Collisional Evolution of the Primordial Trans-Neptunian Disk: Implications for Planetary Migration and the Current TNO Size Distribution

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1. Overview

Recent models of the orbital evolution of the outer planets (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005) suggest that:

- The outer planets were initially a much more compact system (all within 15 AU of the sun)
- Their initial orbits were nearly circular and coplanar
- They slowly migrated for ∼700 Myr due to interactions with the primordial trans-Neptunian disk of planetesimals until Jupiter and Saturn crossed their mutual 2:1 mean-motion resonance (MMR)

The crossing of the 2:1 MMR causes the outer planets to rapidly evolve to their current orbital configuration and destabilizes the disk, driving a large amount of material into the inner solar system and causing the late heavy bombardment (LHB). A small fraction of bodies from the primordial trans-Neptunian disk are driven outwards to form the current population of trans-Neptunian objects (TNOs)

Those authors find that the primordial trans-Neptunian disk, at the time of the 2:1 MMR crossing, must have ∼30-35 earth masses (M_e) in order for this scenario to work. Much more mass causes Jupiter and Saturn to continue migrating and cross their 5:2 MMR, while for too little mass, Jupiter and Saturn never cross their 2:1 MMR. Here explore two related issues:

- Can the primordial trans-Neptunian disk retain ∼30-35 M_e of material for ∼700 Myr without losing that mass to collisional grinding?
- How does the resulting collisionally evolved size distribution compare to the current population of trans-Neptunian Objects (TNOs)?

2. Dynamical Excitation and Collisional Parameters for the Disk

We have calculated the intrinsic collision probability P_i and mean impact velocity $\langle V\rangle$ for a disk of bodies between 15 and 35 AU as a function of the mean eccentricity $\langle e\rangle$ and inclination $\langle i\rangle$ using an algorithm based on Farinella & Davis (1992). We assume energy equipartition such that $\langle e\rangle = 2\langle \sin i\rangle$, which is generally expected from most dynamical excitation mechanisms. Figure 1 shows $\langle V\rangle$ for a range of $\langle e\rangle$.

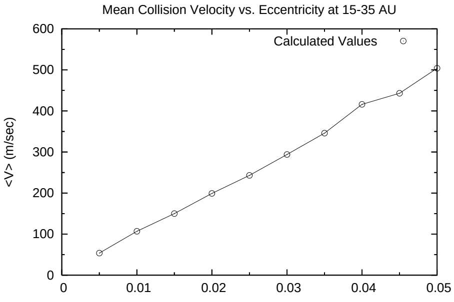

Figure 1: Mean collision velocity $\langle V\rangle$ as a function of the mean eccentricity $\langle e\rangle$

P_i is essentially constant for all $\langle e\rangle$, reflecting the fact that increasing eccentricity decreases the time for which any two specific bodies can collide while correspondingly increasing the number of possible colliding pairs of bodies. For a disk between 15 and 35 AU, we find $P_i = 2.45 \times 10^{-21}\ \mathrm{km}^2\mathrm{yr}^{-1}$, which is roughly 1000 time smaller than the value for the asteroid belt.

3. Collisional Evolution Model

To model the collisional evolution of the primordial trans-Neptunian disk, we construct a simple model based on O'Brien & Greenberg (2003). The main input parameters in this model are:

- The intrinsic collision probability P_i
- The mean collision velocity $\langle V\rangle$
- The catastrophic disruption threshold Q^*_D

While more detailed models exist (eg. Davis et al. (1989), Petit & Farinella (1993), Campo Bagatin et al. (1994), Stern & Colwell (1997), O'Brien & Greenberg (2005)), the model used here minimizes the number of free (and generally poorly constrained) parameters.

In the model, the population is broken into logarithmic bins of width $\mathrm{dLog}D$ (generally set to 0.1). At each timestep and for each size bin, the size of a body D_{dis} that can disrupt a body of diameter D is given by

$$D_{dis} = \left(\frac{2Q^*_D}{\langle V\rangle^2}\right)^{\frac{1}{3}} D. \qquad (1)$$

The lifetime of bodies in each size bin is then given by

$$\tau = \frac{4}{N(>D_{dis})(D + \langle D_{dis}\rangle)^2 P_i}, \qquad (2)$$

where $N(>D_{dis})$ is the number of bodies of diameter D_{dis} or larger and $\langle D_{dis}\rangle$ is the mean disruptor diameter, which will be somewhat larger than D_{dis} itself. The removal rate of bodies from each size bin by collisional destruction is then

$$\left(\frac{\mathrm{d(d}N)}{\mathrm{d}t}\right)_{dest} = -\frac{\mathrm{d}N}{\tau}. \qquad (3)$$

For each body removed by collisional destruction, the resulting fragments are assumed to follow a power law of the form

$$\mathrm{d}N = CD^{-q}\mathrm{d}D, \qquad (4)$$

with a nominal q value of 3.5, and those fragments are added back into the population.

4. Evolution of the Disk

Using our collisional model, we have explored a range of initial populations, mean impact velocities $\langle V\rangle$ (corresponding to the mean eccentricity $\langle e\rangle$), and catastrophic disruption thresholds Q^*_D, to find parameters that allow for the survival of ∼30-35 M_e over 700 Myr of collisional evolution.

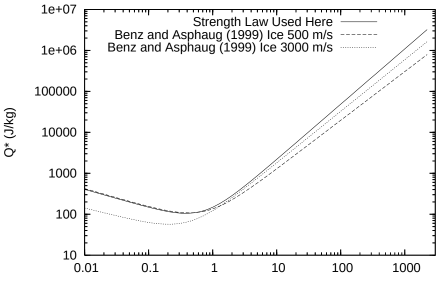

Figure 2: Catastrophic disruption threshold Q^*_D used in our simulations (solid line) compared to hydrocode estimates from Benz & Asphaug (1999).

Starting with an initial mass of 50 M_e, we find that for reasonable parameters such as a mean eccentricity $\langle e\rangle$ = 0.03 (which gives $\langle V\rangle$ = 300 m/s) and a Q^*_D similar to that predicted by Benz & Asphaug (1999) for icy bodies (Fig. 2), the final population after 700 Myr (Fig. 3) has a mass of 30 M_e and a size distribution similar to the observational estimate of Bernstein et al. (2004). Increasing the initial mass has little effect on the final remnant mass in the disk.

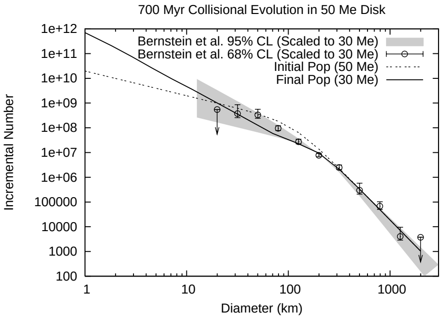

Figure 3: Final population resulting from 700 Myr of collisional evolution in disk from 15-35 AU with an initial mass of 50 M_e and a mean eccentricity $\langle e\rangle$ = 0.03, corresponding to a mean impact velocity $\langle V\rangle$ = 300 m/s. The final population has a mass of 30 M_e and its shape is a reasonable match to the observed population of TNOs from Bernstein et al. (2004) (scaled up to 30 M_e in the plot)

5. Summary

Our preliminary modeling indicates that:

- Given reasonable collisional parameters, 30 M_e of material could survive in the 15-35 AU region for 700 Myr, as required by recent models of the evolution of the outer solar system (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005).
- The resulting size distribution of bodies in that disk is a reasonable match to the observational estimate by Bernstein et al. (2004) for the current population of TNOs. Thus, it is possible that the current size distribution of TNOs was set by collisional evolution in the massive primordial trans-Neptunian disk.

Future work will focus on performing numerical simulations to estimate the likely degree of dynamical excitation in the primordial trans-Neptunian disk due to planetary embryos. In addition, we will refine our collisional model to more accurately treat the production of collisional fragments by incorporating fragment distributions from recent numerical simulations of catastrophic disruption (eg. Durda et al. (2004); Michel et al. (2004)).

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