FAILED OORT CLOUDS AND PLANETARY MIGRATION

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ABSTRACT

Planet formation is accompanied by the formation of comet clouds. In systems where planets migrate on rapid timescales, the diffusive evolution of comet orbits may stall, resulting in a comet cloud intermediate between a flattened Kuiper Belt and a spherical Oort cloud. These ‘failed Oort clouds’ may provide a ‘smoking gun’, indicating that planetary migration has taken place. If some fraction of the scattered component consists of planetary embryos, it may be possible to observe transits of such bodies even when the planetary system is not edge-on to the line of sight.

Subject headings: planetary systems – comets:general – Kuiper Belt – Oort Cloud – planets & satellites:general – occultation

1. INTRODUCTION

Planet formation is a messy business. The process of accumulation of small bodies into large bodies results not only in the formation of large planetary-mass objects but also a significant population of scattered comets and asteroids. Studies of short and long period comets in our solar system (Oort 1950; Fernandez 1980; Duncan, Quinn & Tremaine 1988) point to the existence of two reservoirs of cometary material, the spherically distributed Oort cloud (Oort 1950) and a low inclination population of trans-Neptunian objects, the Edgeworth/Kuiper Belt (Edgeworth 1949; Kuiper 1951). These cometary reservoirs convey valuable information regarding the primordial conditions in the solar system and their manifestations around other stars offer insights into the formation of extrasolar planetary systems. In particular, the detection of infra-red emission from dust in such systems (Backman & Paresce 1993; Trilling & Brown 1998) is thought to be supplied by ongoing evaporation or ablation of comet-like objects (Weissman 1984).

The properties of recently detected extrasolar planets (e.g. Marcy, Cochran & Mayor 1999) suggest that the formation and evolution of planetary systems may be a much more dynamic and violent process than previously envisaged. The purpose of this letter is to examine the impact of this new paradigm on the configuration of cometary reservoirs in such systems. In particular, we will demonstrate the existence of a cometary component intermediate between a disk and isotropic component that will result in systems where significant planetary migration has taken place.

Section 2 reviews the process of formation of an Oort cloud and examines the implications of planetary migration for such a scenario. In section 3 we describe the implications for observations of dust disks around extrasolar planetary systems.

2. PLANETARY SCATTERING & OORT CLOUDS

Oort (1950) inferred the existence of a spherically distributed cometary reservoir containing objects of semi-major axis \( a \sim 10^4 \) Au. Perturbations of comet orbits by passing stars or molecular clouds are responsible for scattering comets into the inner solar system. The origin of these bodies is explained by ejection of primordial material from the solar system. Proto-comets on planet crossing orbits are repeatedly scattered in close encounters with the outer planets and their orbits undergo a diffusive evolution towards large semi-major axis and high eccentricity. This diffusion continues until they are ejected from the solar system entirely or until perturbations at apastron due to the Galactic tide perturb the orbit sufficiently to remove it from a planet-crossing condition (Duncan, Quinn & Tremaine 1987, Tremaine 1993). Continued action of the tidal torques eventually result in an isotropically distributed population, responsible for the long period comets.

The origins of the short period comets seem incompatible with the properties of the Oort cloud (Joss 1973; Duncan, Quinn & Tremaine 1988) and are now thought to be related to a disk-like distribution of primordial protosolar material (Edgeworth 1949; Kuiper 1951; Fernandez 1980) in trans-Neptunian orbits. Recent observations (Jewitt & Luu 1993; Stern 1996) indicate the presence of \( \sim 100 \) km bodies in this region and possible true cometary material as well. (Cochran et al 1995)

2.1. Migration

Implicit in the studies of the formation of the Oort cloud (e.g. Duncan, Quinn & Tremaine 1988) is the assumption that the planets themselves do not move significantly. Recent dynamical studies of the early evolution of our own solar system indicate that some small migration of the outer planets is likely (Fernandez & Ip 1984; Malhotra 1995; Hahn & Malhotra 1998). Recent discoveries of jovian mass planets in very close orbits around other stars (Mayor & Queloz 1995; Marcy & Butler 1996; Marcy, Cochran & Mayor 1999) suggests that, in some cases, far more extensive migration occurred.

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The explanations for the source of this migration invoke either some kind of steady orbital decay (Lin, Bodenheimer & Richardson 1996; Murray et al 1998) or the scattering of several planets in an originally unstable orbital configuration (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1998). However, the emphasis on migration as opposed to in situ formation is still largely theoretical prejudice. As I shall demonstrate, the Oort clouds/Kuiper belts around these systems could provide a potential test of the migration hypothesis.

In the standard picture of Oort cloud formation, a comet scattering off the giant planets returns repeatedly to the inner solar system until either something catastrophic (ejection or collision with a planet) happens or the orbit receives a sufficiently large external perturbation that it no longer enters the inner solar system. However, in a system where the scattering planet(s) are migrating, it is possible that the planet itself moves sufficiently far between encounters so that the comet no longer crosses its orbit and is thus no longer subject to strong perturbations. Thus, the diffusive evolution of comets to large semi-major axes and high eccentricities may ‘stall’ at much smaller radii than in the standard scenario. The timescales to eject comets to the Oort cloud is of order $10^6 - 10^7$ years (e.g. Dones et al 1996), a timescale similar to that on which migration is claimed to occur (Lin et al 1996; Murray et al 1998). Thus it is reasonable that planetary migration will leave many comets stalled in their diffusion process, on eccentric and inclined orbits of moderate semi-major axis. One possible exception is those scenarios which invoke dynamical instability in multi-planet systems, which could occur at much later times when the asteroids & comets have been mostly cleared.

Thus, in the case of steady migration, we expect a cometary component intermediate between a Kuiper belt disk population and an Oort cloud isotropic distribution. The orbital extent and inclination distribution will depend on the rate of planetary migration as well as other evolutionary factors, which we will describe below.

2.2. Cloud Size

Figure 1 shows the comet cloud that results when one considers the formation of a 51 Pegasi-like system in the planetesimal migration scenario of Murray et al (1998). The planet initially begins at 10 Au and migrates to 0.06 Au, leaving behind a cloud of comets or asteroids in a thickened disk. The evolution was followed using a Monte-Carlo code (Hansen et al, in preparation) utilising the Opik approximation (Opik 1976; Arnold 1965). In this particular instance, approximately 50% of the disk planetesimal mass interior to the original orbit is scattered into a "thick" component.

While the appearance of such thickened configurations is generic in single planet migration models, the exact nature of the scattered component will depend on the particular nature of the system, most particularly, the mass of the migrating planet and the rate of migration. Smaller planets migrate faster and result in less thickening. The rate of migration also slows as the planet gets closer in, so that the thickening of the disk increases inwards. Larger mass planets halt migration at larger radii, so that the scattered cloud shows an inner edge. Figure 2 shows the result for a 1 $M_J$ planet that migrates to 0.17 Au. The asteroid cloud truncates near 1 Au.

The comets scattered into inclined, eccentric orbits will also precess under the influence of any undisturbed extended disk component exterior to the original planetary orbit, on timescales $\sim 10^5$ years. The eccentricity and inclination undergo oscillations governed by Kozai’s integral $\Theta = (1 - e^2) \cos^2 i$ (Kozai 1962; Holman, Touma & Tremaine 1997). Thus, the minimum semi-major axis (maximum eccentricity) occurs when the comet lies in the orbital plane again. A small fraction of the comets at the inner edge of the cloud may again be brought into planet crossing orbits by this mechanism and ejected. However, this is only a small fraction ($\sim 5\%$) of the scattered component in the above cases.

The longevity of such a cloud is also affected by the presence of other planets in the system. Additional planets will also scatter planetesimals and may serve to clear out orbits left behind by the original migrating planet. Figure 3 illustrates the situation for two planets starting at 10 and 20 Au. The inner planet migrates down to inside 0.1 Au as in figure 1 while the second, Jupiter mass planet stops at 1.6 Au. The resulting scattered cloud consists of an inner and outer component. The eccentricities of the inner cloud components are restricted by the fact that they cannot cross the orbit of either planet in the final state, otherwise they will be ejected. This is why there is no intermediate cloud left in our own solar system - the limited movement of the outer planets meant that, once a body crossed a planetary orbit it was doomed to continue scattering until it was either ejected or passed into the Oort cloud.

In conclusion, we reiterate that the above calculations represent the situation in the migration scenario of Murray et al(1998). In this case the migration is intimately coupled to the scattering of the planetesimals as these provide the sink for the planet’s gravitational binding energy. As such the results are robust to uncertainties inherent in the Opik approximation (see Dones et al 1996) as these relate primarily to timescale. A similar result will occur in gaseous migration scenarios such as described by Lin, Bodenheimer & Richardson (1996), but the quantitative results will be more sensitive to the relative rates of migration and cometary orbital diffusion.

3. IMPLICATIONS

The search for residual material in known planetary systems is a rapidly advancing field. Observations of infrared excesses and transient absorption events in the Beta Pictoris system have been explained by the existence of cometary bodies (Weissman 1984; Lagrange-Henri et al 1989; Artymowicz & Clampin 1997; Kalas et al 2000). Extensive studies of the dust distribution suggests that the properties change at smaller radii (Lecavalier des Etangs, Vidal-Majar & Ferlet 1996; Li & Greenberg 1998). While this is a reasonable explanation, it should be noted that most models assume a disk of constant opening angle and that the change in the disk properties suggested by the above results can influence the observations as well. A configuration similar to Figure 2 can perhaps explain the inner gap inferred in Beta Pictoris system. The scattered cloud is also a natural reservoir for bodies suggested to give rise to the transient absorption events observed in
this system (Lagrange-Henri et al 1989).

Trilling & Brown (1998) have recently detected infrared excesses using coronagraphic techniques around the 55 Cancri planetary system. They have used the observed axis ratio of the 55 Cancri disk to infer the inclination angle of the system, assuming a thin dust disk configuration and thereby constrain the true planet mass. The presence of a thickened disk as discussed above will change the inclination and mass estimates. The observed ratio of minor to major axis is now \( \sim \cos(\theta + \delta \theta) \), where \( \theta \) is the inclination angle and \( \delta \theta \) the disk thickness. Thus, an appreciably fattened disk will cause an overestimate of the inclination angle and an overestimate of the planetary mass. A significant fraction of the \( \sim 27^\circ \) inclination angle and an overestimate of the plane of the system, assuming a thin dust disk configuration will change the eccentricity distribution. The labels ‘initial’ and ‘final’ indicate the initial and final orbital semi-major axis of the planet.

The inclination distribution for a system of two planets. This results in both an inner and outer thick disk, with a gap \( \sim \) several AU, in between.

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Fig. 1.— The distribution of inclinations for a planetesimal disk through which a planet has migrated to small radii. The inset also shows the eccentricity distribution. The labels ‘initial’ and ‘final’ indicate the initial and final orbital semi-major axis of the planet.

Fig. 2.— As before, we show the inclination distribution of the remnant planetesimal disk. In this case the planetary migration stalled at 1.6 AU, leading to an inner gap in the planetesimal disk.

Fig. 3.— The inclination distribution for a system of two planets. This results in both an inner and outer thick disk, with a gap \( \sim \) several AU, in between.
