Part VI

Transition Objects

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Icy Bodies of the Solar System
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Dynamics, Origin, and Activation of Main Belt Comets

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Abstract. The discovery of Main Belt Comets (MBCs) has raised many questions regarding the origin and activation mechanism of these objects. Results of a study of the dynamics of these bodies suggest that MBCs were formed in-situ as the remnants of the break-up of large icy asteroids. Simulations show that similar to the asteroids in the main belt, MBCs with orbital eccentricities smaller than 0.2 and inclinations lower than 25° have stable orbits implying that many MBCs with initially larger eccentricities and inclinations might have been scattered to other regions of the asteroid belt. Among scattered MBCs, approximately 20% reach the region of terrestrial planets where they might have contributed to the accumulation of water on Earth. Simulations also show that collisions among MBCs and small objects could have played an important role in triggering the cometary activity of these bodies. Such collisions might have exposed sub-surface water ice which sublimated and created thin atmospheres and tails around MBCs. This paper discusses the results of numerical studies of the dynamics of MBCs and their implications for the origin of these objects. The results of a large numerical modeling of the collisions of m-sized bodies with km-sized asteroids in the outer part of the asteroid belt are also presented and the viability of the collision-triggering activation scenario is discussed.

Keywords. minor planets: asteroids, solar system: general, methods: n-body simulations

1. Introduction

The discovery of comet-like activities in four icy asteroids 7968 Elst-Pizzaro (133P/Elst-Pizzaro), 118401 (1999 RE_{70}, 176P/LINEAR), P/2005 U1 (Read), and P/2008 R1 (Garradd) has added a new item to the mysteries of the asteroid belt (Hsieh & Jewitt 2006; Jewitt, Yang & Haghighipour 2009). Known as Main Belt Comets (MBCs), these objects may be representatives of a new class of bodies that are dynamically asteroidal (i.e., their Tisserand parameters† are larger than 3), but have cometary appearance. As shown in Table 1, the orbits of these objects are in the outer half of the asteroid belt (Fig. 1) implying that they may contain sub-surface water ice. In fact the observation of the tail of 7968 Elst-Pizzaro by Hsieh, Jewitt & Fernández (2004) has indicated that the comet-like activity of this MBC is episodic (it is not the ejection of dust particles that were produced through an impact to this object) and is due to the dust particles that have been blown off the surface of this body by the drag force of the gas that was most likely produced by the sublimation of near-surface water ice.

† For a small object, such as an asteroid, that is subject to the gravitational attraction of a central star and the perturbation of a planetary body P, the quantity $a_{\mathrm{P}}/a + 2[(1-e^2)\,a/a_{\mathrm{P}}]^{1/2}\,\cos i$ is defined as its Tisserand parameter T, where a is the semimajor axis of the object with respect to the star, e is its orbital eccentricity, i is its orbital inclination, and a_{P} is the semimajor axis of the planet. In general, $T < 3$ for comets (with respect to Jupiter), whereas those of asteroids are mostly $T > 3$.

Table 1. Orbital Elements of MBCs (Hsieh & Jewitt 2006)

MBC	a **(AU)**	e	i **(deg.)**	**Tisserand**	**Diameter (km)**
(133P)/7968 Elst-Pizzaro	3.156	0.165	1.39	3.184	5.0
118401 (176P/LINEAR)	3.196	0.192	0.24	3.166	4.4
P/2005 U1 (Read)	3.165	0.253	1.27	3.153	0.6
P/2008 R1 (Garradd)	2.726	0.342	15.9	3.216	1.4

The comet-like appearance of MBCs has raised questions regarding the origin of these objects. While the asteroidal orbits of these bodies, combined with the proximity of 7968 Elst-Pizzaro, 118401 (176P/LINEAR), and P/2005 U1 (Read) to the Themis and Beagle families of asteroids (Fig. 1), suggests that MBCs have formed in-situ as the remnants of collisionally broken larger objects, the cometary activities of these bodies may be taken to argue that MBCs are comets that were scattered inward from the outer regions of the solar system and were captured in their current orbits. Such a capture mechanism could not have occurred recently. Simulation of the dynamics of Kuiper belt object by Fernandez *et al.* (2002) have shown that, at the current dynamical state of the solar system, it would not be possible to scatter comets from regions outside the orbit of Neptune to the main asteroid belt. A primordial capture, on the other hand, may not be impossible. Recently Levison *et al.* (2009) have shown that within the context of the Nice model (Gomes *et al.* 2005; Morbidelli *et al.* 2005; Tsiganis *et al.* 2005) many trans-Neptunian objects could have been scattered inwards and captured in orbits in the asteroid belt as close in as 2.68 AU during the early state of the dynamics of the solar system. Whether these objects could be the source of MBCs is, however, uncertain. This paper evaluates this possibility, in particular in comparison with the in-situ formation model, by presenting the results of a numerical study if the dynamics of the currently known MBCs, and discussing their implications for the formation and origin of these objects.

As mentioned above, tails of MBCs are generated through the interactions of dust grains on the surface of these bodies with the gas produced by the sublimation of near-surface water ice (Hsieh, Jewitt & Fernández 2004). As shown by Schorghofer (2008), asteroids in the region between 2 AU and 3.3 AU can maintain sub-surface water ice for several billion years if their surfaces are covered by a layer of dust, even as thick as only a few meters. That implies that in order for an MBC to start its cometary activation, this dusty layer has to be removed. Hsieh & Jewitt (2006) have suggested that collisions between MBCs and objects as small as a few meter in size, can reveal the sub-surface water ice. Such collisions will result in the local exposure of ice which sublimates and creates a thin atmosphere and tail for an MBC. An activated MBC, on the other hand, may terminate its activity after sublimating all the ice at the location of its collision with a m-sized projectile. It may also start new activation if it is collided with a second m-sized object in a later time again. In other words, an MBC may be activated several times till it exhausts all its water ice, or is scattered to an unstable orbit and either leaves the asteroid belt or collides with another asteroid or a planet. It will therefore be useful to study the rate of the collisions of m-size bodies with km-size MBCs, in particular in the outer region of the asteroid belt. This paper presents the results of such simulations and discusses their implications for the activation of MBCs and the possibility of the detection of more of these objects.

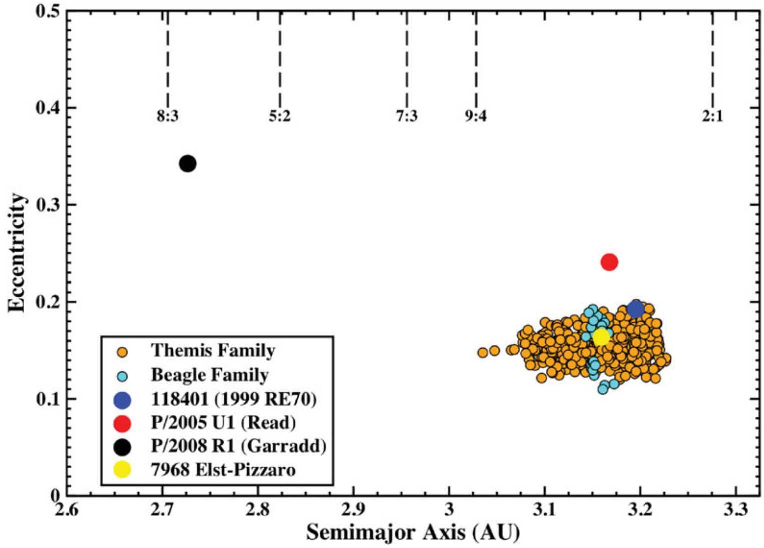

Figure 1. The four currently known MBCs and the Themis and Beagle families of asteroids. As shown here, 7968 Elst-Pizzaro and 118401 (Read) are within the Themis and Beagle families whereas P/2005 U1 is in their proximity. The MBC P/2008 R1 (Garradd) seems to be an object that was scattered out of its forming region. The locations of mean-motion resonances with Jupiter are also shown.

2. Orbital Integrations and Implications for the Origin of MBCs

To study the long-term stability of the four known MBCs, the orbits of these objects were integrated for 1 Gyr. Integrations included all the planets and Pluto, and treated MBCs as non-interacting objects. The effects of non-gravitational forces such as Yarkovsky, and the effect of the mass-loss of MBCs due to their cometary activities were not included. Since the activation of MBCs is episodic and intensifies during the perihelion passages of these objects, which is short compared to their orbital periods, the effect of the mass-loss may not alter the dynamics of these objects significantly. Integrations were carried out with Bulirsch-Stoer and with the Second-Order Mixed-Variable Symplectic (MVS) integrators in the N-body integration package MERCURY (Chambers 1999). The initial orbital elements of the MBCs and planets were obtained from documentation on solar system dynamics published by the Jet Propulsion Laboratory (http://ssd.jpl.nasa.gov/?bodies). The timestep of each integration was set to 9 days.

Figure 2 shows the results of the simulations. As shown here 7968 Elst-Pizzaro and 118401 (176P/LINEAR) maintain their orbits for 1 Gyr. However, P/2005 U1 (Read) and P/2008 R1 (Garradd) become unstable in approximately 20 Myr. Integrations were also carried out for different initial values of the semimajor axes and eccentricities of MBCs, changing these quantities in increments of $\Delta a = 0.0001$ AU and $\Delta e = 0.001$ within the ranges of their observational uncertainties. Similar results were obtained. 7968 Elst-Pizzaro and 118401 were stable whereas P/2005 U1 and P/2008 R1 became unstable in all simulations with a median lifetime of $\sim$57 Myr. For more details on the results of the simulations, in particular on the analysis of the effects of mean-motion resonances on the dynamics of these MBCs, the reader is referred to Haghighipour (2009) and Jewitt, Yang & Haghighipour (2009).

As shown by Fig. 1, the orbit of P/2008 R1 (Garradd) is close to the influence zone of the 8:3 mean-motion resonance with Jupiter. Numerical simulations by Jewitt, Yang

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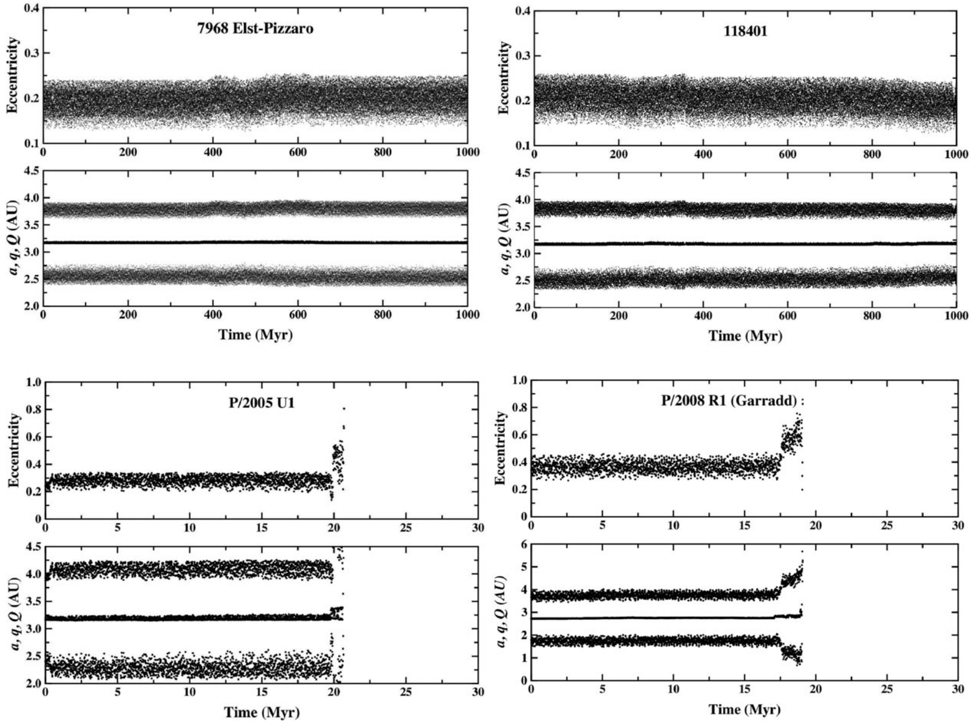

Figure 2. Graphs of the eccentricities, semimajor axes (a), perihelion (q), and aphelion (Q) distances of 7968 Elst-Pizzaro, 118401 (176P/LINEAR), P/2005 U1 (Read), and P/2008 R1 (Garradd). As shown here, 7968 Elst-Pizzaro and 118401 are stable for 1 Gyr whereas P/2005 U1 (Read) and P/2008 R1 (Garradd) become unstable in approximately 20 Myr.

& Haghighipour (2009) have shown that the region in the vicinity of P/2008 R1 is dynamically unstable implying that this MBC must have formed in another region of the asteroid belt and scattered to its current orbit. The orbital instability of P/2005 U1 (Read), on the other hand, may show a pathway to such scattering events. The proximity of P/2005 U1 to the Themis family and the location of the 1:2 mean-motion resonance with Jupiter suggest that this MBC was perhaps formed close to the influence zone of the 1:2 resonance. The original proximity of P/2005 U1 to this resonance has resulted in a gradual increase in its orbital eccentricity which will eventually make its orbit unstable. Such an instability might have also happened to the orbits of other MBCs and resulted in their scattering to other regions. To study this scenario, a large number of hypothetical MBCs were considered around the region where 7968 Elst-Pizzaro, 118401 (176P/LINEAR), and P/2005 U1 (Read) exist. The semimajor axes of these objects were varied between 3.14 AU and 3.24 AU, and their initial eccentricities were taken to be between 0 and 0.4. The initial orbital inclinations of these MBCs were chosen from a range of 0 to 40°.

The orbits of these hypothetical MBCs were integrated for 100 Myr. Figure 3 shows the results. In this figure, green circles correspond to MBCs with stable orbits whereas purple indicates instability. As shown here, 7968 Elst-Pizzaro and 118401 (176P/LINEAR) are in the stable region of the graph whereas P/2005 U1 (Read) is approaching the unstable area.

An interesting result depicted by Fig. 3 is the familiar role of secular resonances in establishing the boundaries of stable zones. Similar to the asteroids in the asteroid belt,

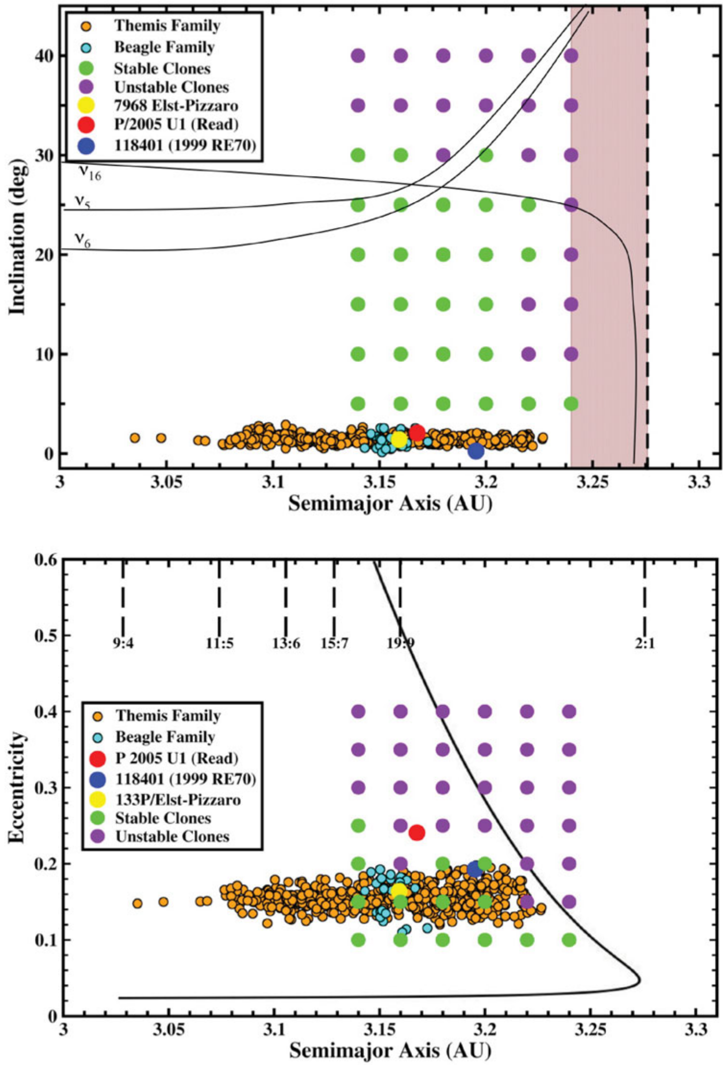

Figure 3. Top: graph of the stability of hypothetical MBCs in terms of their inclinations. The regions of secular resonances ν_5, ν_6, and ν_{16} corresponding to an eccentricity of 0.1 are also shown. Bottom: graph of the stability of hypothetical MBCs in terms of their eccentricities. The brown area in the top graph and solid line in the bottom graph show the region of the 2:1 MMR with Jupiter. Circles in green correspond to initial semimajor axes and eccentricities of stable MBC whereas those in purple show instability. Similar to the asteroid in the main belt, objects with inclinations larger than $\sim 25^\circ$ and eccentricities larger than ~ 0.2 are unstable.

stability of an MBC depends on the values of its initial eccentricity and orbital inclination. Fig. 3 shows that for initial inclinations larger than $\sim 25^\circ$, the orbit of an MBC becomes unstable due to the Kozai and the ν_5, ν_6 and ν_{16} secular resonances. For smaller values of inclination, the apastron distance of an MBC determines its stability. Those hypothetical MBCs close to or inside the region of the 2:1 MMR with Jupiter became unstable in a short time. An analysis of the orbits of the unstable objects indicates that approximately 80% of these bodies were scattered to large distances outside the solar system. This is a familiar result that has also been reported by O'Brien *et al.* (2007) and

Haghighipour & Scott (2008) in their simulations of the dynamical evolution of planetesimals in the outer asteroid belt. From the remaining 20% unstable MBCs, approximately 15% collided with Mars, Jupiter, or Saturn, and a small fraction ($\sim 5\%$) reached the region of 1 AU implying that MBCs might have played a role in delivering water to the Earth.

The stability analysis above has direct implications for the origin of MBCs and favors the in-situ formation of these objects. In this scenario, MBCs are small asteroidal bodies that were formed as a result of the collisional break-up of their larger precursor asteroids. An alternative scenario based on the primordial capture of cometary bodies, although, as shown by Levison *et al.* (2009), efficient in the inward scattering of D-type and P-type asteroids and the delivery of these objects in particular to the region of Trojans, cannot provide information on the inward scattering and distribution of C-type asteroids. That is primarily due to the fact that C-type asteroids are mainly at small semimajor axes, and the difference between their orbital distribution and that of D-type asteroids are not known. Additionally, the colorless feature of MBCs, as indicated by Hsieh & Jewitt (2006) and Hsieh, Jewitt & Fernández (2008) is not consistent with an origin model based on the inward scattering of comets from the Kuiper belt region (the latter objects are optically red).

The in-situ formation scenario is, however, consistent with MBCs orbital and spectral properties. In this scenario, the break up of the precursor asteroids could have produced many km-sized fragments, among which those with large inclinations and large eccentricities became unstable and were scattered to other regions. The remaining objects have naturally asteroidal orbits (i.e. their Tisserand numbers are larger than 3), and similar to their parent bodies, are C-type asteroids with no specific optical color. In regard to 7968 Elst-Pizzaro, 118401 (176P/LINEAR), and P/2005 U1 (Read), this scenario points to the Themis family, and perhaps a smaller ~ 10 Myr sub-family (known as Beagle) within these objects (Nesvorný et al 2008), as the origin of these MBCs. This scenario also suggest that asteroid families, in particular those in the outer half of the asteroid belt and with large parent bodies capable of differentiating and forming ice-rich mantles, are the most probable places for detecting more MBCs. As indicated by the results of the dynamical simulations, some members of such families may interact with giant planets and reach orbits in other regions of the asteroid belt–a scenario that might explain the existence of P/2008 R1 (Garradd) in its current orbit. All sky surveys such as those with Pan STARRS 1 would be capable of detecting such individual MBCs, and are ideal for carrying out targeted surveys for families of these objects.

3. Collision With Small Objects As The Activation-Triggering Mechanism

As mentioned in the introduction, it has been suggested that the tails of MBCs are dust particles that have been carried away from the surfaces of these object by the gas produced by the sublimation of water ice. This idea is based on the fact that the orbits of the currently known MBCs are in the outer part of the asteroid belt where water ice on the surface of asteroids can survive for billions of years when covered by a layer of dust (Schorghofer 2008). A collision between an MBC and an object, even as small as a m-sized boulder, can expose this ice. When such an MBC, with a locally exposed subsurface ice, approaches its perihelion, the ice sublimates and produces a weak atmosphere which lifts and carries dust particles from the surface of the MBC, giving it a cometary appearance.

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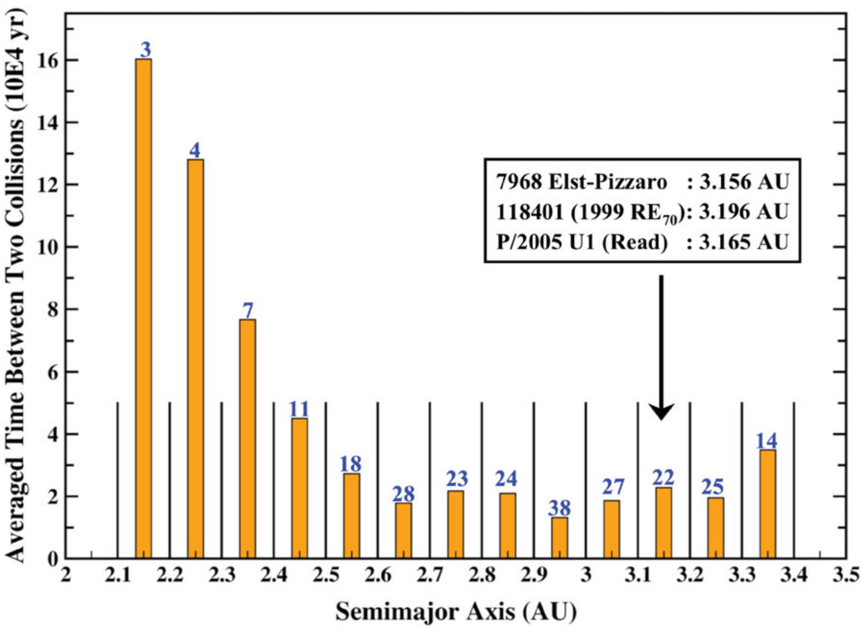

Figure 4. Graph of the averaged time between two successive collisions of m-sized objects with an MBC in the orbit of 7968 Elst-Pizzaro. The numbers on top of each bar indicate the percentage of the boulders of that region that collided with the MBC. As shown here, most of the collisions come from the vicinity of 7968 Elst-Pizzaro. The grand average of the time between two successive collision is approximately 40,000 years.

The number of m-sized boulders and the frequency of such collisions are not exactly known. However, it is possible to develop a simple computational model that can impose an upper limit to these collisions. In doing so, a heuristic model was developed based on the following assumptions.

(a) The asteroid belt was assumed to consist of only one asteroid, 7968 Elst-Pizzaro, and a disk of m-sized bodies. The surface density of the disk was set to have a $r^{-3/2}$ profile.

(b) The accumulative size distribution (N) of objects with diameter (D) was considered to be given by $N \propto D^n$, where n can have a value between -2 and -4. Following Dohnanyi (1969), it was assumed that $n = -2.5$.

(c) A total of 10^6 m-sized boulder were randomly distributed throughout the asteroid belt. The eccentricity of these objects were chosen from a range of 0 to 0.5, and their inclinations were taken to be between 0 and 25°.

The orbits of the m-sized objects and that of the 7968 Elst-Pizzaro were integrated for 10 Myr. Similar to the previous simulations, integrations included all planets and Pluto. Results indicated that on average, one m-sized object collides with this MBC every 40,000 years. As shown in Fig. 4, a larger number of the colliding boulder come from the vicinity of 7968 Elst-Pizzaro. It is important to emphasize that this model is simplistic, and the results represent a high upper limit. In a more realistic model, the numbers of large bodies and the small boulders are much higher. As a result, many of the m-sized objects collide with their neighboring asteroids, or are ejected from the asteroid belt. It is expected that in such cases, the frequency of collisions between km-sized MBCs and m-sized boulders to decrease to approximately one every few thousand years.

4. Conclusions

• Current MBCs seem to have formed through the collision and break up of bigger asteroids. The results of the simulations of the dynamic of these objects point to the Themis family as the origin of 7968 Elst-Pizzaro, 118401 (176P/LINEAR), and P/2005 U1 (Read).

• Interaction with giant planet might have scattered MBCs from their original orbits to other locations in the asteroid belt. P/2008 R1 (Garradd) seems to be one of such scattered MBCs.

• More MBCs may exist in low inclinations and low eccentricities in the vicinity of asteroid families in the outer region of the asteroid belt.

• Collisions with small objects might have activated MBCs or eroded them.

• Many MBCs might have been active in the past and are either no longer active, or will become active if hit by a small body again.

• Many MBCs, with locally exposed sub-surface ice, may still be on their ways to their perihelion distances where they become active, or they may be awaiting collisions with smaller objects to get activated.

• All sky surveys such as Pan STARRS will be able to detect more MBC in near future.

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