Asteroids: their nature and distribution in the Solar System

1600187

24 April 2016

Abstract

This report focuses on the implication of the distributions of the nature of asteroids. The distribution of their compositions provides evidence for planetary migration and therefore contributes towards the Grand Tack and Nice models of the evolution of the Solar System. Current research is focusing on collecting data on asteroids that are still being discovered today. It is also attempting to delve deeper into the interiors of larger asteroids in the hope of providing more or new evidence towards how the Solar System formed.

Table of Contents

1. Introduction

This report will discuss collected data to examine the nature and distribution of asteroids in the Solar System. From this data, one is able to infer certain developmental progressions of aspects of the Solar System due to the composition, shape and distribution of asteroids. This is what makes them such interesting subjects of study.

Using techniques such as observations of spectral reflectance and albedo, the compositions of the asteroids may be deduced. This will be investigated as the distribution of compositions throughout the Solar System can give an insight into its formation. This report will then review the current leading models of the evolution and current formation of the Solar System. The short fallings and potential future research paths will then be assessed.

2. The distribution of asteroids in the Solar System

Firstly, asteroids, or 'minor planets', are defined as rocky or metallic remnants that orbit the Sun and are debris left from the formation of the Solar System (NASA, n.d.). They are the remains of former worlds that failed to form (Lang, 2011).

Asteroids are present throughout the Solar System, though are not uniformly distributed. This section considers the accumulations of asteroids in their heliocentric manner.

Most asteroids are found in the between around 2 and 3.5 AU from the Sun, in an area known as the Main Belt (depicted in Figure 1). This review will use the terms DeMeo et al. (2015) use for the areas of the Main Belt. "Inner", "Middle" and "Outer" Main Belt are located between Mars and Jupiter and are labeled by the distances 2, 2.5 and 2.82 AU from the Sun, respectively. The significance of these distances is that unstable regions, known as Kirkwood Gaps, are located at 2.5 and 2.82 AU, where an asteroid's orbit would be in resonance with Jupiter's orbit (Carry and DeMeo, 2014).

Using the smooth distribution of the solid material of the planets, the Main Belt is expected to contain roughly the mass of the Earth in material, but today it is estimated to only contain approximately 5×10^{-4} Earth masses (DeMeo et al., 2015). This would not have been enough to accrete the larger asteroids that currently exist, and so a period of depletion of mass after the Asteroid Belt formation is theorized and later examined in Section 3 (Weidenschilling and Jackson, 1993).

Also displayed in Figure 1 are: the Hungaria asteroids, located closer to the Sun than the Main Belt; the Hilda asteroids, located near 4 AU; the Cybele asteroids, starting at the edge of the Ouster Main Belt; and the Jupiter Trojans, located in the L4 and L5 Lagrange points of Jupiter's orbit (indicated in Figure 2).

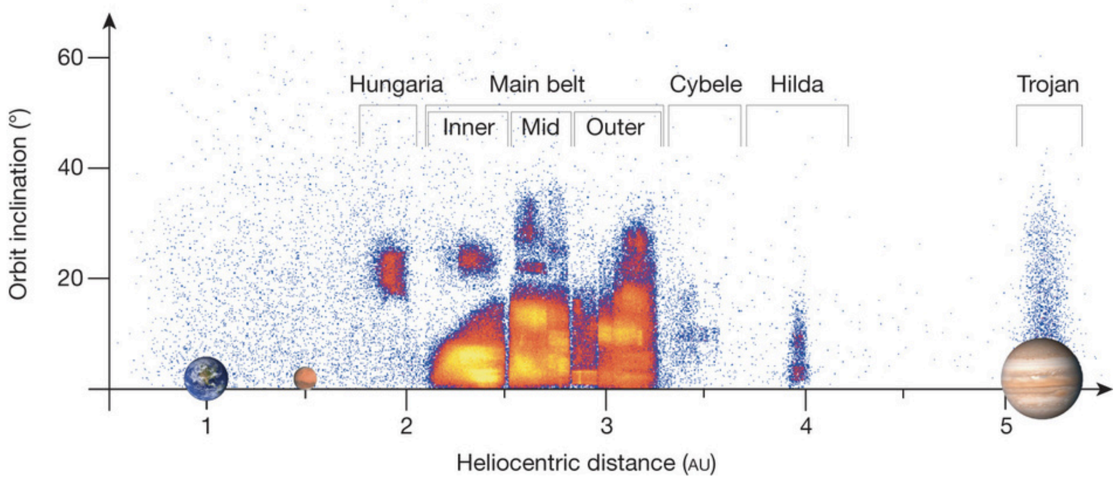

Figure 1: A cartoon graph displaying the main Solar System components with the orbital structure of asteroid inclinations and number density of objects (with a gradient of yellow to blue representing highest to lowest number density). The main groups of asteroids are labeled (Carry and DeMeo, 2014).

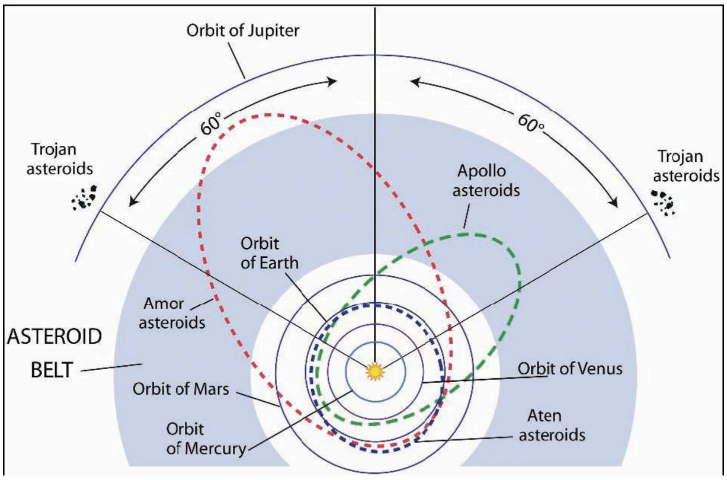

Figure 2: A diagram displaying the orbits of the planets and groups of asteroids of the Middle to Inner Solar System. The Jupiter-Trojan asteroids are indicated at their known L4 and L5 Lagrangian points (Farid, 2011).

2.1. Possible asteroid formation mechanisms

Though Figure 1 indicates a high density of objects in the Main Belt and in other areas of the Solar System, the actual distribution of asteroids with respect to each other is very sparse. This leads to relatively infrequent collisions that often only occur due to gravitational disruption of an asteroid's path by a larger object.

Asteroids appear in various sizes and are most easily measured with a diameter higher than 5km, though asteroids less than a meter across are defined as meteoroids. The largest asteroid is 1 Ceres measured to be 975 km by 909 km (Greicius and Dunbar, 2015).

Smaller asteroids tend to display periodic brightness variations, leading to the conclusion that they are irregular. This irregularity occurs through destructive collisions triggered by larger bodies such as Jupiter accelerating bodies towards each other. Larger asteroids, however, are more spherical and therefore less likely to be destroyed by the collisions initiated by larger bodies. Instead they are more likely to accrete mass, and start formation relatively early (Lang, 2011) (DeMeo et al., 2015).

Asteroids could be formed of chondrules which accrete into chrondrites whilst still hot, therefore within hours of their formation (DeMeo et al., 2015). Most chondrite types have evidence for the presence of chondrules at the time of accretion (DeMeo et al., 2015). This is difficult to reconcile with the asteroids that exist past the snow line as the existence of ice would not be possible after the heat of the chondrules evaporated any water that could have existed on the asteroid originally.

However, Johnson et al., (2015) proposed that chondrules were produced in collisions and then accreted relatively slowly. If this were the case, chondrules would be a byproduct of planetesimal formation rather than an integral part of it, and the principal mechanism for formation is yet to be identified.

2.2. Distribution of asteroid compositions

An asteroid's composition provides insight into its accretion, its origins, and its movement across the Solar System. The history of the Solar System and how it could have developed can then be modeled using this information.

The color of the reflected sunlight of asteroids could indicate that they've formed in different conditions at different distances from the Sun (Lang, 2011). Their inferred compositions in each semimajor axis region (displayed in Figure 3) are also consistent with asteroids accreting from solar nebula at or near their present locations (Gradie and Tedesco, 1982).

Since their formation, there has been little geochemical alteration of the asteroids that are present in the Solar System (Gradie and Tedesco, 1982). There are many different types of asteroid, placed into taxonomic groups in terms of their composition. A letter is used to denote each type, for example the P-type asteroid has a low albedo and spectrum in the red wavelengths (DeMeo et al., 2009). It is widely debated whether they should be put in such groups, as there exist many unclassifiable asteroids in this scheme, and even Ceres is an unusual C-type. Taxonomic types of compositions of asteroids with diameters of over 100km follow a heliocentric distribution in the order S, C, P, D (Gradie and Tedesco, 1982), (DeMeo et al., 2015).

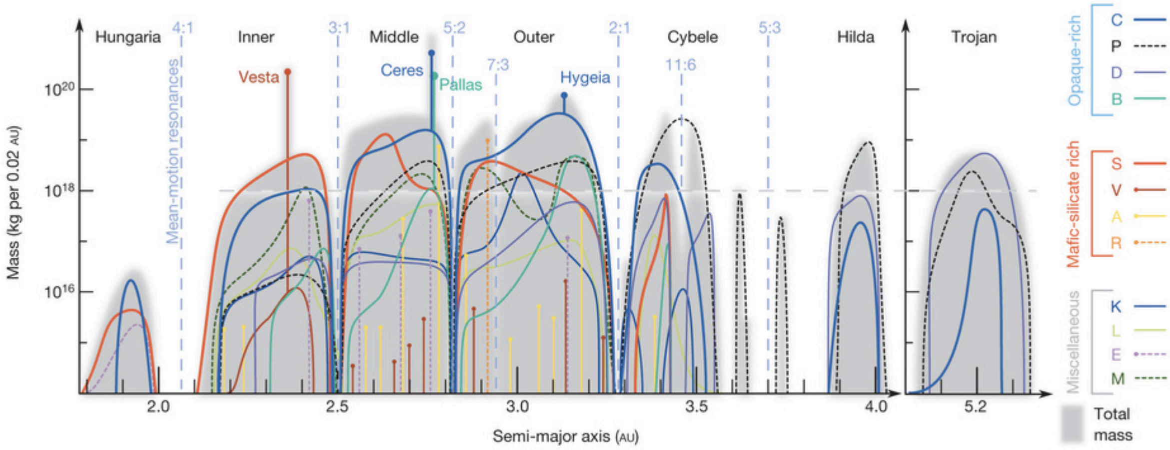

Figure 3: This graph displays mass against semi-major axis, giving a clear insight into distribution of the mass of the Solar System. The grey fill is the total mass within each 0.02-AU bin, with each colour representing different spectral classes of asteroid. The key represents element-rich mass distributions. The horizontal line at 10^{18} kg is the limit of the work from the 1980s (Carry and DeMeo, 2014).

75% of main-belt asteroids are dark, black carbonaceous C-type in the outer half of the belt (Lang, 2011). Another 15% of main-belt asteroids are bright, red silicate S-type in the inner half of the belt (Lang, 2011).

Some asteroids are solid of uniform composition i.e. 433 Eros, or fragments of rocks held together by gravity i.e. 25143 Itokawa (Lang, 2011). Larger asteroids, however, have layers implying they've undergone differentiation. 1 Ceres is round, which also indicates a differentiated interior. This means it probably has a rocky core, thick mantle of ice, and a dusty outer crust (Lang, 2011).

There are also the differences between the asteroids either side of the snow line. Objects beyond the orbit of Jupiter tend to be ice-rich, which could distinguish whether asteroids have origins from the inner or outer Solar System through investigation of the H isotopes (DeMeo et al., 2015). These asteroids are geochemically distinct from other inner Solar System objects, however there's no indication of them being formed much further from the Sun than other asteroids.

2.3. Orbital inclination

The orbital inclination of an asteroid also affects its nature. Asteroids have much higher orbital inclinations than the planets (Carry and DeMeo, 2014). The orbital inclination distribution of some of the asteroids in the Main Belt often protects them from disruption. In particular asteroids within the radius of the inner Main Belt, such as the Hungaria asteroids that have an orbital inclination of 20 degrees, could have been perturbed by Mars, but were not (Carry and DeMeo, 2014) (Spratt and Christopher, 1990). This lack of perturbation reduces the amount of collisions and also influences the mass reduction thought to have occurred in the evolution of the Solar System.

3. The evolution of the Solar System

There are many theories that attempt to ascertain how the Solar System evolved; the leading ones amongst planetary scientists tend to compliment each other. For instance, every theory for the formation of the planetesimals relies on the Nebula Theory. This is the theory that there was a gaseous solar nebula, which reduced material velocities and encouraged accretion of asteroids (Ward, 1981).

Other generally accepted models that describe the later evolution of the Solar System are the Grand Tack Model and the Nice Model. It is theorized that after the formation of the Solar System, the Main Belt was created and sculpted through evolutionary processes. These processes allowed movement of asteroids through the Solar System and give insight into the gradient of the taxonomic types, for example, Bottke et al. (2006) suggest that debris from the terrestrial planet region became inner Main Belt asteroids. This means that the theory that planetesimals are primordial is no longer the leading theory (DeMeo et al., 2015).

After accretion, asteroids were internally heated by the decay of the radionuclide ^{26}Al that was a material of the protosolar molecular cloud (DeMeo et al., 2015). This can be used in the estimations of age, but is complicated by the tidal friction processes present in any asteroid affected by a strong, periodic, gravitational force.

A key feature of the Grand tack model is radial mixing; scattering of most of the Main Belt from different parent populations due to planetary migration (Walsh et al., 2011). The substantial planetary migration causes mass depletion and more radial mixing of the remnant bodies in the dynamically stable Main Belt. One key planetary migration was the path of Jupiter, which travelled towards the Sun then out again. On its travel inwards the number of Main Belt objects was diminished, but as Jupiter migrated outwards again some remnants were returned (DeMeo et al., 2015). This mechanism supports the separate parent populations that would have created the majorly varying compositional classes of the asteroid belt. The larger planets, including Jupiter, accelerated asteroids towards each other, preventing accretion and encouraging higher velocities that caused their pulverization.

It is assumed that mass removal is closely linked to the dynamical evolution of the Solar System and the formation and migration of the planets. The Nice model supports the Grand Tack model, adding a later period of mass depletion thought to have taken place after planetary migration. A primordial Main Belt of 1000 times its present mass would have collisionally expelled enough mass to return it to the current state of the Main Belt. This could have been a good contribution towards the evolutionary theories of the Solar System, however, due the lack of residual evidence of this particularly energetic development, a primordial belt of this size was ruled out.

4. Current Problems and Research

Due to the complexity of the Solar System and the factors in its development, Tsiganis (2015) states that it isn't possible to simulate the Solar System formation theories computationally. To succeed in this the simulation would have to ensure that the mass and orbital distribution of both the terrestrial planets *and* the asteroids are compliant with the current structure of the Solar System.

Complications arise in most models, which are difficult to surmount with the data available. One of the important problems with the Grand Tack Model and Nice Model is in the orbital inclination distribution. In theory, the planetary embryos are meant to excite and remove mass from the Main Belt, but actually only deplete the low inclination asteroids (DeMeo et al., 2015). This is in contrast to the observation of 93.3% of numbered Main Belt asteroids residing within an inclination of 20 degrees (Minor Planet Centre, 2016).

We are limited in our knowledge of composition as the collection of compositional information is fairly difficult; the sheer distance of asteroids prevents easy evaluation and the pure timescale of this data collection is a hindrance in itself. The first spacecraft to land on an asteroid was NEAR. It "circled the near-Earth asteroid 433 Eros for a year, examining its dusty… landscape… obtaining an accurate mass for the asteroid and showing it is solid throughout." (Lang, 2011). There is little physical compositional evidence, though the spacecraft Hayabusa recently returned the first samples of an asteroid (the 25143 Itokawa asteroid) to Earth for evaluation (Lang, 2011).

Another technique available to determine the composition of asteroids is chemical evaluation of meteorites. However, this method is limited with only around 100-150 distinct parental asteroids having been identified from a collection of approximately 40,000 meteorites (DeMeo et al., 2015).

We are able to use remote sensing to measure albedo and other characteristics of asteroids. Recently, many major surveys, including the NEOWISE survey and the Sloan Digital Sky Survey, have created a plethora of measurements of albedos and diameters to be analyzed. As of 24th December 2015, the International Astronomical Union Minor Planet Centre had collected data of nearly 7×10^5 minor planets as can be seen in Tables 1 and 2 (Minor Planet Centre, 2015). New asteroids are regularly being located, showing that our knowledge of the Solar System is far from complete. Furthermore, key aspects of the nature of asteroids are still missing, including information of their interiors, which are significantly indefinite.

Census of Dwarf/Minor Planets

Inner/Mid Solar System	Count
Atiras	23
Atens	970
Apollos	6663
Amors	5840
Hungarias	15039
Mars-Crossers	11918

Mid/Outer Solar System	Count
Main-Belt Asteroids	655615
Hildas	3803
Jupiter Trojans	6389
Distant Objects	2038

Dwarf Planets	Count
Dwarf Planets	5

Orbits and observations of these objects are available on the MPC Database search page.

Table 1: Census of Dwarf/Minor Planets – November 2015 (Minor Planet Centre, 2015)

Near-Earth Objects

Near-Earth Asteroids	13497
1+ KM Near-Earth Asteroids	877
Potentially Hazardous Asteroids	1640
Near-Earth Comets	97

Table 2: Census of Near-Earth Objects – November 2015 (Minor Planet Centre, 2015)

The investigation of asteroids is an important and ongoing research area. Asteroids are dynamic constituents of the Solar System (even without the presence of planetary migration), so they are still accreting and impacting planetary bodies. This would mean that data recorded from these bodies would have to account for these collisions to prevent misinterpretation of data. Current predictions from observations estimate that over $\$6\times10^{20}$ worth of material resides in the asteroids of the Solar System, leading to significant interest into methods of their acquisition (Chodas, 2014). It is thought that, with the current progression of technology, astronauts may land on an asteroid by 2025 (Lang, 2011), which will further our ability to physically evaluate geochemical composition, and hopefully enable a comprehensive understanding of the history and development of the Solar System.

Summary

Asteroids are key constituents of the Solar System that give information towards its development. Their nature – including their geochemical composition, their size, and their shape – is diverse in the sense that each asteroid has a complex history that influenced these characteristics whilst also influencing the same characteristics. For example, a smaller asteroid that has accreted could gradually get smaller and more irregular in shape due to destructive collisions that are only destructive *because* it is so small.

Whilst the importance of the history of each individual asteroid is substantial, asteroids as a whole provide an understanding into more than just their own history. Their distributions exhibit patterns in asteroidal characteristics and lead to insights into the development of the Solar System. Evidence indicates that there has been little geochemical alteration since their formation, but they are not all grouped together in their compositions. The patterns in distribution support the idea of planetary migration and therefore the Grand Tack and Nice Models.

The evidence currently obtained from the limited physical resources available provides enough information to postulate the Solar System's formation. However, as is regularly the case in science, more information would substantially benefit and clarify the current models. Current research aims to further this knowledge through investigation of samples of asteroids and examination of more asteroids using remote sensing. Within the next 20 years we can also hope to see an extensive improvement in the technology used to evaluate the asteroids, and therefore an enhanced examination of their interiors, and ultimately providing a comprehensive picture of the Solar System and its evolution.

Bibliography

Bottke, W.F., Vokrouhlicky, D., Rubincam, D.P. and Nesvorny, D. (2006) 'The Yarkovsky and Yorp Effects: Implications for Asteroid Dynamics.', *The Annual Review of Earth and Planetary Science*, vol. 34, Jan, pp. 157-191.

Carry, B. and DeMeo, F.E. (2014) 'Solar System Evolution from Compositional Mapping of the Asteroid Belt', *Nature*, vol. 505, no. 7485, Jan, pp. 629-634.

Chodas, P. (2014) *Near Earth Object Program: FAQ*, 22 Dec, [Online], Available: http://neo.jpl.nasa.gov/faq/#why1 [15 Mar 2016].

DeMeo, F.E., Alexander, C.M.O., Walsh, K.J., Chapman, C.R. and Binzel, R.P. (2015) 'The Compositional Structure of the Asteroid Belt', in Michel, P. (ed.) *Asteroids IV*, Tuscon: University of Arizona Press.

DeMeo, F., Binzel, R.P., Slivan, S.M. and Bus, S.J. (2009) *EAR-A-VARGBDET-5-BUSDEMEOTAX-V1.0. Bus-DeMeo Asteroid Taxonomy V1.0.*, 10 Jul, [Online], Available: http://sbn.psi.edu/pds/resource/busdemeotax.html [16 Apr 2016].

Farid, M. (2011) *Near Earth Objects Danger and Studies*, 04 Feb, [Online], Available: http://astromic.blogspot.co.uk/2011/02/near-earth-objects-danger-and-studies.html [24 Dec 2015].

Gradie, J. and Tedesco, E. (1982) 'Compositional Structure of the Asteroid Belt', *Science*, vol. 216, no. 4553, June, pp. 1405-1407.

Greicius, T. and Dunbar, B. (2015) *Dawn - Ceres and Vesta*, 31 Jul, [Online], Available: http://www.nasa.gov/mission_pages/dawn/ceresvesta/index.html [24 Apr 2016].

Johnson, B.C., Minton, D.A., Melosh, H.J. and Zuber, M.T. (2015) 'Impact jetting as the origin of chondrules', *Nature*, vol. 517, no. 7534, Jan, pp. 339-341.

Lang, K. (2011) *The Cambridge Guide to the Solar System*, 2nd edition, Cambridge: Cambridge University Press.

Minor Planet Centre (2015) *The International Astronomical Union Minor Planet Centre*, 24 Dec, [Online], Available: http://www.minorplanetcenter.net/ [24 Dec 2015].

Minor Planet Centre (2016) *The MPC Orbit (MPCORB) Database*, 16 Apr, [Online], Available: http://www.minorplanetcenter.org/iau/MPCORB.html [16 Apr 2016].

NASA *Asteroids: In Depth*, [Online], Available: http://solarsystem.nasa.gov/planets/asteroids/indepth#! [24 Dec 2015].

Spratt and Christopher, E. (1990) 'The Hungaria group of minor planets', *Journal of the Royal Astronomical Society of Canada*, vol. 84, no. 2, Apr, pp. 123–131.

Tsiganis, K. (2015) 'How the Solar System didn't form', *Nature*, vol. 528, no. 7581, Dec, pp. 202-204.

Walsh, K.J., Morbidelli, A., Raymond, S.N., O'Brien, D.P. and Mandell, A.M. (2011) 'A low mass for Mars from Jupiter's early gas-driven migration', *Nature*, vol. 475, no. 7355, Jun, pp. 206-209.

Ward, W.R. (1981) 'Solar nebula dispersal and the stability of the planetary system: I. Scanning secular resonance theory', vol. 47, no. 2, Aug, pp. 234-264.

Weidenschilling, S.J. and Jackson, A.A. (1993) 'Orbital resonances and Poynting-Robertson drag.', *Icarus*, vol. 104, no. 2, Aug, pp. 244-254.