# The Kuiper Belt

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#### 1 Introduction

The Kuiper Belt is a swarm of trans-Neptunian objects, including Pluto, which can be broadly regarded as artefacts of the sun's proto-planetary solar nebula (PPSN). It is considered to be the source of most of the short period comets observed.

Although the first detection of a Kuiper Belt Object (KBO) was achieved in 1992 (Jewitt and Luu, 1993), there was a precedent for its detection; the idea of a group of objects existing beyond Pluto had been suggested a number of times previously.

In a discussion of the then-recent discovery of Pluto, Leonard (1930) suggested that Pluto may constitute the first detection in a series of 'ultra-Neptunian' bodies, which would have sizes and compositions similar to that of Pluto.

When considering the of the formation of the planetary disk, Edgeworth (1949) suggested that the material scattered during planetary formation could have formed a disk outside the orbit of Neptune, who's density decreased with radius. Occasionally, objects in this 'vast reservoir of comets' would be disturbed from their orbit and entered the inner solar system.

The planetesimals that make up the Kuiper Belt are roughly divided into a dynamically 'cold' classical population and dynamically 'hot' scattered population. This distinction is based on the eccentricity ( $\epsilon$ ) and inclination (*i*) of an object's orbit.

# 2 Kuiper Belt Populations

The cold population of KBOs can be further subdivided into two groups, referred to as classical and resonant; this distinction was well outlined in Luu and Jewitt (2002).

The classical population is characterised by semimajor axes of 42 < a < 48AU, eccentricities of  $0 < \epsilon < 0.2$  and perihelia of q < 35 AU. The other distinctive characteristic of this population is that their orbital

motion is not significantly influenced by the gravitational influence of Neptune.

In contrast to this, the resonant population is observed to have orbital periods which form a ratio of integers with the period of Neptune; resonant KBOs have been captured into these orbital resonances via Neptune's gravitational influence. Also, resonant KBOs generally have larger eccentricities and inclinations that the classical population.

The dynamically hot population, or the scattered Kuiper Belt objects (SKBOs), is characterised by large, high eccentricity, highly inclined orbits.

#### **3** Spectral and Colour Features

A review of features observed in the spectra of KBOs was provided by Brown (2012). In this text, the KBOs discussed were classified according to size. The size of KBOs are primarily determined via the use of radiometry to estimate the emitting surface area of an object under scrutiny.

Pluto, the largest and perhaps best-studied KBO, is rich in absorption features of  $CH_4$ ,  $N_2$  and CO. These features have also been detected on Triton, which is thought to have been captured from the Kuiper Belt into its current orbit around Neptune (Brown et al., 1995).

High quality direct imaging of Pluto and its satellites Charon, Nix and Hydra may be obtained by the NASA New Horizons mission when the satellite reaches Pluto in July 2015; the LORRI imager and the Ralph telescope will both be used for this purpose (Reuter et al. (2008), Cheng et al. (2008)). The primary goal of New Horizons' onboard UV spectrometer, Alice, is to obtain data with which the molar fraction of CO,  $N_2$ , CH<sub>4</sub> and other molecules in Pluto's upper atmosphere can be calculated (Weaver et al., 2008).

 $CH_4$  is relatively easy to detect via its strong absorption bands in the near infrared, and has been definitively detected on 6 of the largest known KBOs (Brown, 2012).

Midsized KBOs (of diameters  $\sim$ 500-1000 km) are too small to retain surface volatiles against Jeans' escape. The fact that they lack an uniform outer layer of frost makes these objects more interesting spectroscopically. However, their smaller size and resultant dim magnitudes makes them much harder to study with any accuracy.

The ability of an object to retain volatiles against Jeans escape is dependent on its mass. Retention also depends on the surface temperature being low enough to prevent the surface frost from having a high vapour pressure. Modelling of the size and temperature of objects allowed Brown et al. (2011) to plot this for numerous KBOs (figure 1).

Studies of the smallest members of the Kuiper belt are often restricted to the spectroscopy of observational proxies, the centaur population. Centaurs are former KBOs who's orbits have been disturbed such that they



Figure 1: A model of volatile retention and loss in the Kuiper Belt. Objects on the left of the  $CH_4$ , CO and  $N_2$  lines are too small and hot to retain those surface volatiles over the age of the solar system. Objects in red have had  $CH_4$  detected on their surfaces. Figure taken from Brown et al. (2011) based on an updated model of that introduced by Schaller and Brown (2007).

now have semi-major axes between those of Jupiter and Neptune; they are better illuminated by the sun and are hence easier to accurately study spectroscopically (Brown, 2012).

Colour values obtained from photometry of the Kuiper Belt can be used to highlight general trends in the surface compositions of KBO populations. The centaur population exhibits a wide range of colour, similar to Kuiper Belt populations. However, the Centaur population has an apparent gap in the middle of this distribution of colour values (Tegler et al., 2008).

Trujillo and Brown (2002) showed that the B-R colours of non-resonant KBOs show a negative correlation with the inclination of the object's orbit.

The classical cold population is observed to have a unique colour distribution among KBOs. Objects in the cold classical population are consistently red, unlike other KBO populations (Trujillo and Brown, 2002). This fact, along with the cold population's unique size distribution (Levison and Stern, 2001), higher albedo than other populations (Brucker et al., 2009), and a number of other unique features has led Brown (2012) to conclude that it had an evolutionary path or place of origin that was distinct from the rest of the Kuiper Belt. This distinctive origin for the cold classical belt is often used as a constraint in the evaluation of evolutionary models for the Kuiper Belt.

#### 4 Origin and Evolution

For an evolution mechanism or model to be considered for the formation of the Kuiper Belt, it must adhere to the variety of constraints that arise from our observations of the Belt. Numerous evolutionary scenarios and mechanisms have been suggested and modelled for both the dynamically cold and hot KBO populations. A illustrative review and critique of a number of these competing scenarios was provided by Morbidelli et al. (2008). Evolutionary models must account for observed constraints, such as the following:

- The abrupt cut off in the density of objects observed at a radius of ~48 AU, as noted by Allen et al. (2001).<sup>1</sup>
- The small cumulative mass of KBOs in proportion to values estimated for the mass of the original Kuiper Belt. Kenyon and Luu (1999) estimated that mass in the form of observable KBOs to be 100 times less massive than was originally in this form in the Kuiper Belt.
- The distinctive formation of a dynamically cold KBO population and a hot scattered KBO population should be accounted for in an evolutionary model.

These criteria, along with a number of others, serve to restrict and influence the discussion of formation scenarios. It is worth noting that constraints become more concise as new data is obtained and as the quality of data improves.

A number of evolutionary mechanisms have been put forward to explain the characteristics of the Kuiper Belt. In an attempt to explain the  $\sim$ 48AU cutoff and the high eccentricities and inclinations of KBO orbits >42AU, Ida et al. (2000) modelled an flyby encounter with a neighbouring star. Gomes (2009) pointed out that this scenario could not account for the separation of hot and cold populations, which are thought to have distinctive origins.

Brunini and Melita (2002) suggested that a Mars-sized planet at an orbital radius of  $\sim$ 60AU could account for the observed edge of the Kuiper Belt. It is unlikely however, that there exists an as yet unidentified object as large as this at this distance.

Fernandez and Ip (1984) first demonstrated that if the Jovian planets were placed in a planetary disk, the outer three bodies, Uranus, Saturn and Neptune would gain angular momentum with time and migrate outwards, while Jupiter would move towards the sun. Neptune, as it migrated outwards, could capture planetesimals into a resonance orbit. Such a mechanism would excite the orbital eccentricities of the resonance-trapped objects. This mechanism was initially introduced to explain Pluto's orbit (Malhotra, 1993) and

<sup>&</sup>lt;sup>1</sup>Note that a study by Sheppard and Trujillo (2013) may shed some light on potentially undetected objects beyond this limit. Sedna, at a distance of 76 AU, is the only significant object that has been detected beyond the 50AU cut off point; this study aims to determine if it is unique in its orbit by searching for similar objects.

was subsequently extended to other high eccentricity orbits in resonance with Neptune (Malhotra, 1995). Such an event could also have resulted in changes to the orbital motion of non-resonant, classical KBOs. Mechanisms involving giant planet migration with resonance-sweeping are utilised in a number of models to explain the observed orbital characteristics of the resonant and non-resonant Kuiper Belt.

One model which has had great success in reproducing features seen in the Kuiper Belt, and indeed in the entire solar system, is the "Nice" model (Gomes et al., 2005). In this scenario, the giant planets were formed in more compact, lower  $\epsilon$  obits than they currently occupy. They subsequently underwent planetary migration under the influence of gravitational scattering by a population of planetesimals, as first described by Fernandez and Ip (1984). Jupiter and Saturn eventually reached their mutual 2:1 resonance which increased the eccentricity of both orbits. This created a period of dynamical instability in which Uranus and Neptune were scattered to their current orbits and, as a result, both the classical and scattered KBO populations were formed (Morbidelli et al., 2008). This period of dynamical instability also provides a mechanism by which the late heavy Bombardment (LHB), evidentiated by craters on the moon's surface, could have taken place. Levison et al. (2008) modelled this process and found very good agreement of the results of their model with the observed orbital elements of the Kuiper Belt populations (see figures 2 and 3 for a comparison of the model with observations).



Figure 2: Observed orbital elements of Kuiper Belt Objects. Black dots represent objects whose orbits are in resonance with Neptune. Green dots represent objects which are currently interacting with Neptune. Red dots are non-resonant objects in stable orbits. (A) Eccentricity versus semi-major axis. (B) Inclination versus semi-major axis. Figure taken from Levison et al. (2008)



Figure 3: The eccentricity and inclination plotted as a function of semi-major axis for particles in a execution of the Nice model. Same annotation as figure 2. Figure taken from Levison et al. (2008).

## 5 Discussion and Conclusion

Since it was discovered in 1992, the study of the Kuiper Belt has cast light onto the evolution of the solar system as a whole. The composition of the Kuiper Belt remains for the most part uncertain. Spectroscopy of these objects is difficult due to their dim surfaces; this problem is more severe for the smaller KBOs. One objective of the New Horizons mission is to spectroscopically analyse the surface of Pluto, its moons and if possible, another KBO. This may shed light on the subject of KBO surface compositions.

However, analysis of the interiors of these objects is primarily restricted to calculations of density, which can only be calculated for the small number of KBOs which have a similarly sized satellite object.

Planetary migration processes have been utilised to explain features of the Kuiper Belt and have in turn allowed us to evaluate dynamical processes elsewhere in the solar system such as that which may have triggered the LHB. Much uncertainty remains regarding the Kuiper Belts evolution; as our model and the quality of observations improve, we may further restrict possible evolutionary scenarios. Developments will certainly have implications for our understanding of the development of the solar system as a whole.

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