968 Elst–Pizarro (1996 N2)               | 0.15653| 3.16549| 2.66999| 3.66100| 3.184| 0.06  | –    |
| 118401 LINEAR (1999 RE70)                 | 0.19346| 3.19936| 2.58040| 3.81832| 3.165| 0.07  | –    |
| 238P/Read (2005 U1)                       | 0.25333| 3.16169| 2.36074| 3.96263| 3.153| –     | –    |
| 259P/Garradd (2008 R1)                    | 0.34153| 2.72744| 1.79594| 3.65894| 3.217| –     | –    |
| 300163 (2006 VW139)                       | 0.20073| 3.04889| 2.43689| 3.66090| 3.204| –     | –    |
| 313P/Gibbs (2014 S4)                      | 0.24168| 3.15435| 2.39200| 3.91669| 3.133| –     | –    |
| 324P/La Sagra (2010 R2)                   | 0.15379| 3.09376| 2.61798| 3.56953| 3.100| 0.01  | –    |
| 358P/PANSTARRS (2012 T1)                  | 0.23612| 3.15546| 2.41038| 3.90053| 3.134| –     | –    |
| 427P/ATLAS (2017 SS)                      | 0.31304| 3.17084| 2.17822| 4.16345| 3.092| –     | –    |
| 248370 (2005 QN173)                       | 0.22555| 3.06412| 2.37301| 3.75524| 3.193| 0.054 | –    |
| P/2013 R3 (Catalina-PANSTARRS)            | 0.27345| 3.03294| 2.20359| 3.86230| 3.184| –     | –    |
| P/2015 X6 (PANSTARRS)                     | 0.16962| 2.75458| 2.28734| 3.22182| 3.319| –     | –    |
| P/2016 J1-A (PANSTARRS)                   | 0.22826| 3.17208| 2.44801| 3.89615| 3.113| –     | –    |
| P/2016 J1-B (PANSTARRS)                   | 0.22823| 3.17200| 2.44806| 3.89595| 3.113| –     | –    |
| P/2018 F3 (PANSTARRS)                     | 0.41590| 3.00712| 1.75647| 4.25777| 3.096| –     | –    |
| P/2021 A5 (PANSTARRS)                     | 0.13981| 3.04693| 2.62094| 3.47292| 3.147| –     | –    |
| P/2020 O1 (Lemmon-PANSTARRS)              | 0.11982| 2.64635| 2.32927| 2.96343| 3.376| –     | –    |

In MBCs, the sublimation of ice is the most plausible cause of dust production; in fact, this activity, often quite prolonged, is repeated for a certain number of revolutions always near the perihelion [17], exactly as it happens for classical comets. This is clearly shown in Figure 1, where it is seen that, in particular, the activity occurs mainly after the perihelion, as also reported by Ferrin et al. [22]. According to Hsieh [17], this is exactly what one would expect due to the non-negligible time needed for the thermal wave to cross the ice-free surficial crust that each object possesses (see discussion below) and to reach the buried ice, triggering its sublimation.
A notable example of MBC is 313P/Gibbs (see Figure 2), which was one of the first objects of this type to be discovered in 2014. This comet has a nucleus with a radius of 0.5 km [24] and shows a fan-shaped dust tail and, in some images, also a very faint elliptical coma [25]. The dust, composed of grains of 50–100 microns in diameter, is produced at a rate of 0.2–0.4 kg/s [24]. The long-lasting dust production around the perihelion and especially the repetition of this production in the two observed returns suggest that the activity is due to sublimation. Indeed, according to Jewitt and colleagues [24], the equilibrium sublimation of dirty water ice from an exposed patch, covering only 0.1% of the nucleus surface, is the most convincing mechanism accounting for the measured dust production rate. This cometary-like activity is also suggested by the presence of non-gravitational effects in the motion of this object, detected by Hui and Jewitt in 2017 [26].
Figure 2. Images of 313P/Gibbs taken on different days of 2014 by: the Keck I telescope at Mauna Kea, Hawaii (October 2); the Danish telescope at La Silla, Chile (October 22); and the Hubble Space Telescope (October 14 and 28). The yellow arrow in each panel shows the direction to the projected antisolar vector, while the green arrow indicates the projected anti-velocity vector. In each panel north is up and east is on the left. Note the appearance quite similar to that of a classical comet, despite the considerably lower activity of this object, also characterized by the absence of detectable gaseous emission. This last feature is common to all MBCs except one (see text). (Original source: Figure 2 of [24]).

In addition to 313P/Gibbs, other MBCs have been discovered in recent years and are listed in Table 1. To these active asteroids one can add 34 objects, listed in Table 2, which belong to the Taurid Complex and have been studied by Ferrin and Orofino [27] through the analysis of their secular light curves. This analysis indicated that in these objects the activity is cometary, as it is recurrent near the perihelion. In Table 2 is also reported the anomalous comet 249P/LINEAR, described by Fernandez et al. [28], whose orbit is much more similar to that of a near-Earth asteroid than to that of a classical comet. In all likelihood, 249P/LINEAR belongs to the Taurid Complex; in fact, for this object the value of the D parameter, which measures the orbital differences of the body with respect to the comet Encke, progenitor of the complex, is indicative of the possibility that 249P/LINEAR is dynamically linked to the group and most likely has the same origin, as discussed in Section 5 (for details on the D-criterion for the attribution of the membership to the Taurid Complex, see the thorough discussion in [27]).
Table 2. Physical properties of the members of the Taurid Complex [27]. The table reports the name of the object as well as the eccentricity (e), the semi-major axis (a), the orbital inclination (i), the D parameter, the Tisserand parameter with respect to Jupiter (T_J), the geometric albedo (p_v), and the spectral type (ST). In this last column, (S) indicates a SMASII spectral type [18], while (T) stands for a Tholen spectral type [19]. High albedos are expected for 16960 and 612050 due to their spectral types. Note that 2101 Oljato is in common with the list reported in Table 1. Data taken from the NASA/JPL Small-Body Database site.

| Name               | e    | a (au) | i (°) | D   | T_J  | p_v  | ST   |
|--------------------|------|--------|-------|-----|------|------|------|
| 2101 Adonis        | 0.76 | 1.87   | 1.3   | 0.11| 3.551| —    | —    |
| 2201 Oljato        | 0.71 | 2.17   | 2.52  | 0.12| 3.298| 0.4328| Sq (S)|
| 2212 Hephaistos    | 0.84 | 2.16   | 11.5  | 0.13| 3.099| 0.163 | SG (T)|
| 4183 Cuno          | 0.63 | 1.98   | 6.7   | 0.20| 3.571| 0.097 | Sq (S)|
| 4486 Mithra        | 0.66 | 2.19   | 3.03  | 0.16| 3.338| 0.297 | —    |
| 5143 Heracles      | 0.77 | 1.83   | 9.02  | 0.14| 3.582| 0.227 | O (S)|
| 5731 Zeus          | 0.65 | 2.26   | 11.42 | 0.22| 3.277| 0.031 | —    |
| 6063 Jason         | 0.76 | 2.21   | 4.9   | 0.06| 3.185| 0.21  | —    |
| 8201               | 0.71 | 2.53   | 9.55  | 0.20| 3.024| 0.154 | O (S)|
| 16960              | 0.86 | 2.2    | 17.54 | 0.24| 3.000| High  | Sq (S)|
| 17181              | 0.67 | 2.37   | 10.7  | 0.21| 3.175| —    | —    |
| 30825              | 0.68 | 2.44   | 8.73  | 0.20| 3.127| —    | —    |
| 69230 Hermes       | 0.62 | 1.65   | 6.0   | 0.25| 4.020| —    | —    |
| 85182              | 0.78 | 2.22   | 3.12  | 0.06| 3.164| 0.242 | —    |
| 100004             | 0.70 | 2.6    | 16.0  | 0.29| 2.975| 0.0668| —    |
| 106538             | 0.76 | 2.42   | 10.33 | 0.16| 3.013| —    | —    |
| 153792             | 0.74 | 2.1    | 11.0  | 0.15| 3.314| —    | —    |
| 154276             | 0.69 | 1.7    | 8.7   | 0.20| 3.872| 0.143 | —    |
| 162195             | 0.77 | 1.6    | 5.89  | 0.18| 3.956| —    | —    |
| 189008             | 0.79 | 2.17   | 8.08  | 0.08| 3.178| —    | —    |
| 192642             | 0.77 | 2.64   | 6.79  | 0.19| 2.873| —    | —    |
| 405212             | 0.73 | 1.37   | 5.0   | 0.26| 4.487| —    | —    |
| 503941 (2003 UV11) | 0.76 | 1.45   | 5.92  | 0.23| 4.259| 0.376 | —    |
| 1999 VR6           | 0.76 | 2.19   | 8.52  | 0.10| 3.211| —    | —    |
| 2011 UD            | 0.78 | 2.03   | 8.83  | 0.10| 3.332| —    | —    |
| 380455             | 0.8  | 2.24   | 14.64 | 0.19| 3.081| —    | —    |
| 2004 TG10          | 0.86 | 2.23   | 4.18  | 0.06| 2.991| 0.018 | —    |
| D/1766 G1          | 0.85 | 2.66   | 7.9   | 0.20| 2.705| —    | —    |
| 169P/NEAT          | 0.77 | 2.6    | 11    | 0.21| 2.888| —    | —    |
| P/2003 T12         | 0.78 | 2.57   | 11    | 0.21| 2.894| —    | —    |
| 612050 (1997 GL3)  | 0.78 | 2.27   | 6.7   | 0.08| 3.106| High  | V (S)|
| 139359 (2001 ME1)  | 0.87 | 2.63   | 5.9   | 0.19| 2.673| —    | —    |
| 2001 QE34          | 0.73 | 2.16   | 5.6   | 0.09| 3.283| —    | —    |
| 252091 (2000 UP30) | 0.76 | 2.25   | 9.4   | 0.12| 3.152| —    | —    |
| 249P/LINEAR        | 0.82 | 2.77   | 8.4   | 0.24| 2.707| —    | —    |

Although, as already mentioned, there are strong indirect indications that the activity shown by the MBCs is due to ice sublimation, compelling spectroscopic evidence of such a process (through the identification of the gaseous species emitted by the object) is still missing, though large telescopes 8–10 m in diameter have been used in these studies [17]. The radical commonly used as a marker of gaseous emission is CN, which is a strong emitter in the visible spectrum, particularly in the range 3590–4220 Å. The mechanism of the production of this radical in cometary comas is reported by Jewitt and Guibert-Lepoutre [29]. So far, none of the studied MBCs, except for one (2201 Oljato—see Section 2.1), have shown measurable emissions of CN; for such objects, it is possible to evaluate only the upper limits of the CN production rate, which are between \(1.3 \times 10^{21}\) mol s\(^{-1}\) (133P/Elst–Pizarro) and \(1.3 \times 10^{24}\) mol s\(^{-1}\) (288P/2006 VW\(_{139}\)) [30].
Furthermore, if one assumes that for MBCs the $Q(H_2O)/Q(CN)$ ratio between the production rates of water vapor and CN is the same as that typically observed in classical comets (equal to 350 [31]), then, starting from the upper limits of $Q(CN)$, those of $Q(H_2O)$ can also be indirectly derived; the latter are roughly between $10^{25}$ and $10^{26}$ mol s$^{-1}$ [30]. However, it should be emphasized that these upper limits have been obtained under the hypothesis, very common in the literature, that for MBCs the $Q(H_2O)/Q(CN)$ ratio is identical to that observed in classical comets. However, according to many authors (for example [30,32]), this hypothesis does not seem entirely reasonable. In fact, MBCs likely formed closer to the Sun than classical comets. This would imply, due to the higher surface temperatures of MBCs compared to classic comets, that the former should have, with respect to the latter, a lower content of more volatile elements than water. Consequently, a higher $Q(H_2O)/Q(CN)$ ratio would be expected for MBCs than for classical comets.

Note that the upper limits of the $Q(CN)$ reported above are comparable with the lowest values of the CN production rate measured for classical comets; however, the latter show in most cases $Q(CN)$ values at least a few times greater than $10^{23}$ mol s$^{-1}$ [30,31]. A similar situation applies to the upper limits of $Q(H_2O)$, which do not exceed $10^{26}$ mol s$^{-1}$ [30], while classical comets have water production rates at 1 au typically greater than $10^{28}$ mol s$^{-1}$ [33].

From these data, it is clear that MBCs are generally less active than classical comets. Of course, it cannot be ruled out that this is due to the fact that we are observing a short period of their life in which they are active before their volatile supplies run out and they become extinct comets. However, as discussed below in this section, the reason for these differences may lie in the different characteristics of the surface layers of the two types of comets.

To assess the similarities or differences more accurately between MBCs and classical comets, a classification that takes into account the spectral type and albedo of the various objects appears very useful. For this purpose, four possible groups, listed in Table 3, can be considered.

### Table 3: Classification of active objects by ice sublimation with asteroidal orbits ($T_J > 3$) based on their albedo and their spectral characteristics.

| Group | Description | Properties |
|-------|-------------|------------|
| Ia    | Object, similar to a classical comet, with typical cometary albedo and spectrum | Low albedo ($A < 0.07$) coupled with C, P, T, and D spectral classes |
| Ib    | Object, similar to a classical comet, with low albedo but with spectrum not available | Only low albedo ($A < 0.07$) |
| IIa   | Atypical comet with typical silicaceous (rocky) spectrum | High albedo ($A \geq 0.07$) and S-type or similar spectral classes |
| IIb   | Atypical comet with spectrum not available | Only high albedo ($A \geq 0.07$) |

The objects of group I have albedos and spectral classes (or simply albedos) very similar to those of classical comets, from which they differ only in the type of orbit. On the contrary, the objects of group II differ from classical comets not only in their dynamic properties but also as regards the albedo and/or the spectral class.

While MBCs may differ from classical comets only in their dynamic characteristics (since they can have the same spectral type as classical comets), atypical comets differ from classical ones both in the type of orbit and in the surface composition and therefore constitute an interesting category, deserving of detailed studies.

Unfortunately, at present, in most cases, spectral types and albedos are unknown (see Tables 1 and 2), and therefore the classification defined in Table 3 does not allow us to reach statistically significant conclusions. Indeed, among the 19 MBCs listed in Table 1, only 6 have known and reliable albedos and/or spectral types (as reported in the NASA/JPL Small-Body Database site). However, this classification still provides some interesting indications. In fact, among the six MBCs mentioned above, one (4015 Wilson–Harrington)
belongs to group Ia; three (133P/Elst–Pizarro, 324P/La Sagra, and 2005 QN173) belong to group Ib; one (2201 Oljato) belongs to group IIa; and one (118401 LINEAR) belongs to group IIb.

The geometric albedo and spectral class are also known for 1 Ceres, which is sometimes reported in the literature as a MBC. This asteroid, which is the largest in the Solar System, is particularly interesting since it is the only one for which some authors \cite{34,35} have found evidence of activity clearly due to the sublimation of subsurface ice outcrops probably produced by a recent impact. However, this feature, combined with the obvious inconsistency between the relatively high albedo (0.09) and typically dark spectral class (C type), makes this asteroid very difficult to classify. For this reason, I have cautiously excluded this object from the group of MBCs.

An object in some respects similar to Ceres is 24 Themis. Indeed, water ice is present on its surface \cite{36}, and a very rarefied exosphere was recently discovered around the asteroid by Busarev et al. \cite{37}. However, Themis is not considered in the literature as a MBC, as this object has never shown signs of cometary-type activity \cite{29,38}.

In addition to the MBCs traditionally reported in the literature, the other 35 objects, listed in Table 2, belonging to the Taurid Complex \cite{27} can also be considered in this study. Although these objects have orbits that assimilate them to near-Earth asteroids rather than to the objects of the MB, in this work, they will also be called MBCs for economy and simplicity of notation, as well as in consideration of the fact that they generally reside within the MB for a fraction of their orbital period certainly greater than that of classical comets (see Section 2.1). Among the members of this group, 15 objects have known and reliable albedos and/or spectral classes (as reported in the NASA/JPL Small-Body Database) and can be classified using the scheme reported in Table 3. In this way, it is possible to see that among these none belongs to group Ia; three (5731 Zeus, 100004, and 2004 TG10) can be classified in group Ib; six (2201 Oljato, 4183 Cuno, 5143 Heracles, 8201, 16960, and 612050) belong to group IIa; and the other five (4486 Mithra, 6063 Jason, 85182, 154276, and 503941) belong to group IIb. Note that one object (2212 Hephaistos) does not appear unambiguously classifiable, while two others (16960 and 612050) have been reported as class IIa, because their albedos, although not measured, are expected to have high values based on their spectral type (see Tables 2 and 4 of \cite{11}).

Although the statistics are insufficient for definitive conclusions, all these examples suggest that, of all MBCs, relatively few are carbonaceous, as would be expected for classical comets (i.e., those few objects whose nucleus has been solved and studied). On the contrary, a far from negligible fraction consists of atypical comets, that is, objects characterized by a relatively high albedo (A ≥ 0.07) or even a high albedo coupled with a silicaceous composition (S-type and similar spectral class).

At this point one might wonder why all classical comets have low albedos, while among MBCs there are both low- and high-albedo objects. A possible explanation lies in the different crust types of the two types of objects. Although according to some recent theoretical modeling \cite{39} the situation seems different for certain objects, the crust of many classical comets should be of the irradiation mantle type \cite{40} (see Figure 3a) and was formed in the places of origin of these objects, namely the Oort cloud (OC) and the Edgeworth–Kuiper Belt. Here, in fact, the intensity of the solar magnetosphere is too weak to act as a shield against the continuous bombardment of the originally frozen surface of these bodies by galactic cosmic rays of energy much greater than MeV. As the experiments show \cite{41,42}, such bombardment damages the molecular bonds in the upper few meters of the nucleus, producing a preferential escape of hydrogen and an increase in the chemical complexity of the irradiated material, so that many complex carbon compounds can be formed. Eventually, a carbon-rich, hydrogen-depleted refractory mantle with a very low albedo is produced. For this reason, the albedo of classical comets typically has values between 0.02 and 0.06 \cite{10}. When these comets are introduced into the internal parts of the Solar System, the ice below the mantle sublimes and exerts a pressure which, at some points where the crust thickness is lower, can overcome the mechanical strength of this coat;
in this way, fractures are produced, through which the gas escapes from the nucleus, taking away with it considerable quantities of dust. Thus, the typical phenomena of cometary activity take place, which usually lead to the appearance of coma and tails.

Conversely, the crust of MBCs should be of the rubble mantle type [40,43]. This formed during the early stages of the formation of the Solar System, when these frozen bodies were sent into the innermost regions of our system (see Section 5). Here, the sublimation of the surface ices produced a porous residue made up of dust grains and pebbles too large to be carried away by the sublimating gas [40] (see Figure 3b). Over time, this coat typically became thick enough (about 2–5 m [22]) to seal the volatiles inside. Obviously, in this case as well, near the Sun the sublimation of the ice below the crust can exert a pressure capable of overcoming the tensile strength of the crust, fracturing the latter and

![Figure 3. Cross-sections through a piece of a cometary nucleus showing the formation process of the two types of cometary mantle: irradiation mantle (a) and rubble mantle (b). In (a), at initial time T0, the comet nucleus consists of a mixture of ices (yellow) and rocks (red). At a later time T1, cosmic rays irradiate the nucleus surface and begin to damage the molecular bonds in the icy material. As time passes (time T2) the degree of damage done by the cosmic rays increases. At the final time T3, the process is saturated. The cosmic rays with energy between several hundreds of MeV to many GeV, responsible for the most extensive damage in terms of depth, produce the greatest effects down to a few meters in ice, so the irradiation layer would be about this thick. The time difference T3–T0 is thought to be about 100 million years. In (b) at initial time T0, the comet nucleus consists of a mixture of ices (yellow) and rocks (red). At a later time T1, sunlight heats the nucleus surface from above and sublimates the ice. Dust particles and the smaller rocks are entrained in the gas flow (arrows) and are ejected from the nucleus. Large pieces of rock are too heavy to be lifted. By time T2, about half the surface is covered by large pieces of rock left behind as a lag deposit. At the final time T3, the surface is almost completely sealed by the rubble mantle. The time difference T3–T0 is uncertain but probably very short. Rubble mantles could form within a single orbit. (Credits: D. Jewitt, University of California at Los Angeles, USA).](image-url)
producing the emission of gas and dust. However, two characteristics of this type of crust can reduce these phenomena of cometary activity. First, the high porosity (>40% in laboratory simulations performed by Thiel et al. [43]), providing the sublimated gas small escape routes through the crust, tends to prevent a pressure increase beyond the critical breaking value represented by the tensile strength of the crust. Furthermore, the strength (exceeding 5 MPa in the experiments of Thiel and colleagues [43]) appears to be high enough to prevent large fractures. This would explain why these active asteroids do not show the phenomena of intense activity that are typical of comets.

As far as the albedo of the nuclei of MBCs is concerned, it is determined by the composition of the dust that is present, together with ice, inside them. To estimate the albedo of this dust, reference can be made to the works of Krishna Swamy et al. [44], Hanner et al. [45], and Sarmecanic et al. [46]. These authors have found that, to fit the infrared spectra of various classical comets, mixtures of silicates (with high albedos) and organic–carbonaceous materials (with low albedos) are always required: sometimes silicates prevail in the mixtures [44], and sometimes carbonaceous materials are the dominant component [46]. Assuming that the composition of dust in MBCs is the same as that observed in the coma of classical comets, it is reasonable to expect that, depending on the prevalence of one of the two dust species, bodies with both low- and high-albedo rubble mantles may exist. This is precisely what, as reported above, the observations seem to show.

Note that the classical comet and MBC models described above are oversimplified. In fact, these bodies do not always have a simple structure consisting of an innermost icy matrix containing dust and pebbles, surrounded by an irradiation mantle (in the case of classical comets) or by a rubble mantle (in the case of MBCs). It may indeed be the case that the underlying part of the mantle is not a simple, more or less homogeneous mixture of ice, dust, and pebbles, but has a composite structure of the rubble pile type [47], that is, comprising elementary, rocky, and/or carbonaceous blocks, held together inside an icy matrix able to produce cometary activity. For example, Ferrin and Orofino [27] have recently suggested that such a structure may have characterized the giant comet whose fragmentation originated the Taurid Complex (see Section 5); this would explain why some members of this complex are active while others are inactive.

Finally, it should be noted that, according to Hsieh [17], for selective effects the sample of MBCs could be much more numerous than what is indicated by the observations. In fact, the MBCs have orbital eccentricities on average greater than those of the outer MB asteroids, whose eccentricity distribution peaks at e~0.1 [17]. This conclusion, reached by Hsieh in 2016 on the basis of the objects known at that time, continues to be valid even today, as seen from Table 1. This means that the known MBCs have perihelion and aphelion distances from the Sun that are systematically lesser and greater than the corresponding distances of the typical objects of the outer MB; therefore, MBCs tend to experience higher temperatures at the perihelion and lower temperatures at the aphelion than the outer MB asteroids. Consequently, compared to other ice-rich objects with an asteroidal appearance present in the outer MB, MBCs are expected to present stronger sublimation-driven activity near the perihelion, also experiencing a slower depletion of their remaining volatile material elsewhere in their orbits. For this reason, such bodies, exhibiting brief periods of more intense activity, should be more easily identifiable by surveys than lower-eccentricity objects that might present more uniform, but generally weaker, activity along their orbits [17].

In any case, it should be emphasized that a perihelion close to the Sun represents only a necessary but not sufficient condition for an object to be active, because other factors (for example the thickness of the external crust and, obviously, the availability of volatiles) play an equally important role. For example, as observed by [27], 4197 Morpheus, an object of the Taurid Complex, is a typical inactive asteroid, even if its perihelion distance is quite small (q = 0.52 au), while 2201 Oljato, another member of the complex (q = 0.62 au) is active.
2.1. The Oljato Case

A MBC that is certainly very interesting in many respects is 2201 Oljato. This object, whose physical characteristics are reported in Table 4, since its discovery in 1947, has been classified as an Apollo-type high-albedo rocky asteroid. It spends approximately 36% of its orbital period within the asteroid MB. By comparison, this figure is just 15% in the case of Jupiter-family comet 67P/Churyumov–Gerasimenko, which, in turn, has a much longer MB crossing time than other classical comets belonging to the group of Halley-like and Oort cloud comets.

Table 4. Physical parameters of 2201 Oljato (1947 XC), classified as an Apollo asteroid, near-Earth object (NEO), and potentially hazardous asteroid (PHA). Data taken from the NASA/JPL Small-Body Database site.

| Parameter               | Value             | Uncertainty (1-Sigma) | Units |
|-------------------------|-------------------|-----------------------|-------|
| Eccentricity (e)        | 0.712780882406    | 0.000000031245        |       |
| Semi-major axis (a)     | 2.175495144458    | 0.000000088149        | au    |
| Perihelion distance (q) | 0.62483913193     | 0.000000065993        | au    |
| Aphelion distance (Q)   | 3.726146375698    | 0.00000015098         | au    |
| Inclination (i)         | 2.5219230408      | 0.00000037504         | deg   |
| Orbital Period (P)      | 3.208820176394    | 0.00000019503         | yr    |
| Diameter (D)            | 1.8               | 0.1                   | km    |
| Geometric albedo (p_V)  | 0.433             | 0.030                 |       |
| Rotation Period (P_R)   | 26                |                       | h     |
| Tisserand Param. (T_J)  | 3.298             |                       |       |
| Spectral Type Sq        |                   |                       |       |

The first indications of the possible cometary-type activity of Oljato came from the discovery of disturbances in the interplanetary magnetic field measured by the Pioneer Venus probe in 1980 and 1983 and attributed to material released by this object near the perihelion [48]. This first indirect indication of cometary activity was confirmed by photometric observations conducted in the same period. In fact, Oljato is so far the only MBC for which a production rate of CN, equal to \((8.9 \pm 4.5) \times 10^{23} \text{ mol s}^{-1}\) [49], has been measured (in 1979 and 1983), which has subsequently decreased (in 1992) below an upper limit of \(1 \times 10^{23} \text{ mol s}^{-1}\) [50], comparable with that of other MBCs (see above).

Indications of activity due to ice sublimation are also provided by the analysis of the photometric data of Oljato present in the database of the Minor Planet Center (MPC). In fact, by applying the methodology of secular curve of light (SLC) analysis [51] to these data, collected from 1995, Ferrin and Orofino [27] found recurrent increases in Oljato’s brightness near the perihelion with an \(A_{sec}\) amplitude of the SLC equal to \((0.79 \pm 0.02)\) mag, which, compared with the amplitudes of the SLC of classical comets (between 4.4 and 14.7 mag [51]), indicates low levels of cometary activity. Further indications of cometary activity come from the association between Oljato and some meteor showers [52], which are mainly cometary in nature, and from the presence of non-gravitational effects in the motion of the asteroid reported by Ziolkowski [53], although a subsequent analysis [26] found no convincing evidence of such effects.

In conclusion, there are strong indications of past cometary activity, even if research and the identification of coma and/or tails originating from Oljato have not been reported in the literature. Most likely, Oljato, after the outburst of the 1979–1983 period, reduced its activity to much lower levels, as suggested by the negative outcome of a new study on interplanetary magnetic field disturbances conducted by Venus Express from 2006 to 2012 in the same conditions as the 30-year-old Pioneer Venus experiment [54]. However, the reduced activity following the outburst does not seem to have escaped the analysis of Oljato’s SLC obtained from the MPC database considering the latest appearances of the object [27]. Targeted observations of Oljato searching for coma or tails are desirable to identify possible outbursts of the object and confirm the presence of non-gravitational effects in its orbital motion.
2.2. Extinct MBCs

Among the objects located on typically asteroid orbits ($T_J > 3$) and which do not show signs of activity, not all are certainly asteroids, because the group could contain MBCs so weakly active that they appear extinct or indeed truly extinct MBCs. Extinct comets with $T_J > 3$ have been known to exist for some time (see for example [22,55]). A recent example could be Ryugu, visited in 2018 by the Japanese spacecraft Hayabusa 2, whose typically asteroidal nature has never been questioned. Although in the literature the origin of this object is attributed to the re-accumulation of fragments of a previous catastrophic collision between larger asteroids [56,57], the Japanese mission revealed physico-chemical characteristics of this body that could suggest an alternative origin. Numerical simulations performed by Miura et al. [58] have shown, in fact, that the spinning-top-shaped rubble-pile structure of Ryugu, along with its potentially high organic content, are better explained by a transformation process from a comet to an asteroid through water ice sublimation.

In any case, the question of the nature of this body is not very clear. In fact, recent laboratory analyses showed elemental abundances of collected samples of Ryugu similar to those of CI chondrites, supporting a likely asteroidal origin of the object [59,60]. On the other hand, numerical dynamical simulations suggest that the parent body of Ryugu formed in the outer part of the Solar System and was very rich in ice [60]. This cometary object should have experienced collisional fragmentation, eventually producing, by ice sublimation, the object we see today [60]. Therefore, further detailed studies are needed to definitively settle the matter.

3. C/2014 S3 and the other Rocky Comets

In September 2014, the Pan-STARRS telescope located at Haleakalā, Hawaii, discovered a long-period comet, called C/2014 S3, which at that time was weakly active at 2.1 au from the Sun (see Table 5 for the physical characteristics of this comet).

Table 5. Physical characteristics of the comet C/2014 S3 (Pan-STARRS). Data taken from the NASA/JPL Small-Body Database site and from Meech et al. [61].

| Parameter                  | Value         | Uncertainty (1-Sigma) | Units |
|----------------------------|---------------|-----------------------|-------|
| Eccentricity (e)           | 0.97675738    | 0.00087411            |       |
| Semi-major axis (a)        | 88.1684       | 3.3263                | au    |
| Perihelion distance (q)    | 2.04926524    | 0.00024291            | au    |
| Aphelion distance (Q)      | 174.2876      | 6.5753                | au    |
| Inclination (i)            | 169.32062467  | 0.00068333            | deg   |
| Orbital Period (P)         | 827.900       | 46.850                | yr    |
| Diameter (D)               | 0.5–1.4       |                       | km    |
| Tisserand Param. ($T_J$)   | −1.675        |                       |       |
| Spectral Type              | S(IV)         |                       |       |

Observations showed that, apart from the small nucleus, C/2014 S3 is a very particular comet. Unlike most long-period comets, which typically show long, bright tails, this object is practically tailless; for this reason, it has been called a Manx comet, after the tailless cat. This nearly tailless appearance is also linked to a very low level of activity, 5–6 orders of magnitude lower than that of a typical long-period comet at a similar distance [61]. In this respect, this object is very similar to a MBC, such as 2021 Oljato, from which, however, it differs as regards its dynamic behavior (as can be clearly seen from the comparison between Tables 4 and 5). In addition to this weak cometary-like activity, another similarity exists between 2021 Oljato and C/2014 S3. The spectrum of the latter (see Figure 1 of [61]) has a band at around 1 μm and a continuum trend in the visible spectrum (in particular the slope), which make it very similar to those of type-S rocky asteroids [61]. Indeed, the spectrum of C/2014 S3 is best fitted by the S(IV) asteroidal class, a class of asteroids that are considered to most likely consist of rocky material that has never undergone processing at very high temperatures [61]. Due to its composition, C/2014 S3 could be assimilated to
the type of MBC that we defined in the previous section as atypical comets, from which it would differ only in the orbital characteristics.

Other Manx candidates have been discovered. An interesting example is C/2013 P2 (PANSTARRS), due to its very low activity and orbit [62]. Unfortunately, however, neither the spectral type nor the albedo of this object is known, so its classification remains uncertain.

Since C/2014 S3 is the only known body with a rocky surface originating from the OC, one might wonder how rare these objects actually are. In this regard, the simulations by Shannon et al. [63] indicate that ~8 billion bodies currently located in the OC (equal to ~4% of the total mass of the cloud) should have formed within 2.5 au of the Sun, and hence should be ice-free rock–iron bodies [63]. To this number we must add the one of bodies of mixed composition, precisely what C/2014 S3 appears to be, which could be the result of the coagulation of bodies of various kinds (ice-free and ice-rich), later sent to the OC (see Section 5). In conclusion, about ten billion totally or partially rocky bodies should populate the OC and could potentially be located on orbits that intersect the Earth’s.

Obviously, objects of this type could be very dangerous for the Earth because they are very fast like classic comets but are dimmer due to their low activity and are therefore more difficult to detect in time for countermeasures. Fortunately, according to Shannon and colleagues [63], the probability of collision with our planet is low, since globally catastrophic impacts should only occur about once per billion years.

4. Objects with High Orbital Inclination

Based on the traditional ideas about the formation of the Solar System starting from a very flat disk of gas and dust around the Sun, one would expect that the bodies present in the MB have orbits that are not too eccentric and above all not very inclined with respect to a plane (the ecliptic) coinciding with that of the original protoplanetary disk.

However, the distributions of the orbital eccentricities and inclinations of the MB objects do not follow this simplistic expectation, as asteroidal orbits are dynamically excited, with eccentricities ranging from zero to above 0.3 and inclinations from zero to 20° and beyond (see Tables 6 and 7). In particular, the orbital inclination can even reach (92 ± 18)° in the case of 2010 EQ169 (data from NASA/JPL Small-Body Database site). According to Nagasawa et al. [64], these orbital eccentricities and inclinations are too large to be accounted for by planetary perturbations in the present configuration as well as by gravitational scatterings between asteroids. Furthermore, these high eccentricities and inclinations are not caused by collisional disruptions; this is because collisions, being a dissipative process, on average tend to damp the eccentricities and inclinations rather than excite them [64].

These results were later confirmed by Carruba and Machuca [65], according to whom the mechanisms of dynamical mobility operating in today’s Solar System could hardly increase the initial small inclination of an asteroid to relatively high values, and therefore the presence of highly inclined asteroidal orbits should be due to processes operating in the early phases of the Solar System. These authors, studying a sample initially consisting of 10,073 asteroids with a semi-major axis between 2.0 and 3.4 au and with an inclination i greater than 17.5° (sin (i) > 0.3), found that the distribution of these asteroids in the plane a—sin(i) is far from homogeneous, with densely populated regions very close to nearly object-free areas. In particular, in this plane, Carruba and Machuca [65] found two regions which, although stable on a time scale of the order of 100 Myr or more, are very depleted. Since this depletion cannot be due to statistical fluctuations, these authors concluded that the presence of unpopulated dynamically stable regions could indicate that the primordial asteroidal population might not have reached all the available zones of high inclination. Although some alternative hypotheses have been put forward to explain these high orbital inclinations of the asteroid population (see for example [64]), a very interesting explanation is provided by the Grand Tack model [66], which will be discussed in the next section.
Note that the currently known population of objects with high orbital inclinations may be underestimated due to important selection effects. In fact, since surveys generally explore regions of low ecliptic latitude, several objects could easily escape detection. Therefore, studies aimed at the discovery and characterization of high-inclination objects are necessary, and an opportunity in this sense is provided by the Euclid mission, which will be discussed in Section 6.

Table 6. Distribution of the orbital eccentricities of all the MB asteroids. $N$ is the number of objects with eccentricity $e$ in each range, while $N'$ is the number of objects with $e$ less than or equal to the second extreme of each range. It should be noted that a non-negligible percentage of the entire population of the asteroidal MB, equal to $8\%$, has orbital eccentricities greater than 0.25. Data taken from the NASA/JPL Small-Body Database site.

| Range       | $N$   | $N'$   |
|-------------|-------|--------|
| 0.00–0.05   | 81,999| 81,999 |
| 0.05–0.10   | 216,766| 298,765|
| 0.10–0.15   | 265,720| 564,485|
| 0.15–0.20   | 261,370| 825,855|
| 0.20–0.25   | 167,876| 993,731|
| 0.25–0.30   | 66,640| 1,060,371|
| 0.30–0.35   | 19,411| 1,079,782|
| 0.35–0.40   | 3657| 1,083,439|
| 0.40–0.45   | 779| 1,084,218|
| 0.45–0.50   | 122| 1,084,340|
| 0.50–0.55   | 0| 1,084,340|
| 0.55–0.60   | 0| 1,084,340|

Table 7. Distribution of the orbital inclinations of all the MB asteroids. $N$ is the number of objects with inclination $i$ in each range, while $N'$ is the number of objects with $i$ less than or equal to the second extreme of each range. Note that a non-negligible percentage of the entire population of the asteroidal MB, equal to $4\%$, has orbital inclinations greater than 20°; note also the only MB asteroid (2010 EQ169) with an orbital inclination greater than 90° (see text). Data taken from the NASA/JPL Small-Body Database site.

| Range     | $N$   | $N'$   |
|-----------|-------|--------|
| 0–5°      | 347,997| 347,997|
| 5–10°     | 357,240| 705,237|
| 10–15°    | 252,582| 957,819|
| 15–20°    | 78,017| 1,035,836|
| 20–25°    | 25,095| 1,060,931|
| 25–30°    | 18,501| 1,079,432|
| 30–35°    | 4420| 1,083,852|
| 35–40°    | 404| 1,084,256|
| 40–45°    | 46| 1,084,302|
| 45–50°    | 18| 1,084,320|
| 50–55°    | 9| 1,084,329|
| 55–60°    | 4| 1,084,333|
| 60–65°    | 3| 1,084,336|
| 65–70°    | 3| 1,084,339|
| 70–75°    | 0| 1,084,339|
| 75–80°    | 0| 1,084,339|
| 80–85°    | 0| 1,084,339|
| 85–90°    | 0| 1,084,339|
| 90–95°    | 1| 1,084,340|

5. A Possible Evolutionary Scheme

The long-term integration of the orbits of the MBCs indicates in several cases a high stability and therefore an origin in the MB [67]. In other words, many MBCs should have
formed where we see them today [30, 68] when the so-called snow line, which is now at around 3.1 au from the Sun, was closer to our star (see [69] and references therein). Indeed, according to Martin and Livio [69], at the time of planetesimals formation this boundary was located at a heliocentric distance of about 2.7 au. In that position, the MBCs would have been dormant for a long time (otherwise they would have quickly exhausted their ice content) with their volatiles protected under a thick crust (carbonaceous or silicaceous). A subsequent fracturing of the crust, either due to internal tensions or due to small impacts, would have exposed the underlying ice, activating, or reactivating, the comet.

Another group of MBCs may have formed in the outer solar system, particularly in the origin region of the Jupiter-family comets [70]. A recent example of this dynamical evolution was tentatively provided by Moreno et al. [71] as far as the object P/2021 A5 (PANSTARRS) is concerned.

An interesting and very likely possibility is that the MBCs, with their mixed composition of dust and volatile substances, could have formed in the outer parts of the Solar System, well beyond the snow line, by the homogeneous coalescence of various icy and dusty bodies (cometesimals). Subsequently, according to the Nice model [72], during the early period of the Solar System, many of these objects would have been scattered inwards and captured in the asteroid MB as close in as 2.68 AU (see [73] and references therein).

Alternatively, as already mentioned in Section 2, the MBCs could have been formed beyond the snow line by the heterogeneous coalescence of icy and rocky bodies. The latter were sent to those external regions of the Solar System due the migration of the planet Jupiter described by the Grand Tack model [66]. According to this model, Jupiter and Saturn, immediately after their formation, would have undergone a double orbital migration (first inwards and then outwards), which would have distorted the original distribution of the orbital parameters (a, e, and i) of the numerous planetesimals with which these two planets interacted. Consequently, many rocky bodies would have been transferred from their birth places, close to the Sun, to the region beyond the snow line, where, in principle, they could have coalesced with bodies made by volatile materials (carbonaceous/organic and icy). This coalescence may have produced objects with a structure similar to a rubble pile [47], that is, comprising elementary, silicate-rich (rocky), or carbonaceous blocks, held together inside an icy matrix necessary to produce cometary activity. After their formation in the outer regions of the Solar System, these objects would have migrated to their current orbits in the MB, according to the same transport mechanisms described by the Nice model (see above).

Finally, some MBCs should have arrived where we now see them relatively recently following the fragmentation of a much larger object [73]. This seems, for example, to have been the case of the MBCs of the Taurid Complex [27], as well as of 7968 Elst–Pizzaro, 118,401 (176P/LINEAR), and 238P/Read and their respective families [73]. In particular, according to various authors (e.g., [74]) the Taurid Complex was created by the fragmentation of a giant comet (~100 km in diameter), which entered the inner Solar System 20 ky ago. In fact, over the last ~10 kyr, this object experienced a series of fragmentation/splitting events that produced both meteoroids (responsible for the meteor streams observed on Earth) and much larger fragments now present as near-Earth asteroids [75], some of which were reported in Table 2.

Although this hypothesis has been criticized in the past on the basis of dynamic considerations [76], recent numerical simulations performed by Egal et al. [77] have shown, on the contrary, an orbital convergence of various members of the complex, which is compatible with the fragmentation of a large parent body 5000–6000 yr ago, in rough agreement with the first evaluation by Steel and colleagues [75]. Egal and colleagues found that other alternative mechanisms are also capable of explaining the observations. However, the hypothesis of cometary fragmentation certainly represents a more than concrete possibility. This scenario is also supported by the recent discovery by Ferrin and Orofino [27] that a large fraction (67%) of the asteroids of the complex are active, as
discussed in Section 2. In addition, these authors found an original body diameter of 120 km, in good agreement with previous estimates [74].

Whatever the mechanism of the formation of the MBCs, a fundamental question concerns the ice preservation processes in a region of the Solar System within the snowline. To study this problem, Schorghofer [78] developed a simple model to evaluate the loss rate of buried ice from spherical bodies in the MB (with heliocentric distances between 2.0 and 3.3 au). The author found that ground ice can persist for billions of years under a protective dusty layer only a few meters deep throughout the asteroid MB and that the most favored objects are those far from the Sun, slowly rotating, with a spin axis slightly inclined on the orbital plane and with surfaces made up of small particles (grain size in the order of 0.1 mm) [78]. However, these results have not been confirmed by Prialnik and Rosenberg [79], who, using in the particular case of the MBC 133P/Elst–Pizarro a more detailed model than the previous one, found that the thickness of the crust necessary to prevent the sublimation of the ground ice should be equal to 50–150 m, on a time scale in the order of the age of the Solar System (4.6 Byr). This would make the activation of the object more difficult, since, to expose buried ice through an impact, collisions with much larger bodies would be required than if the mantle thickness were equal to that found by Schorghofer in 2008. On the other hand, using a more recent model of ice loss, Schorghofer [80], again in the case of 133P/Elst–Pizarro, found that the burial depths under a dust mantle are of the order of 0.1 m for an estimated age of the object equal to 10 Myr. This would imply that 133P/Elst–Pizarro could be easily activated by small impacts that would expose the buried ice.

In conclusion, the models do not provide a clear and univocal solution to the problem of ground ice survival in MBCs. These models deal with idealized situations that could be very different from real cases, and this explains the differences in the results. The variations in the results obtained by the three models could also be partially due to the different modeling approaches or the practically unknown initial thermo-physical properties assumed in the models. Nor is it possible to use classical comets as a proxy, because the characteristics of the mantles surrounding these objects should be very different in genesis from those of the mantles of the MBCs (see Section 2).

It should be noted that the Grand Tack coupled with the Nice model (hereafter referred to as the Grand Tack–Nice model) is not the only model that explains the dynamic characteristics of the MB population as well as the presence of icy objects in this belt and rocky objects in the OC; other models are also able to obtain the same results (for a review of these models, see [81]). In addition to the Grand Tack–Nice model, other models (see [61] and references therein) also predict the presence of a large number of entirely or partially rocky objects in the OC, as discussed in Section 3. However, the Grand Tack–Nice model explains, better than static models that do not predict planetary migrations, the detectability of C/2014 S3-like objects [82]. Furthermore, it also explains the observed distribution of C-type and S-type asteroids inside the MB, the low mass of Mars, and the presence, discussed in Section 4, of a large number of asteroids on high-inclination orbits (see Figure 4) that cannot be due to mechanisms operating in the current configuration of the Solar System [64]. Finally, it provides for the evolution of the Solar System similar to that of other star systems, in which the presence of Hot Jupiters strongly suggests ancient planetary migrations.
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Figure 4. Distribution of inclination (upper boxes) and eccentricity (lower boxes) of the orbit of volatile-poor (red dots) and volatile-rich (blue dots) objects at different stages of the migration of the two giant planets Jupiter and Saturn (black disks), according to a simulation performed using the Grand Tack–Nice model. The time elapsed since the start of Jupiter’s migration is reported in each panel. Note the presence, at the final time point, of volatile-rich (carbonaceous) objects in the inner parts of the Solar System and volatile-poor (rocky) objects in the outer parts (Credit: Kevin J. Walsh, Southwest Research Institute, Boulder, USA and Sean N. Raymond, Laboratoire d’Astrophysique, Univ. Bordeaux, CNRS, France).

It is worthwhile to note that, according to Snodgrass et al. [30], meteoritic evidence [83] would seem to rule out an origin of the C-type asteroids (the parent bodies of carbonaceous chondrite meteorites) beyond Jupiter’s orbit, as suggested by the Grand Tack model. However, other studies on the isotopic composition of meteorites reached the exact opposite conclusion (see [84] and references therein). Indeed, today it is reasonable to assume that, according to the Grand Tack model, all parent bodies of carbonaceous chondrites (i.e., C-type asteroids) formed beyond Jupiter, and possibly even Saturn.

In conclusion, this model, combined with the Nice model, constitutes an extremely promising theoretical framework that provides an interesting unitary explanation of all the strange objects discussed in this work.

6. Conclusions and Future Developments

In the previous sections, various pieces of evidence were presented that do not support the simplistic picture of the Solar System consisting of objects (planets and minor bodies) located on nearly coplanar orbits and made up of volatile-poor (silicaceous) materials in the inner regions and volatile-rich (icy and carbonaceous) substances in the outer parts. Various observations have shown, in fact, many strange objects or interlopers that do not fit the above-described scenario. In particular, the traditional distinction between asteroids (essentially rocky bodies with $T_J > 3$) and comets (essentially icy bodies with $T_J \leq 3$) is much less clear-cut than it was thought to be a few decades ago. Indeed, although cometary
nuclei and asteroids are two types of objects that are completely different in origin and composition, in various cases it is very difficult to distinguish between asteroids and cometary nuclei. Dynamic and spectrophotometric criteria combined together can help, but they are not always decisive. In light of the above, the question of identifying the nature of several minor bodies of the Solar System remains open.

In this context, the MBCs are interesting transition objects, sharing characteristics with both comets and asteroids. These objects are of considerable importance for studies on the formation of the Solar System. In the literature, only two possible origins for MBCs are commonly reported: (1) in the MB (where we see them today), when the snowline was closer to the Sun [69], and (2) in the outer regions of the Solar System, from where they were subsequently sent to the MB due to, for example, the migrations of Jupiter or other processes [70,81]. However, a catastrophic origin is also likely, due to the shattering of a large comet, as seems to have happened, at least in the case of the Taurid Complex [27,74,75].

In the present work, it was seen that there are objects with a rocky (or in any case silicaceous) surface that show cometary activity. This is the case of the OC comet C/2014 S3, as well as a subgroup of MBCs that in this paper were called atypical comets, since, while showing cometary activity, they have dynamic and spectral characteristics quite similar to those of rocky asteroids. Among the 19 MBCs traditionally reported in the literature (listed in Table 1), to which we can add other 34 active asteroids of the Taurid Complex [27] (listed in Table 2), only 8 have known and reliable spectral types. Among these eight objects, five (Oljato, Cuno, Heracles, 8201, and 16960) belong to spectral classes clearly indicative of a silicaceous surficial composition. This composition is very different from the organic/carbonaceous composition of the nuclei of classical comets, which only one object (4015 Wilson–Harrington) should possess.

So far, the spectral classification of active asteroids by ice sublimation (that is, MBCs) has been neglected in the literature, also due to a lack of data; however, in the future, it could provide useful information on the true nature of these objects. To increase the size of the database on the spectra and albedos of asteroids and comets, it will be possible to use the data collected by the Gaia mission of the European Space Agency (ESA) and, in particular, its very recent third data release, Gaia DR3, in which spectral data for about 60,000 asteroids were published [85]. In this way, we hope to classify an increasing number of objects in the various groups defined in Table 3, making this classification statistically significant.

Naturally, in addition to the classification of MBCs, targeted observations of the objects that we defined as atypical comets, including Oljato, are necessary to confirm the indications of their cometary activity, through the identification of possible dust coma and/or tails, as well as of gaseous emission.

Other important future developments should concern the study of high-inclination asteroids, which, as mentioned in Section 4, are very important for the understanding of the formation process of the Solar System, but whose number is most likely underestimated. For this reason, studies should be aimed at identifying and characterizing these objects, and this research will be carried out during the Euclid mission of ESA and the Euclid Consortium. This mission will use a 1.2 m space telescope, operating in the visible to near infrared spectrum, and is planned to be launched in 2023 by ESA. This telescope will measure the shapes of galaxies at varying distances from Earth and investigate the relationship between distance and redshift. The objective of the Euclid mission is essentially cosmological, since it will study the dark energy and the dark matter by accurately measuring the acceleration of the universe. However, an interesting by-product of this mission will be the study of Solar System objects (SSOs), with particular regard to those with high orbital inclination [86]. This is because the images, taken as part of a survey of deep-sky galaxies, before being analyzed for this purpose, must be cleaned of the contamination of known and unknown SSOs, which therefore must be identified and characterized [87]. The instrument aboard Euclid, a low-resolution photometer, is not able to accurately determine the taxonomic class of SSOs. However, observing outside the ecliptic plane, Euclid is ideal for studying these
high-i objects by monitoring their actual number and classifying them, as well as validating the theoretical models that have been proposed to explain their existence [87].

Other important future developments will be achieved thanks to JWST observations of the spectral features of faint SSOs [88], as well as the Vera Rubin Observatory, which is devoted to sky surveys and is expected to discover and potentially study in color a large number of SSOs [89].

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