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Constraining the Size of the Protosolar Nebula

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Abstract

Observations indicate that the gaseous circumstellar disks around young stars vary significantly in size, ranging from 10s to 1000s of AU. As we try to unravel the events leading to the formation of our own solar system, we would like to understand the properties of our own primordial disk. Fortunately, the dynamics of objects in the Kuiper belt provide interesting constraints. After Jupiter formed, it must have scattered a significant number of planetesimals into eccentric orbits. If there had been a massive, extended protoplanetary disk at that time, then the disk would have excited Kozai oscillations in the scattered objects, driving some into high-inclination, low-eccentricity orbits. The dissipation of the gaseous disk would strand some objects in these high-inclination orbits; orbits that are stable on Gyr timescales. The fact that we have yet to observe Kuiper belt objects on these orbits therefore places strict size limits on the disk at the time of planet formation, revealing important information about the environment from which our solar system emerged.

1. Introduction

In this paper we present a technique in which we use the additional dynamical information present in our own solar system to allow us to place constraints on the protosolar nebula. After the formation of the giant planets, left-over planetesimals are scattered to high eccentricity orbits. Without the presence of a gaseous disk, the perihelia of these planetesimals remains constant throughout the scattering, meaning that the planetesimal is likely to undergo additional scattering. The presence of a massive disk exterior to the scattered particle forces some of the particles to undergo Kozai oscillations, a situation in which the inclination grows at the expense of the eccentricity. As the objects change from from low-inclination, eccentric orbits to inclined more circular orbits they may no longer cross the planets' orbits. The particles oscillate between the two states, but after the disk dissipates, some of the objects are stranded in high inclination orbits that are stable for the age of the solar system. This dynamical mechanism has been previously identified [1] but here we use it to place constraints on the size of the disk.

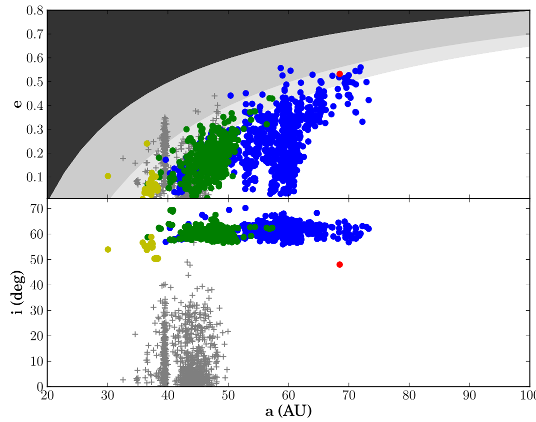

Figure 1: The eccentricity and inclination of objects produced by a disk that is 50, 60, 80, and 100 AU (red, yellow, green, blue respectively) with a MMSN profile and a sharp cutoff. The shaded regions indicate different perihelia cutoffs (20, 30, and 35 AU). The grey crosses indicate the current observed distribution of KBOs from the minor planet center.

2. Numerical Method

We calculate the orbital evolution of the scattered planetesimals using the `SWIFT` numerical integrator [2]. We represent the planetesimal as randomly distributed massless test particles in the planet forming region and integrate their orbits over 5 Myr in the presence of the gaseous disk. The gas disk extends from 1 AU to the outer disk radius, which varies in each simulation, and the gas disk is depleted exponentially over a given timescale. The dynamical process described here only can happen for particles large enough for particles to be decoupled from gas drag ($\gtrsim$ 10 km) [1], therefore we neglect gas drag in these calculations. We then integrate planetesimals on the resulting orbits for 4.5 Gyr in order to assess their stability.

3. Results

In figure 1 we show the orbital distribution of particles remaining after 4.5 Gyr for a disk with a Minimum Mass Solar Nebula (MMSN) profile [3] truncated at various radii. The details of the distribution depends upon the slope of the gas surface density profile and the sharpness of the outer disk truncation. In figure 2 we show that the fraction of particles trapped in these stable orbits is relatively insensitive to the disk mass and lifetime, so long and they are above a minimum value. If we approximate a disk of mass M_d as a narrow ring of radius R_d, then the characteristic timescale for a Kozai oscillation (for a particle of semi-major axis a) is

$$\tau_K \sim \frac{4}{3}\frac{M_\odot}{M_d}\left(\frac{R_d}{a}\right)^3\sqrt{\frac{a^3}{GM_\odot}}. \qquad (1)$$

For our fiducial MMSN disk truncated at 100 AU, $\tau_K \approx 2 \times 10^4$ yr for relevant particles. The minimum mass required for a single Kozai oscillation to occur in the fiducial disk lifetime (2 Myr) is $2 \times 10^{-4}\ M_\odot$, or 0.01 the MMSN value. So long as the disk lifetime is long compared to this Kozai timescale then fraction of particles left in these stable orbits is relatively constant.

To estimate the number of bodies trapped in these orbits we assume that the initial amount of material in planetesimals is comparable to the amount of solids incorporated into the planets ($\sim 40M_\oplus$). This is likely a somewhat conservative estimate as, per encounter, the probability of ejection is much greater than the probability of accretion for the gas giants [4]. So in order to form the cores of the giant planets within the lifetime of the gaseous disk the mass in planetesimals must be a few-10 times larger than the MMSN [5–7]. If we assume that all of this material is 10 km-sized objects, this corresponds to more than 10^{10} initial objects. Therefore with a capture efficiency around 10^{-3}, we expect the mass in this reservoir to be $> 0.04M_\oplus$, or $> 10^7$ objects, comparable to the mass of the observed Kuiper Belt.

4. Summary and Conclusions

If the size of the protoplanetary disk at the time of the formation of Jupiter was larger than ~ 50 AU, Kozai cycles driven by the gaseous disk will produce a population of high inclination objects comparable in mass to the Kuiper belt, a population that has not been observed. At the conference we will discuss the current constraints set by the detection limits of the Deep Ecliptic Survey (DES) [8]. This presents an independent constraint on the size of our own protosolar nebula.

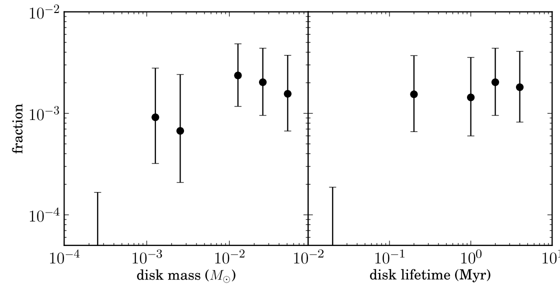

Figure 2: The fraction of objects left in high-inclination, low-eccentricity orbits as a function disk mass (left) and lifetime (right) with 2-σ error bars.

Acknowledgements

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