The Size Distribution of the Kuiper Belt Objects

Cheng-Pin Chen & Ing-Guey Jiang
Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan

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The size distribution is determined directly from the current known Kuiper Belt Objects (KBOs). We found that there is a peak for the size distribution around 230 km in diameter. For the objects larger than 230 km, the KBOs populate as $N(s) \propto s^{-4}$ as we see in Jewitt et al. (1998). For the objects smaller than 230 km, we found $N(s) \propto s^3$. This result from the current observational data is new and very different from the conventional concept of the KBO size distribution. Though the true size distribution might change from what we have after more KBOs be discovered, we argue that the existence of a peak around 150 km to 250 km is likely.

Subject headings: comets: general – Kuiper Belt, Oort Cloud – solar system: formation
1. Introduction

After the first KBO was discovered in 1992 (Jewitt & Luu 1993), it is known that the outer solar system beyond Neptune is populated by small bodies. The total number of KBOs is increasing quickly and the general picture of the outer solar system is changed. There are three classes of KBOs according to the current observations. One of the population are the Resonant KBOs. They are trapped in 3:2 mean-motion resonance with Neptune at 39.4 AU. About one-third of the total population are in this class. The second class mainly occupies the region between 41 AU and 46 AU with small eccentricities. They are called the Classical KBOs and about two-third of KBOs belong to this class. Finally, several KBOs which behave very differently from the above two were discovered since 1996 (Luu et al. 1997) and form a new class. They are Scattered KBOs and they are moving on the large semi-major axises, highly eccentric, and inclined orbits. These KBOs of new dynamical class could originate from the scattering by Neptune.

One of the most important properties of KBOs is the size distribution because it tells the possible total number of KBOs and also gives the hint of density profile of Solar nebula. To extract the size distribution from the luminosity function, Jewitt et al. (1998) used Monte Carlo models to simulate the survey under the necessary assumptions about the geometric albedos and distance distributions of the KBOs. In principle, they assume a power-law size distribution as \( \propto r^{-q} \) and determine the best value of \( q \) by reproducing the luminosity function from the models. They found \( q = 4.0 \pm 0.5 \) and claimed this value of \( q \) is consistent with \( q \approx 3.5 \) from what was expected from a collisional production function in Dohnanyi (1969). Kenyon & Luu (1999) did some planetesimal accretion calculations in a single annulus at 35 AU. They found that all models produce two power-law size distributions, \( q = 2.5 \) for radii \( \lesssim 0.3 - 3 \) km and \( q = 3 \) for radii \( \gtrsim 1 - 3 \) km and the results are nearly independent of the initial mass in the annulus.
Different from the approach in Jewitt et al. (1998), we first get the number of KBOs against absolute magnitude histogram directly from the data of current known KBOs. Then, we convert this histogram into the size distribution. In addition to the size distribution for all current known KBOs, the Plutinos and Classical KBOs’ size distributions are studied separately. These results would be in Section 2 and there are concluding remarks in Section 3.

2. The Results

We get the data of current known KBOs from the daily updated List of Transneptunian Objects at the website: [http://cfa-www.harvard.edu/iau/lists/TNOs.html](http://cfa-www.harvard.edu/iau/lists/TNOs.html) and Figure 1 is the plot of eccentricity against semi-major axis for all KBOs from these data. There are 282 KBOs in the list on 27th July 2000. We regard the Plutinos to be those objects with semi-major axises from 38.1 AU to 40.5 AU. The Scattering KBOs are those objects with eccentricities \( e > 0.3 \) and semi-major axis \( a > 40.5 \) AU. All the rest are the Classical KBOs. Therefore, 63 of these current known KBOs are Plutinos, 212 objects belong to Classical KBOs and 7 objects are Scattering KBOs.

We use the table of converting absolute magnitudes to diameters at the same website to get the diameters. However, we transform the values of diameters in the table to be the values for albedo = 0.04. The histogram for number of KBOs against the absolute magnitude is then plotted. This plot can be transformed to the histogram for number of KBOs against the diameters, i.e. the size distribution easily.
2.1. All Known KBOs

Figure 2 is the result for all current known KBOs and it shows that there is a peak around 230 km. For those objects larger than this peak value, the size distribution follows

\[ N(s) = \frac{150}{(s/200)^4} \]  

approximately, where \( s \) is the diameters (km) of the objects. For those objects smaller than the peak value, the size distribution becomes

\[ N(s) = 90(s/200)^3. \]

It is encouraging that those objects larger than 230 km follow the same size distribution as in Jewitt et al. (1998), i.e. \( q = 4 \) power-law. However, the existence of this peak around 230 km and the different size distribution for objects smaller than the peak value has never been mentioned and discussed before. One might argue that this current observational result is not complete enough to confirm this peak. The size distribution would be completely different after all 100 km size KBOs are discovered. However, considering that all KBOs around or larger than 100 km are all within the detection limit and thus the detection probability is proportional to the number of objects. Equation 1 gives us \( N(100)/N(230) \approx 28 \) and thus the current known 100 km size KBOs should be about 28 times more than 230 km size KBOs if all sizes of KBOs follow the size distribution of Equation 1. It would be a puzzle that the current number of 230 km size KBOs is larger than the number of 100 km size KBOs if the size distribution is described by single power-law only.

Therefore, it is obviously that the peak we discover from the data of current known KBOs should be real and Equation 2 might be a good approximation for objects between 70 km to 230 km, though probably not for objects smaller than 70 km due to current detection limit.
2.2. Plutinos

As suggested by Malhotra (1995), the resonance sweeping due to the migration of Neptune might explain the trapping of KBOs into the 3:2 resonance. During this resonance sweeping process, it is possible that not all KBOs of different sizes can be trapped and become the Plutinos. Therefore, the size distribution for Plutinos might give us information about this.

According to the histogram in Figure 3, we found that for the objects larger than 150 km, the size distribution can be fitted by a $q = 4$ power-law

$$N_p(s) = \frac{17}{(s/200)^4},$$

for the objects smaller than 150 km, we have:

$$N_p(s) = 60(s/200)^4.$$

Comparing these results with Figure 2, it seems that the distribution is narrower and sharper around the peak and the peak is about 150 km. This might imply that there is a particular size, i.e. about 150 km, which is preferable to the resonance trapping process. This result of Plutinos’ size distribution might be important for the dynamical calculations of resonance sweeping.

2.3. Classical KBOs

Different from the Resonant and Scattering KBOs, the Classical KBOs might be the better tracer for the primordial Solar nebula because there were not trapped or scattered by Neptune and thus closer to where they were formed. Therefore, it would be interesting to know the size distribution for the Classical KBOs only.
According to the histogram in Figure 4, we found that for the objects larger than 230 km, the size distribution can be fitted by

\[ N_c(s) = \frac{140}{(s/200)^4}, \]  

for the objects smaller than 230 km, we have:

\[ N_c(s) = 65(s/200)^3. \]

These results are pretty much the same as the results for all KBOs because at least two-third of all KBOs are in fact the Classical KBOs.

3. Concluding Remarks

We have used the current known data of KBOs to study their size distribution. We found that there is a peak around 230 km and therefore the size distribution is unlikely to be described by one single power-law. What does this observational result imply?

The size distribution is related to the density of the Solar nebula because during the formation stage of KBOs, the amount of available material determined the final size and therefore the size distribution of KBOs. In fact, the initial density of the Solar nebula is one of the most important factors to lead the evolution of the Solar system. One possibility is to use the current mass distribution of planets to set up the ‘minimum mass Solar nebula’ model, then rescale to a higher density value but keep the same density profile because there must be certain amount of mass loss during the planet formation. From these assumptions, we can calculate that there was more than 20 Earth mass between 30 to 50 AU. However, the total mass of discovered KBOs is only about 0.07 Earth mass from the results in Section 2 or up to 0.26 Earth mass by Jewitt et al. (1998). Because of this contradiction, one might argue that the ‘minimum mass Solar nebula’ model could be wrong, especially for the outer Solar system.
One way to approach this problem is to study the formation of KBOs. Stern (1995) claimed that the timescale to produce the QB1s is longer than the disc lifetime and suggested that the present-day disc is not representative of the ancient structure. Kenyon & Luu (1999) did some accretion calculations and conclude that the ‘minimum mass solar nebula’ would be enough to form large KBOs in a reasonable timescale. Thus, from these calculations of Stern (1995), Kenyon & Luu (1999), we do need the outer Solar system to be at least as massive as the ‘minimum mass Solar nebula’ model to form the current observed KBOs through the accretion. Therefore, the outer Solar system between 30 to 50 AU was at least two order of magnitude more massive and the depletion in this region definitely happened during the formation of the Solar system.

On the other hand, the accretion calculations in Kenyon & Luu (1999) told us the size distribution for QB1s can approximately described by single power-law when these QB1s were formed. We therefore come to the conclusion that the size distribution should have changed during the depletion.

Jewitt (1999) suggested that for collisions to have removed 99 percent of the initial mass, one would have to postulate a steep initial size distribution ($q \approx 5$ in which objects large enough to escape commotion carry only 1 percent of the mass. This suggestion implies that the size distribution can be different in the past and also that the larger objects can survive easier than the smaller objects during the depletion. It is therefore possible that the peak we discovered was formed during this depletion process. A complete simulation to combine the accretion process and the orbital dynamics as in Jiang, Duncan & Lin (2000) might help the understanding of this depletion and thus the evolution of size distribution.
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Fig. 1.— The eccentricity against semi-major axis for all current known KBOs. The Plutinos are those between two dotted lines, i.e. with semi-major axises from 38.1 AU to 40.5 AU. The Scattering KBOs are those with $e > 0.3$ and semi-major axis $a > 40.5$ AU. All the rest are the Classical KBOs.
Fig. 2.— The histogram of number of objects against their diameters for all current known KBOs, where the dashed and dotted lines are the fitting curves (See Equation 1 & 2).
Fig. 3.— The histogram of number of objects against their diameters for all current known Plutinos, where the dashed and dotted lines are the fitting curves (See Equation 3 & 4).
Fig. 4.— The histogram of number of objects against their diameters for all current known Classical KBOs, where the dashed and dotted lines are the fitting curves (See Equation 5 & 6).