
If the asteroid belt formed near its current location, the geochemically unaltered bodies provide insight into the thermodynamic conditions of the region between the inner silicate-rich planets and the outer volatile-rich planets. The main point of this study was to use spectral reflectance and albedo measurement observational data to infer the composition of asteroid belt bodies, leading to the result that there is compositional structure with distance in the asteroid belt and six distinct compositional groups.

**Methods.** The authors determine that previous asteroid composition surveys have been limited and biased for two reasons. First, they have only used spectral data in their analyses, which can easily lead to misidentifications of different asteroid types, especially E, M, and P. These asteroid types are spectrally similar, but have differences in albedos, possibility related to mineralogical differences. Second, previous studies have only observed asteroids with semi-major axes between 2.2 and 3 AU, which is a limited portion of the main belt. Thus, the authors take an approach to produce an improved catalog of classifications of different bodies within the main belt, utilizing albedo measurements (from 10-20 micron radiometry) and spectroscopy (0.3 to 1.1 micron) and exploring 1.8 to 5.2 AU for completeness. The authors utilize a previously defined classification scheme (table 1; refs in caption). To produce a true compositional distribution, the authors remove multiple biases from their data, including (1) effects of an incomplete survey, (2) observation bias toward nearer, larger, and brighter asteroids, (3) increased observation of specific asteroid families that may bias the survey towards those types, and (4) unknown formation locations of planet-crossing asteroids. In total, the authors produced a survey sample of 1373 asteroids.

**Findings and Results.** The main findings of this paper are illustrated in figure 1. The authors determine that, while some of the asteroids are not classifiable in the utilized scheme (only 656 of the 1373 are classifiable), it is evident that the asteroid belt can be broken up into six different semi-major axis regions, each corresponding to a different asteroid type. There is a non-random distribution of the different types with increasing distance. However, it is important to note that the relative abundances shown in figure 1 are not representative of a mass distribution because many of the large main belt objects, including Vesta and Pallas, are deemed unclassifiable and much of the asteroid belt mass is held within a few large objects. The authors also warn the reader of a few caveats in their study: (1) observed abundances of different types may have been enhanced by collisional effects, (2) the largest E-type asteroid, is not within the E + R region, a single failed case study, (3) the distinct boundaries between types may be related to resonances with Jupiter, and (4) there is interpolation in the data at large distances from the Sun because of gaps in the distribution (figure 1), but the authors follow predicted trends for those regions anyway.

The authors conclude that the observed compositional variation with distance from the Sun may represent compositional changes across the belt if the asteroids formed at their current heliocentric distance. Additionally, the authors suggest that the observed structure is consistent with solar system chemical condensation models. This conclusion does not unequivocally conclude that the mineralogy of the different types is consistent with the condensation models.

There is compositional structure in the belt and the asteroids may have formed there. “Chemical composition (of asteroids) can be used to provide constraints on small-scale thermodynamic conditions of the solar nebula in the transition region”.

**Outstanding questions and critiques.**

It would be unlikely to produce this taxonomic distribution if the asteroid belt was a culmination of objects transported randomly from elsewhere in the solar system. However, it has more recently been argued that the distribution of planets may be related to giant planet migration, during which much of the asteroid belt material has been delivered from elsewhere. Would improved studies debunk this paper, suggesting that the composition of the belt is not taxonomically distributed? Does the non-random distribution argue against planetary migration models?

Approximately half of the observed asteroids did not fit within the classification scheme. Do you think a better classification scheme is required for accurate completion of this study? It may be interesting to see if the distribution is as clear if all studies asteroids were classified.

The authors state that if the asteroid belt was not formed at its current location, “additional problems in celestial mechanics must be addressed”. As suggested by [1] and is an important factor of the Nice Model [2,3], it is possible that evolution of the solar system and migration of the giant planets has put material into the asteroid belt from both very large heliocentric distances and the terrestrial-planet region. What are the other mechanisms that could produce the observed structure?

Summary: This work is a refined, bias-corrected asteroid taxonomy based visible spectra from an all-sky asteroid survey, the SDSS. They present the distribution of asteroids throughout the belt in terms of number (as in previous works), surface area, volume, and mass. They argue that their new distribution shows robust evidence for D-types in the inner main belt, which is not predicted in current dynamical evolution models.

Important methods, figures, and findings: The SDSS was an automated survey of over 100 thousand asteroids. Collected asteroid spectra had 5 VIS-NIR bands (0.3 – 1.0µm): u', g', r', i', and z'. Band u' was discarded due to high error, so spectra had four points. The spectra used in the original Bus-DeMeo (2009) classification were resampled to this resolution (see Fig. 4 in the paper). To define taxonomic classes, they plot gri slope (based on bands g', r', and i') vs. z-i (the difference between bands z' and i', which corresponds to the presence of a 1µm absorption) (Fig. 1). They plot the resampled Bus-DeMeo spectra (colored) and the SDSS spectra (gray), and adjusted the lines between the Bus-DeMeo-defined taxa based on manual analyses of the spectra.

Figure 1: Data used to create asteroid taxonomy for SDSS data (gray) based on the resampled spectra of the data used in forming the original Bus-DeMeo taxonomy (colored points).

They go through a thorough explanation of their bias-corrections. For example, using an automated, all-sky survey prevents bias toward asteroid families or regions of the belt. Calculation of discovery completeness and distribution of each class allows for careful correction within each region of the belt independently. These corrections change the relative importance of different classes at various positions in the belt (Figs. 9 and 10 in the paper).

They present distributions in terms of total surface area (Fig. 12 in the paper), volume (Fig. 13 in the paper), and mass (Fig. 14 in the paper). In Fig. 2 below, we can see the relative importance of each class in each region. One of their main conclusions is that, even when everything is rigorously bias-corrected in ways that have not been done in previous distribution models, they have robust detections of primitive D-type asteroids in the inner belt, which is not predicted in the Nice Model.

Figure 2: The calculated fractional mass distribution of each asteroid class across the belt.

Questions:

- Without any provided spectra, are we comfortable with the fact that they relabeled K- and L-types detected within the Hildas and Trojans as X- and D-types? They did the same thing with S-types detected in Eos, relabeling them as K-types. How are these unexpected findings erroneous while the primitive D-types detected in the inner belt are not?

- If we had infinite, perfect data, are there other ways we would want to present the distribution, other than number, surface area, volume, and mass?

Other references:


- For the original Bus-DeMeo taxonomy and high-resolution spectra that are shown resampled in this paper: DeMeo, F.E., Binzel, R.P., Slivan, S.M., Bus, S.J., 2009. An extension of the Bus asteroid taxonomy into the near-infrared. Icarus 202, 160180.


Main points: The dynamics of the Nice model result in the insertion of primordial, icy trans-Neptunian objects into the outer asteroid belt. Thus the compositional differences observed in the asteroid belt are not a direct reflection of the original condensation sequence of the protoplanetary disk, as suggested in previous models where asteroids formed in situ (e.g., Gradie and Tedesco et al., 1982). The authors find that the captured bodies are weaker, and more susceptible to collisional evolution than typical, indigenous main-belt asteroids, and therefore more likely to be a source of micrometeorites.

Brief Summary:

Nicé model. The authors model the trajectories of small bodies during the dynamical events proposed in the Nice model. In this model, giant planets formed in an initial compact configuration, surrounded by a disk of planetesimals. After ~600 Myr, the giant planets became unstable and Uranus and Neptune scattered outwards, scattering constituents outward as well.

Methods. (1) The authors track the evolution of objects formed in the primordial comet disk as the orbits of the giant planets evolve. The model is fed a steady flux of planetesimals through the Jupiter-Saturn system over 10 Myr. The authors tracked the long-term evolution of the captured comet population to compare it with observations. (2) They model the orbits, total number, and distribution of the comet-like asteroids using a self-consistent code, CoDDEM. (3) Finally, Levison et al. explore cometary disruption by dividing the amount of energy required to catastrophically disrupt a comet by a factor $f_Q$. Successful collisional models are where $f_Q \geq 3$.

Results. (1) A significant number of objects are captured either in Trojan orbits (as in Morbidelli et al., 2005) or in orbits inside that or Jupiter. The model produces a substantial population of Trojans (13%) and Hilda (8%) asteroids (Fig. 1). There is reasonable agreement between the orbital element distribution between the modeled captured objects and the known primitive asteroids, indicating that most primitive asteroids formed beyond ~15 AU. (2) The model reproduces the size-frequency distributions of Trojan and Hilda populations of bodies with diameters > 40, confirming that the model parameters and assumptions are reasonable. (3) The authors conclude that captured comets are weaker than native asteroids. Dark, captured bodies are thus more inclined to collisional evolution and a tremendous source of micrometeorites.

Outstanding questions:

1. Planet migration contributed to contamination of the asteroid belt, and the main belt may sample conditions across the Solar System. Yet why do certain groups, such as the Hilda asteroids and the Jupiter Trojans, appear distinctly homogeneous?
2. How biased is our sample collection? What population of the asteroid belt does it really reflect?

Additional references:


Morbidelli, A. et al., 2005. Chaotic capture of Jupiter’s Trojan asteroids in the early Solar System. Nature, 435, 462–465. [This reference is referred to in the article as ref. 3; the authors use the planets’ equations of motion used in the ‘fast migration’ run.]

Vokrouhlický, D. et al., 2016. Capture of trans-Neptunian planetesimals in the main asteroid belt. Astro. J., 152, 39. [This more recent publication presents a five-giant-planet instability model that produces better overall constraints than the Levison et al. (2009) model.]