

Embedding Comets in the Asteroid Belt

Harold F. Levison

Southwest Research Institute

1050 Walnut St, Suite 300

Boulder, CO 80302 USA

`hal@boulder.swri.edu`

William F. Bottke

Southwest Research Institute

Boulder, CO USA

Matthieu Gounelle

Laboratoire d'Étude la Matière Extraterrestre

Muséum National d'Histoire Naturelle

Paris, France

Alessandro Morbidelli

Observatoire de la Côte d'Azur

Nice, France

David Nesvorný

Southwest Research Institute

Boulder, CO USA

Kleomenis Tsiganis

Department of Physics

Aristotle University of Thessaloniki, Greece

Received _____; accepted _____

The main asteroid belt, which inhabits a relatively narrow annulus $\sim 2.1\text{--}3.3$ AU from the Sun, contains a surprising diversity of objects ranging from primitive ice/rock mixtures to igneous rocks [1]. The standard model used to explain this assumes that most asteroids formed in situ from a primordial disk that experienced radical chemical changes within this zone [2]. Here we show that at least some of this variation was produced by dynamical processes, namely the capture of numerous comets in the outer belt during a violent period of planetary orbital evolution. These results fundamentally change our view of the asteroid belt because they imply that the observed diversity says as much about the dynamical processes of planet formation as it does about the intrinsic variation of the proto-planetary disk. The captured comets, composed of physically weak, organic-rich primitive materials, would have been more susceptible to collisional evolution than typical main belt asteroids. Accordingly, while our numerical results indicate comets once dominated the outer main belt, they have since been reduced by collisions over billions of years to a few tens of percent of the present-day population. Their weak nature makes them a prodigious source of micrometeorites — sufficient to explain why most are primitive in composition and are isotopically different from most macroscopic meteorites [3, 4].

It has recently been argued that the Trojan asteroids near Jupiter, the irregular satellites of the giant planets, and Kuiper belt objects share a common origin — they formed in a primordial trans-planetary disk and were transported to their current locations by the early dynamical evolution of the planets [5, 6, 7]. This idea is supported by the spectral characteristics of these bodies. In particular, the vast majority of Trojans are D- or

P-types (hereafter referred to as D/P-types), low albedo asteroids with featureless, flat to reddish spectra in visible wavelengths. These properties are thought to indicate organic-rich primitive compositions and are a good match to the observed dormant comets [8].

The results described above naturally lead to the new and innovative idea that the most primitive objects, like D/P-type asteroids (see discussion in Supplemental Material, hereafter SM, §S0), followed a similar evolutionary history. The main sticking point with this hypothesis is the presence of D/P-type objects on orbits completely interior to that of Jupiter, which is unexpected for objects that were at one time gravitationally scattered by the giant planets (cf. Fig.1). In particular, most of the Hildas (see caption of Fig.1) and about 20% of the larger outer main belt (objects beyond 2.8 AU; hereafter either outer MB or OMB) are D/P-types. In addition, there are several known OMB asteroids that display cometary activity [9].

The issue thus becomes whether the evolution of the giant planets could dynamically implant the correct number of these objects onto their currently observed orbits. To investigate this intriguing possibility, we performed a series of numerical simulations similar to the ones in Ref. [5]. Our techniques are explained in detail in SM §S1 and §S3, but are briefly reviewed here.

Our simulations were performed in the context of the so-called *Nice model* [10, 11, 5] because it is the most successful model to date at explaining the characteristics of the outer Solar System. In the Nice model, the giant planets are assumed to have formed in a compact configuration (all were located between 5–15 AU) and be surrounded by a $\sim 35M_{\oplus}$ planetesimal disk stretching between ~ 16 –30 AU. Slow migration was induced in the planets by gravitational interactions with planetesimals leaking out of this disk. After a period of time that could have been as long as 1.2 Gyr, Jupiter and Saturn crossed their mutual 1:2 mean motion resonance (MMR, the location when the ratio of their orbital periods

equals to $1/2$). This event triggered a global instability in the orbits of the planets that led to a violent reorganization of the outer Solar System. Uranus and Neptune penetrated the trans-planetary disk, scattering its inhabitants throughout the Solar System. The interaction between the ice giants and the planetesimals damped the orbits of these planets - leading them to evolve onto their current orbits.

The Nice model is compelling not only because it can quantitatively explain the orbits of the Jovian planets [10]. The dispersal of the primordial trans-planetary disk can also explain the origin of the so-called Late Heavy Bombardment (LHB), a spike in the cratering history of the terrestrial planets that occurred ~ 650 Myr after planet formation [11]. Furthermore, as noted above, some of the original inhabitants of this disk are captured onto stable orbits and thus can be seen today. In particular, this model explains the existence of the Trojan asteroids of both Jupiter [5] and Neptune [10], the Kuiper belt and scattered disk [7], and the irregular satellites of the giant planets [6]. These accomplishments are unique among models of outer Solar System evolution.

To investigate the possible capture of cometary planetesimals into the asteroid belt, we first integrated the orbits of a large number of massless planetesimals initially on Saturn-crossing orbits under the gravitational influence of the Sun, Jupiter and Saturn. The planets were forced to migrate by including a suitably chosen acceleration in the planets equations of motion, so that they reproduced the evolution of the ‘fast migration’ run in Ref. [5] (see SM §S1 for more detail). The integrations covered 20 Myr. During the first 10 Myr of the simulation, we supplied a steady flux of planetesimals through the Jupiter-Saturn system. These objects represent the planetesimals that originally formed in the trans-planetary disk, but were destabilized and fed inward by Uranus and Neptune. In all we followed the evolution of ~ 1.2 million such particles. At the end of the calculation there were 1270 particles captured into orbits decoupled from Jupiter.

Next, we tracked the long-term evolution of the population of the particles captured during the migration simulations in order to compare it to observations. This population is affected by two processes: dynamical erosion and collisional grinding. We address each of these separately.

It is well known that the long-term dynamical stability of asteroids, particularly those in MMRs with the giant planets, is sensitive to the exact orbits of the planets [12, 13]. So, although the above migration simulations place Jupiter and Saturn on roughly their current orbits, we found we needed to correct for some small differences. In addition, the long-term stability of MB asteroids is also affected by the terrestrial planets. Thus, we developed a technique, which is described in SM §S1, for transferring our particles from the final planetary system in the migration runs (containing Jupiter and Saturn only), to the real planetary system (containing all the planets but Mercury).

We integrated the system containing the 1270 particles and seven planets for a total of 100 Myr. We followed this with a 3.9 Gyr integration where we placed the terrestrial planets into the Sun and used a timestep of 0.4 yr. We removed any object if it either became Mars-crossing or reached 15 AU. Fig. 1 shows that, not only do the above calculations generate reasonable Trojan and Hilda populations, but they cover the range of the orbital elements of the D-type asteroids taken from the database of D. Tholen [14] and S. J. Bus [15]. A total of 174 particles survived the integration: 18 (10%) were Trojans, 7 (4%) were Hildas, and 149 (85%) were in the outer main belt (cf. Fig. 1). For comparison, among bodies with diameter $D > 40$ km (a size above which all the populations of interest here are presumably complete) there are 304 (39%) real Trojans, 58 (7%) Hildas, and 417 (54%) OMB asteroids ($2.82 < a < 3.27$ AU). (To calculate these numbers we assumed that Hildas and Trojans have albedos of 4% and the OMB objects have albedos of 9%; see SM §S3.1.)

The next and last step in our analysis is to estimate the total number of primitive

objects we expect to find in each population and compare them to observations. To accomplish this, we not only need to account for their long-term dynamical evolution, but for their collisional evolution as well. We used CoDDEM, a self-consistent code capable of following the collisional evolution and dynamical depletion of multiple interacting size-frequency distributions (SFDs) [16, 17]. We tracked five populations: (1) indigenous inner MB ($a < 2.82$ AU), (2) indigenous OMB, (3) captured OMB, (4) Hildas, and (5) Trojans. The collision probabilities and impact velocities with both themselves and each other were computed from the observed objects or, in the case of the Trojans, were taken from the literature [18, 19, 20]. Objects in pop. 1 and 2, which represent native asteroids, had a bulk density of 2.7 and 2.0 g cm^{-3} , respectively, and were assumed to follow the same disruption scaling law of undamaged basalt [21]. We also assumed that the MB SFDs had approximately the same shape 3.9 Gyr ago as they do today.

The captured populations (3, 4, and 5) have a bulk density of 0.5 g cm^{-3} , which is consistent with observations (see SM §S3.2). In addition, we employed a disruption scaling law consistent with fragmented ice [22] for these objects (see SM §S3 for a fuller discussion). Note that this implies that the implanted comets are easier to break up than the indigenous asteroids. For reasons explained in SM §S3.2, we assume that the initial shape of the SFDs of these populations was the same as that of the currently observed Trojans.

CoDDEM also requires us to input the dynamical depletion rates of the populations due to long-term orbital instabilities. For the captured populations we know this evolution from our dynamical simulations above. Unfortunately, the dynamical evolution of the indigenous asteroids is unknown. For simplicity sake, we assume that these asteroids decayed at the same rate as the captured MB objects (pop. 3, see the discussion in SM §S1).

The results of our collisional calculations are shown in Fig. 2a,b. We find that our model reproduces the SFDs of both the Trojan and Hilda populations for $D > 40 \text{ km}$ fairly

well given our model uncertainties. This is important because each population has unique characteristics that test our model’s assumptions. For example, while the Trojan and Hilda populations are both composed of weak primitive objects, comminution in the former comes mainly from Trojan objects hitting one other, while that in the latter is driven by impactors from across the asteroid belt. Matching the SFDs of these populations simultaneously in the same model, therefore, increases our confidence that our assumptions are reasonable.

The initial and final states of the captured OMB is shown in Fig. 2c. Because of our choice of a weak disruption scaling law, a much larger fraction of the captured objects are destroyed by impacts than their stronger indigenous counterparts. As a result, the remaining population of captured objects only makes up $\sim 15\%$ of the current OMB with diameters $D > 40$ km. This is consistent with the best available bias-corrected estimates of the fraction of D/P-types within the OMB over the same size range ($\sim 20\%$; [23, 24, 25]). The model also predicts that the SFD of the primitive bodies is steeper than that of the indigenous population for $D \gtrsim 20$ km, so that the fraction of D/P-types should increase for decreasing diameter. Though bias-corrected data at smaller sizes is limited, this also appears to match observations [23].

It should be noted that our ability to match observations is strongly dependent on the disruption scaling laws that we chose, particularly on the fact that captured comets are much weaker than native asteroids. While the true disruption scaling law for cometary material is unknown, test runs using asteroid-like disruption laws for all of these objects cannot reproduce the observed Trojan, Hilda, and main belt SFDs. They also predict that at least 90% of the OMB should be cometary, results that are inconsistent with observations (although see the discussion in SM §S0). Thus we conclude that our basic model requires that comets be significantly weaker than asteroids.

If the implanted objects are indeed weaker than the indigenous objects, then we can

also solve another long-lasting problem in planetary science. The micrometeorites collected on the Earth are dominated by material reminiscent of carbonaceous chondrite meteorites. At most 16% of these objects are believed to be associated with ordinary chondritic material [26] (see SM §S4). And yet, the asteroid belt, which has traditionally been considered the dominant source of this material [27] (see discussion in SM §S4.2), is roughly an equal mix of ordinary chondrite-like asteroids (e.g. S-types) and carbonaceous chondrite-like asteroids (e.g. C-types), see SM §S4.1. So the question has been why the micrometeorites do not reflect this ratio.

In our collisional grinding model we find that, at the current epoch, the implanted population produces nearly three times as many micrometeorites as the rest of the entire main belt, despite that fact that it accounts for only 15–20% of the outer belt population (see SM §S4.2 for details). And since the material that it produces is mineralogically indistinguishable from that produced by C-type asteroids¹, the model predicts that the overall proportion of ordinary chondritic dust is roughly 10% (i.e. less than 16%), in good agreement with observational constraints. This would not be possible if the implanted population were not significantly weaker than the indigenous one.

Our model also provides an explanation for the surprising fact that there are not many micrometeorite analogs in our meteorite collection. If we suppose that these micrometeorites are generated by the collisional cascade of embedded comets, we would not expect to see many macroscopic samples for two reasons. First, our implanted population resides in a region of the main belt from where it is very difficult to get meteorites [29, 30]. In

¹The difficulty in distinguishing between C-like and D-like micrometeorites based on mineralogy is due to the small size of these objects, to the continuum observed among the different Solar System objects [28], and to the heterogeneous nature of carbonaceous chondrites at the scale of micrometeorites ($\sim 100\mu\text{m}$).

particular, macroscopic objects leaving this region of the asteroid belt are most likely to be ejected from the Solar System by Jupiter, while the microscopic bodies, which are more susceptible to radiation forces, are more likely to be delivered to the Earth (see introduction to SM §S4). In addition, the presumed weak nature of the captured objects probably makes their macroscopic fragments unlikely to survive the passage through the Earth’s atmosphere or, if they do, survive for long on the Earth’s surface. In fact, in terms of oxygen isotope composition, the majority of the micrometeorites lie along a single fractionation line, and the only primitive meteorites that fall on this line are the CIs and Tagish Lake (see SM §S4.2). The nature of these very rare meteorites (6 in total) supports our hypothesis because they are weak, primitive objects. More importantly, Tagish Lake has been spectroscopically linked to D-type objects [31], and Orgueil’s orbit has been shown to be compatible with that of a comet [32].

We conclude that the primitive asteroids, including the Trojans and Hildas, could have formed at large heliocentric distances and been injected on to their current orbits by the early dynamical evolution of the giant planets. Our results, coupled with the idea that, at least, some metallic asteroids come from the terrestrial planet region [33], have a profound effect on our view of the asteroid belt. The traditional interpretation of the diversity of the asteroid belt is that it represents the original condensation sequence in the proto-planetary disk [2]. Indeed, their orbital distribution has been used to constrain both the thermal structure of the nebula and the effectiveness of various heating mechanisms as a function of heliocentric distance (e.g., the decay of short-lived radionuclides like ^{26}Al) [34]. If most D/P-types in the inner solar system are captured from farther out, however, our models of the proto-planetary disk will have to be significantly revised. Indeed, the diversity in the asteroid belt may be telling us more about the dynamical processes that controlled planet formation than about the physical characteristics in the proto-planetary nebula. In particular, the main asteroid belt has been a collection point for rogue planetesimals from

across the Solar System.

REFERENCES

- [1] Gradie, J., & Tedesco, E. Compositional structure of the asteroid belt. *Science* **216**, 1405-1407 (1982).
- [2] Bell, J. F., Davis, D. R., Hartmann, W. K., & Gaffey, M. J. Asteroids - The big picture. In *Asteroids II*, Arizona Press, pp. 921-945 (1989).
- [3] Matrajt, G., Guan, Y., Leshin, L., Taylor, S., Genge, M., Joswiak, D., & Brownlee, D. Oxygen isotope measurements of individual unmelted Antarctic micrometeorites. *Geochimica et Cosmochimica Acta* **70**, 4007-4018 (2006).
- [4] Clayton, R. N. Oxygen isotopes in meteorites. *Ann. Rev. Earth Pl. Sci.* **21**, 115-149 (1993).
- [5] Morbidelli, A., Levison, H. F., Tsiganis, K., & Gomes, R. Chaotic capture of Jupiter’s Trojan asteroids in the early Solar System. *Nature* **435**, 462-465 (2005).
- [6] Nesvorný, D., Vokrouhlický, D., & Morbidelli, A. 2007. Capture of irregular satellites during planetary encounters. *AJ* **133**, 1962-1976 (2007).
- [7] Levison, H. F., Morbidelli, A., Van Laerhoven, C., Gomes, R., & Tsiganis, K. Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune. *ArXiv e-prints* **712**, arXiv:0712.0553 (2007).
- [8] Licandro, J., de León, J., Pinilla, N., & Serra-Ricart, M. Multi-wavelength spectral study of asteroids in cometary orbits. *Advances in Space Research* **38**, 1991-1994 (2006).
- [9] Hsieh, H. H., & Jewitt, D. A Population of comets in the main asteroid belt. *Science* **312**, 561-563 (2006).
- [10] Tsiganis, K., Gomes, R. S., Morbidelli, A., & Levison, H. F. Origin of the orbital architecture of the giant planets of the Solar System. *Nature* **435**, 459-461 (2005).

- [11] Gomes, R. S., Levison, H. F., Morbidelli, A., & Tsiganis, K. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **435**, 466-469 (2005).
- [12] Gomes, R. S. Dynamical effects of planetary migration on the primordial asteroid belt. *AJ* **114**, 396-401 (1997).
- [13] Ferraz-Mello, S., Michtchenko, T. A., & Roig, F. The determinant role of Jupiter’s Great Inequality in the depletion of the Hecuba gap. *AJ* **116**, 1491-1500 (1998).
- [14] Tholen, D. J., & Barucci, M. A. Asteroid taxonomy. In *Asteroids II*, Arizona Press, pp. 298-315 (1989).
- [15] Bus, S. J., & Binzel, R. P. Phase II of the Small Main-Belt Asteroid Spectroscopic Survey. A feature-based taxonomy. *Icarus* **158**, 146-177 (2002).
- [16] Bottke, W. F., Durda, D. D., Nesvorný, D., Jedicke, R., Morbidelli, A., Vokrouhlický, D., & Levison, H. The fossilized size distribution of the main asteroid belt. *Icarus* **175**, 111-140 (2005).
- [17] Bottke, W. F., Durda, D. D., Nesvorný, D., Jedicke, R., Morbidelli, A., Vokrouhlický, D., & Levison, H. F. Linking the collisional history of the main asteroid belt to its dynamical excitation and depletion. *Icarus* **179**, 63-94 (2005).
- [18] Jewitt, D. C., Trujillo, C. A., & Luu, J. X. Population and size distribution of small Jovian Trojan asteroids. *AJ* **120**, 1140-1147 (2000).
- [19] Yoshida, F., & Nakamura, T. Size distribution of faint Jovian L4 Trojan asteroids. *AJ* **130**, 2900-2911 (2005).
- [20] Szabó, G. M., Ivezić, Ž., Jurić, M., & Lupton, R. The properties of Jovian Trojan asteroids listed in SDSS Moving Object Catalogue 3. *MNRAS* **377**, 1393-1406 (2007).

- [21] Benz, W., & Asphaug, E. Catastrophic disruptions revisited. *Icarus* **142**, 5-20 (1999).
- [22] Leinhardt, Z. M., Stewart, S. T., & Schultz, P. H. Physical effects of collisions in the Kuiper belt. *ArXiv e-prints* **705**, arXiv:0705.3943 (2007).
- [23] Mothé-Diniz, T., Carvano, J. M., & Lazzaro, D. Distribution of taxonomic classes in the main belt of asteroids. *Icarus* **162**, 10-21 (2003).
- [24] Carvano, J. M., Mothé-Diniz, T., & Lazzaro, D. Search for relations among a sample of 460 asteroids with featureless spectra. *Icarus* **161**, 356-382 (2003).
- [25] Burbine, T. H., Rivkin, A. S., Noble, S. K., Mothé-Diniz, T., Bottke, W. F., McCoy, T. J., Dyar, M. D. & Thomas, C. A. Oxygen and Asteroids. In *Oxygen in the Solar System*, in press.
- [26] Genge, M. J. Ordinary Chondrite micrometeorites from the Koronis asteroids. *37th Annual Lunar and Planetary Science Conference* **37**, 1759 (2006).
- [27] Dermott, S. F., Durda, D. D., Grogan, K., & Kehoe, T. J. J. Asteroidal dust. In *Asteroids III*, Arizona Press, pp. 423-442 (2002).
- [28] Gounelle, M., Morbidelli, A., Bland, P. A., Spurný, P., Young, E. D., & Sephton, M. A. Meteorites from the outer solar system? In *The Solar System beyond Neptune*, Arizona Press, pp. 525-541 (2008).
- [29] Morbidelli, A., & Gladman, B. Orbital and temporal distributions of meteorites originating in the asteroid belt. *Meteoritics and Planetary Science* **33**, 999-1016 (1998).
- [30] Bottke, W. F., Jr., Rubincam, D. P., & Burns, J. A. Dynamical evolution of main belt meteoroids: Numerical simulations incorporating planetary perturbations and Yarkovsky thermal forces. *Icarus* **145**, 301-331 (2000).

- [31] Hiroi, T., Zolensky, M. E., & Pieters, C. M. The Tagish Lake meteorite: a possible sample from a D-type asteroid. *Science* **293**, 2234-2236 (2001).
- [32] Gounelle, M., Spurný, P., Bland, P. A. The orbit and atmospheric trajectory of the Orgueil meteorite from historical records. *Meteoritics and Planetary Science* **41**, 135-150 (2006).
- [33] Bottke, W. F., Nesvorný, D., Grimm, R. E., Morbidelli, A., & O’Brien, D. P. Iron meteorites as remnants of planetesimals formed in the terrestrial planet region. *Nature* **439**, 821-824 (2006).
- [34] Grimm, R. E., & McSween, H. Y. Heliocentric zoning of the asteroid belt by aluminum-26 heating. *Science* **259**, 653-655 (1993).
- [35] Campins, H., private communication
- [36] Clark, B. E., Rivkin, A. S., Bus, S. J., & Sanders, J. X, E, M, and P-Type Asteroid Spectral Observations. *BASS* **35**, 955 (2003)
- [37] Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. Numerical recipes in FORTRAN. The art of scientific computing. Cambridge: University Press (1992).

Figure Captions

Figure 1: The semi-major axis (a), eccentricity (e), and inclination (i) distribution of asteroids in Hilda (objects which orbit in the 2:3 MMR with Jupiter near 3.9 AU), Trojan, and MB populations. The small blue dots show all the numbered objects in the IAU Minor Planet Center database. As such, they illustrate the overall distribution of asteroids. The red symbols show the D-type asteroids as cataloged by refs. [14] and [15]. It is important to note that asteroid (336) Lacadiera at $a = 2.25$ AU, $e = 0.1$, and $i = 5.6^\circ$, which is classified as a D-type by ref. [14], has an unusual spectrum [35], and thus is probably a different type of object. Thus, we used a smaller dot to plot the location of this object and do not include it in our analysis. We only include D-type asteroids here because it is difficult to distinguish P-types from other, more processed, asteroids, such that the catalog of P-types probably suffers from significant contamination [36]. The black dots show the location of objects captured during our simulations. Both the Hildas and the Trojans are well reproduced. Indeed, a Kolmogorov-Smirnov test [37] shows a reasonable statistical agreement between the predictions of our model and observations for both populations (see SM §S2). The main result of our simulations is that, in addition to the resonant asteroids, a significant number of objects are trapped in the OMB. Unfortunately, it is not possible to do a direct comparison between the orbital element distribution of our trapped objects and that of the D-types because the observations are biased due to selection criteria, asteroid families, and the like. However, we find noteworthy the fact that the inner edge of both populations are at $a \sim 2.6$ AU.

Figure 2: The beginning and end states of the SFDs in three of the regions studied. The left and center panels show the two resonant populations, while the right is the OMB, as defined in SM §3.1. In each plot, the blue curve shows the initial conditions for the captured populations in our CoDDEM simulations, which were assumed to have commenced at the end of planet migration. The shape of the initial SFDs for these populations were taken from the currently observed Trojan SFD. We chose the Trojans because, as we show below, these objects have been least affected by collisional grinding. In particular, using the cumulative number $N(> D) \propto D^{-q}$, we assigned $q = 6.4$ for $D > 105$ km and $q = 1.8$ for $D < 105$ km, where D is diameter. The overall scales of the SFDs for the captured populations are derived from a combination of the observed Trojans and the results of the 20 Myr migration simulations. For details see SM §S3.2—§S3.4. As described in SM §S3.5, we performed many simulations where we slightly changed the initial conditions and seeds for the random number generators. The red curves show one of our best-fit model’s prediction for the present day SFDs of the captured objects. For the Hildas and Trojans we expect the model SFD to match observations (black curves). The agreement is quite good, particularly given the large uncertainties in parameters of our models (see the Supplemental Material). Of particular note, the Trojans are known to have a significantly steeper SFD at $D \gtrsim 100$ km than the Hildas. Our model reproduces this because the Hildas, which cross the MB, undergo more collisional grinding. The comparison for the main belt is more complicated because it contains a mixture of different asteroid types. However, our model predicts that roughly 15% of $D > 40$ km objects in this region are comet-like, which is in good agreement with the observed relative abundance of D/P-type asteroids in this region.

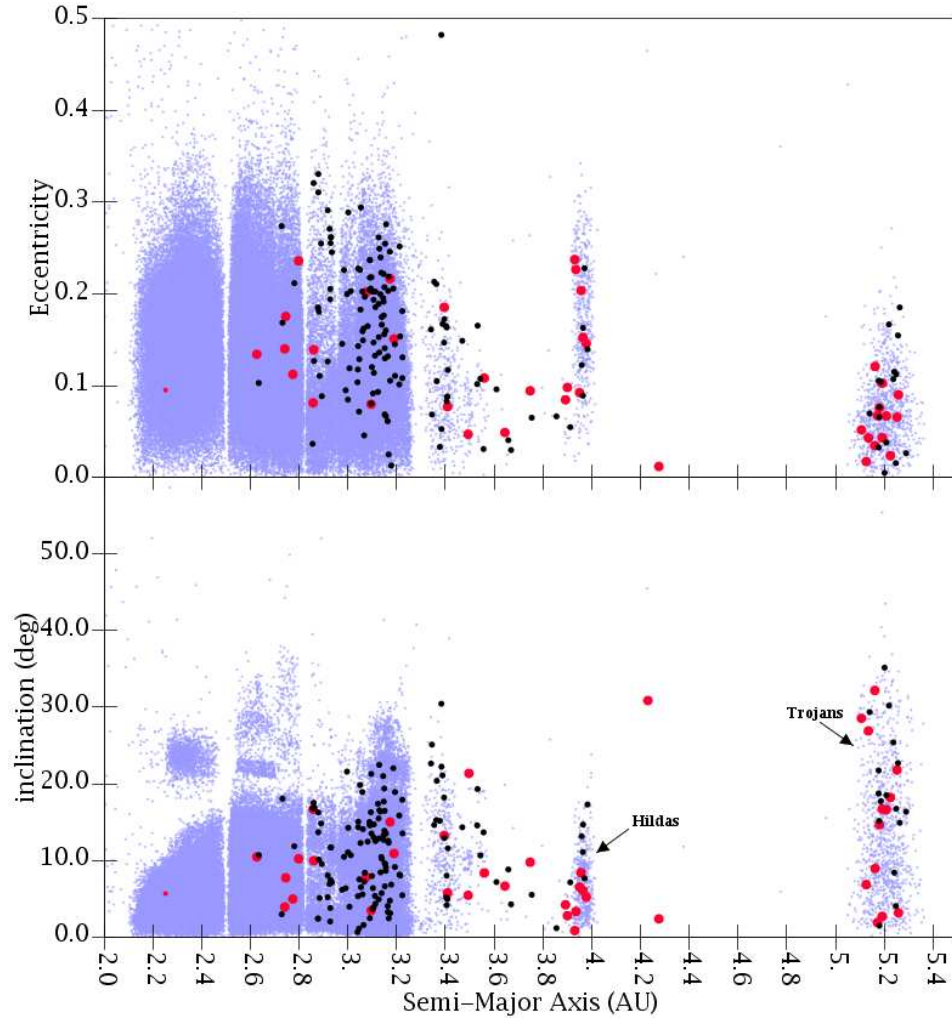


Fig. 1.—

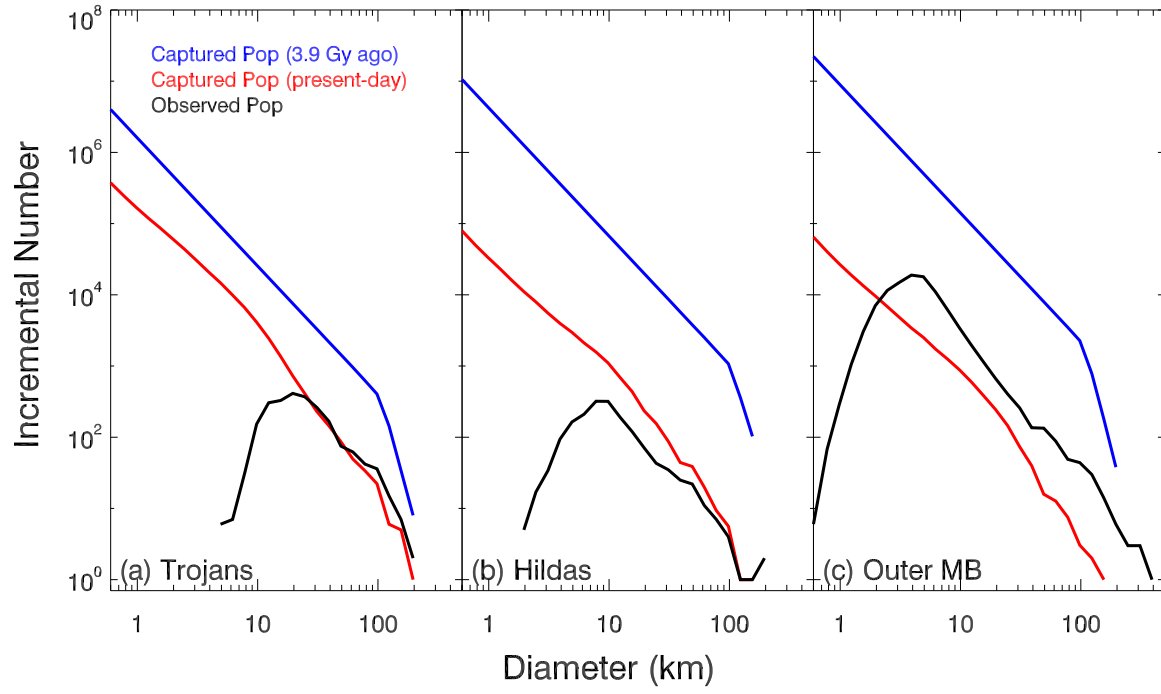


Fig. 2.—