

The Total Number of Giant Planets in Debris Disks with Central Clearings

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ABSTRACT

Infrared spectra from the Spitzer Space Telescope (SSC) of many debris disks are well fit with a single black body temperature which suggest clearings within the disk. We assume that inside the clearing orbital instability due to planets removes dust generating planetesimal belts and dust generated by the outer disk that is scattered or drifts into the clearing. From numerical integrations we estimate a minimum planet spacing required for orbital instability (and so planetesimal and dust removal) as a function of system age and planet mass. We estimate that a 10^8 year old debris disk with a dust disk edge at a radius of 50 AU hosted by an A star must contain approximately 5 Neptune mass planets between the clearing radius and the iceline in order to remove all primordial objects within it. We infer that known debris disk systems contain at least a fifth of a Jupiter mass in massive planets. The number of planets and spacing required is insensitive to the assumed planet mass. However an order of magnitude higher total mass in planets could reside in these systems if the planets are more massive.

1 INTRODUCTION

Recent observations made with the Spitzer Space Telescope (SSC) have added to the total number of known debris and circumstellar disks (Rieke et al. 2005; Beichman et al. 2005; Gorlova et al. 2006; Chen et al. 2006; Bryden et al. 2006; Beichman et al. 2006). These disks have total opacity, as estimated from the fraction of stellar light re-emitted in the infrared, in the range 10^{-3} - 10^{-5} . The fraction of stars with disks increases from 2% for $\tau > 10^{-4}$ to 12% for $\tau > 10^{-5}$ (Bryden et al. 2006), and the fraction of stars with disks detected increases with decreasing stellar age (Rieke et al. 2005; Gorlova et al. 2006). Infrared spectra of many debris disks are well fit with a single black body temperature suggesting that they possess inner holes (Chen et al. 2006). Planets are expected to be responsible for the inner clearings, however the number and masses of these planets has yet to be constrained by dynamical arguments. An example of a nearby system with an inner clearing that has been resolved with imaging is the Fomalhaut system (e.g., Kalas et al. 2005).

With the discovery of multiple planet extrasolar systems, the stability of planetary systems has been investigated with renewed interest (e.g., Ford et al. 2001; Barnes & Raymond 2004; Lepage & Duncan 2004; Ford et al. 2005; Raymond & Barnes 2005; Barnes & Greenberg 2006; Chatterjee et al. 2007). A system of two planets on low-inclination and eccentricity orbits will never experience mutual close encounters if the initial semi-major axis difference, Δ_m , measured in mutual Hill radii, exceeds $2\sqrt{3}$ (Gladman 1993). For multi-planet systems, Chambers et al. (1996) numerically investigated

the dependence of the timescale of the first planetary encounter, t_e , on the planet mass, M_p , number of planets, N_p , and the spacing between them, Δ_m . When all planets have the same mass, they found that \log_{10} of the timescale is proportional to the planet spacing in Hill radii. When the number of planets $N_p \gtrsim 5$, the timescale is not strongly dependent on the number of planets. Here $\mu = M_p/M_*$ is the planet mass in units of the stellar mass. The total mass in planets in a system would be $M_{p,total} = M_p N_p$.

For the number of planets $N_p = 3$, the time to first encounter, t_e , varies from 10^4 to 10^6 years for planet masses μ ranging from 10^{-5} - 10^{-9} where a year represents the orbital period of the innermost planet. Large variations in planet mass are required to significantly change the timescale required for instability to develop (e.g., see Figure 4 by Chambers et al. 1996). The time to first planet/planet encounter is much more sensitive to planetary spacing than it is to planet mass since the hill radius is only dependent on mass ratio to the one third. This implies that a higher total mass in planets can be resident in a stable system when the mean planet mass is higher even though the planets must be somewhat further apart. A nearly unstable system with a larger number of Earth mass planets must have spacings such that the system has lower total mass in planets than a nearly unstable system containing small number of somewhat more widely spaced Jupiter mass planets. For example, a planetary system that has not suffered a near encounter in 10^6 years has spacing greater than distance in mutual Hill radii, $\Delta_m > 7.5$ for planet mass ratio $\mu = 10^{-9}$ but only $\Delta_m > 6$ for $\mu = 10^{-5}$ and .

For a system observed with a dusty disk containing an

interior clearing, we assume that bodies residing between the planets must have been removed via dynamical processes on a timescale shorter than the age of the system. If numerous planetesimals lie interior to the clearing they could efficiently produce dust in the clearing. Dust produced in the outer disk can scatter into the clearing because the collision timescales estimated from the dust opacity is significantly shorter than the ages of the systems. Dust can also drift into the clearing because of radiative forces. Studies of dust particle integrations suggest that massive planets, at least Neptune in size, are required to account for a clearing in the dust distribution (e.g., Ozernoy et al. 2000; Liou & Zook 1999; Moro-Martín & Renu 2002; Deller & Maddison 2005; Quillen 2006, 2007). Sharp eccentric edges such as that in the Fomalhaut system (Kalas et al. 2005) imply that clearing by planets is required in some systems (Quillen 2006). Our assumption is consistent with scenarios for the evolution of our solar system. Most orbits in between Jupiter and Neptune become planet orbit crossing within the age of the solar system (Duncan et al. 1989). Nevertheless cratering history suggests that there was an epoch of early bombardment possibly associated with the clearing of interplanetary debris (e.g., Gomes et al. 2005; Bottke et al. 2005; Strom et al. 2005). We note that some systems with detected IR excesses may contain evidence for inner exo-zodiacal belts (e.g., HD12039; Hines et al. 2006) in their spectral energy distribution or they may be present but below the detection limit. Nevertheless if planetesimals are originally widely distributed and contain enough mass to form planets (as suggested by the cratering record in our solar system), then the lack of bright or detected exo-zodiacal belts implies that most planetesimals have been ejected, accreted onto planetary bodies or have fallen into the central star.

In this paper we combine the assumptions that planetesimals within a dust disk edge must be removed within the age of the system with estimates of the timescale t_e for the first planet/planet encounter in a multiple planet system. While other explanations for clearing exist, such as a single planet migrating outward constantly eroding away the inner edge of the disk (Gomes et al. 2005), we only consider clearing via multiple planet induced instability. We estimate a minimum spacing between planets such that objects placed between them are likely to be removed on a timescale shorter than the age of the system while the planets themselves remain stable. For simulations with planets, only the timescale until first planet/planet encounter depends on the planetary spacing and planet mass. Here we estimate the planet spacing for the instability of interplanetary objects by requiring the planets to be twice as far away as required for a first planet/planet encounter to occur during the age of the system. Such a system will have planets which will be stable on a timescale much longer than the age of that system. However, particles between the planets will have timescales shorter than the age of the system (e.g., Duncan et al. 1989). We expect that interplanetary particles residing in the system should have instability timescales similar to those estimated from N-body simulations of planets spaced at half the spacing. By doubling the spacing, we ensure that under these timescales, the planets will be stable while the planetesimals will be cleared. The age of the system is a timescale for planetesimal clearing, not planetary instability. As all massive bodies influence each other and low mass

bodies do not influence massive ones, we expect that our estimate for the required planetary spacing is conservative. Our spacing estimate will be larger than the actual one required for efficient clearing of interplanetary bodies and so will lead to a lower limit on the number of, and total mass, in planets required to clear particles from clearings.

2 NUMERICAL INTEGRATIONS

Integrations were done using John Chambers' MERCURY package version 6.¹ Mercury6 contains several N-body algorithms. We use the hybrid symplectic/Burlesch integrator since it is relatively fast and has the ability to compute close encounters.

Ten massive bodies of all the same mass ratio were used. Chambers et al. (1996) finds that as long as the number of planets in a system exceeds five, then the mean stability is nearly independent of number of planets. That is, a system of five planets has similar close encounter timescale dependence on separation as a system of ten or twenty planets. As we desire an estimate for the number of planets, we compute the stability timescale for a larger number of bodies in such a way as to be insensitive to actual number of planets. Each body has zero initial eccentricity, inclination, longitude, periastron and mean anomaly. All planets were assumed to have density 1 g cm^{-3} . They felt no non-gravitational forces.

The initial semi-major axis, a_{n+1} , of the $n+1$ -th planet was initially set to depend only on the semi-major axis of the planet just interior or a_n with a spacing δ such that

$$\begin{aligned} a_{n+1} &= (1 + \delta) a_n \\ &= \left[1 + \Delta \left(\frac{r_H}{a_n} \right) \right] a_n \\ &= \left(1 + \Delta \sqrt[3]{\frac{\mu}{3}} \right) a_n, \end{aligned} \tag{1}$$

where r_H is the Hill radius for the n -th planet and Δ is the spacing in Hill radii. The spacings chosen for our integrations ranged from $\Delta = 2.5$ to 11.0. This definition for planet spacing is somewhat different than the spacing used by Chambers et al. (1996). They use multiples of the mutual Hill radius rather than the Hill Radius. For small values of μ , the definitions are the same except for a factor of $2^{1/3}$.

We carried out a series of integrations for each planet mass ratio with different initial values of δ setting the planetary spacings. Timescales for the simulation are given in orbital periods of the innermost planet. Integrations were calculated for ten million years or until a close encounter occurred. A close encounter is defined as when the distance between two planets was less than one Hill radius. When this circumstance occurred, the system was assumed unstable and the integration terminated. The integrations did not include collisions. After every 1000 years, the six orbital elements for each planet was output and recorded. Planets were ejected from the system if their semi-major axis exceeded 200 AU. Mass ratios of 10^{-3} , 10^{-5} , and 10^{-7} were used. We have used larger mass ratios than Chambers et al. (1996) so we can consider systems with massive planets.

The timescale to first close encounter time for our integrations are plotted as a function of planet spacing $\delta/\mu^{1/4}$ in

¹ Available to download at: <http://www.arm.ac.uk/~jec/>

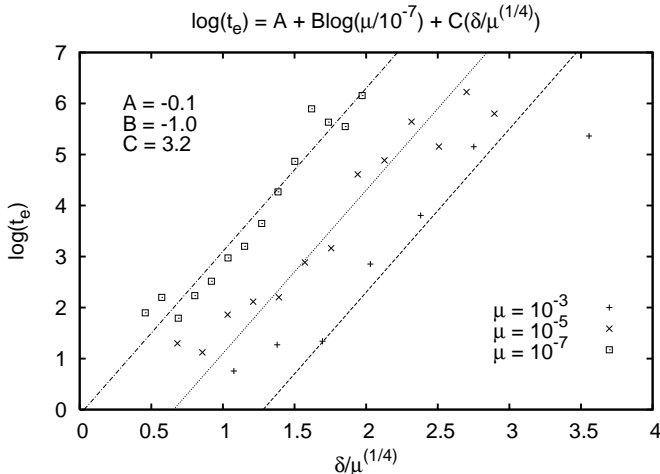


Figure 1. The relationship between planet spacing, δ , (see equation 2) and time to first close planet/planet encounter, for systems with 10 coplanar planets. The spacings are multiplied by $\mu^{1/4}$ so that the sets of integrations with the same planet mass lie on lines with the same slope. Three sets of integrations are shown, those with planet mass ratio $\mu = 10^{-3}$ (pluses), 10^{-5} (x's) and 10^{-7} (open squares). A fit to the three sets of integrations is shown with the solid lines. The fit is described with a single equation that relates timescale of first encounter to planet mass ratio and spacing (equation 2).

Figure 1. Chambers et al. (1996) found a linear relationship between timescale of first encounter and planetary spacing in Hill radii but the slope of this relation is dependent on planet mass ratio. Only when rescaled by $\mu^{1/4}$ (see their figure 4) does the slope become independent of mass ratio. We confirm this here.

We have fit the points shown in Figure 1 measured from our integrations with a single equation;

$$\log_{10}\left(\frac{t_e}{\text{yrs}}\right) = -0.1 - \log_{10}(\mu/10^{-7}) + 3.2(\delta/\mu^{1/4}). \quad (2)$$

This relationship is shown with solid lines for the three mass ratios shown in Figure 1. The slopes of the lines in Figure 1 are consistent with those found by Chambers et al. (1996).

The above equation is useful as it can be used to estimate a minimum spacing required for instability as a function of system age. Rearranging equation 2 we find

$$\delta = \frac{\mu^{1/4}}{3.2} \left[\log_{10}\left(\frac{t_e}{\text{yrs}}\right) + 0.1 + \log_{10}(\mu/10^{-7}) \right]. \quad (3)$$

We confirm that δ is not strongly dependent on planet mass, as we discussed in Section 1. Faults in this equation are discussed in the final section of this paper.

3 ESTIMATE OF A LOWER LIMIT ON TOTAL MASS IN PLANETS

We use the relationship measured from the integrations (equation 3) to estimate the minimum spacing between planets required for bodies to be removed within a clearing. We set t_e in the above equation to the age of the system, requiring particle removal in the clearing within the lifetime of the star. Assuming that all planets have the same mass

ratio, and that they are all spaced at twice δ (defined by equation 2), the total number of planets, N_p , must be larger than that satisfying

$$(1 + 2\delta)^{N_p} = \frac{R_{out}}{R_{in}}, \quad (4)$$

where R_{out} is the semi-major axis of the outermost planet and R_{in} is the semi-major axis of the innermost planet. The factor of two is used to ensure that over this timescale, the planetesimals are cleared while the planets themselves remain stable. Equation 4 for N_p can be solved given R_{in} , R_{out} , and as δ depends on t_e and μ , given the age of the star and an assumed planet mass ratio.

The outermost planet must reside within the dust disk clearing so we can set R_{out} to the radius corresponding to the dust temperature estimated from infrared spectra. We conservatively estimate R_{in} to be the distance at which water freezes (the iceline) based on the luminosity of the central star and given by:

$$R_{in} = \left[\frac{L_*}{4\pi\sigma T_f^4} \right]^{(1/2)}, \quad (5)$$

where $T_f = 273\text{K}$ is the freezing point of water, L_* is the luminosity of the star, and σ is the Stefan-Boltzmann constant. The iceline represents a convenient limit for the inner radius. While massive planet formation models favor formation outside the iceline, planets could migrate closer to the star. Massive planets could reside within the iceline so our estimate for the total number of planets is a lower limit.

The number of planets in a system is then given by:

$$N_p = \frac{\log_{10}(R_{out}/R_{in})}{\log_{10}(1 + 2\delta)}. \quad (6)$$

The factor of 2 for δ on the right hand side follows because we have set the planets to be twice as far away as that required for instability in the pure 10-body system (see discussion in section 1).

The remaining quantity that we must choose to estimate the number of planets is the planet mass ratio, μ . Recent studies suggest that maintenance of a clearing in the dust distribution requires at least a Neptune mass planet (e.g., Ozernoy et al. 2000; Liou & Zook 1999; Moro-Martín & Renu 2002; Deller & Maddison 2005; Quillen 2006, 2007). We adopt this mass ratio, $\mu = 5 \times 10^{-5}$ as a starting point and then will consider the effect of varying this ratio. Once we estimate the number of planets present, the total mass in planets

$$M_{p,total} \gtrsim \mu M_* N_p. \quad (7)$$

The actual mass in planets is likely to be higher than the above estimate for a number of reasons: There may be massive planets within the iceline. We have assumed that all planets have the same mass. If more massive planets are present then a larger total planet mass could be present. This follows because δ is not strongly dependent on planet mass. Our integrations were run with ten planets but we may estimate that the number of required planets is fewer and systems with fewer planets are likely to be more stable.

We apply our framework for estimating the minimum number and total mass in planets to the disks studied by Chen et al. (2006). Chen et al. (2006) has measured the radii of the clearings in the dust based on dust temperatures

measured from spectra observed with the Infrared Spectrograph on board the SSC. Their sample consists of main sequence stars which are located within 150pc and stars that are part of OB associations or moving groups. The properties of these stars are listed in Table 1 with our calculated limits on the number of planets, N_p , and total mass in planets, $M_{p,total}$ within the clearings. We find that 3-6 planets of Neptune mass ratio are required and the total mass in planets is likely to be larger than $\sim 0.2M_J$ where M_J is a Jupiter mass.

Our estimates for the number of planets and total mass in planets depends on the assumed planet mass ratio, μ . We investigate how the estimates depend on the assumed ratio. From the same stellar sample we have computed the mean number of planets using μ ranging from 10^{-3} to 10^{-7} . The results are plotted in Figure 2. The vertical line on this plot shows the location for Neptune’s mass ratio. We find that the total number of planets is insensitive to the assumed mass ratio for $\mu > 10^{-5}$. Planets with ratios lower than this are unlikely to be able to effectively eject material from central clearings within the lifetime of the system. While the total number of estimated planets is likely to be low, the total mass in planets could be an order of magnitude higher than given in Table 1. Jupiter mass planets with similar number and only slightly larger spacings would be capable ejecting material from the clearings during the lifetime of these systems.

It is interesting to compute the total number of planets for our solar system assuming a dust belt in the Kuiper Belt were detected (as predicted by Liou & Zook 1999). Using $R_{out} = 30$ AU and an iceline at 1.0 AU for R_{in} we would predict $N_p = 6.6$ Neptune mass planets, giving a total planetary mass of $0.36 M_J$. Much lower than the actual planetary mass in our solar system in this semi-major axis range ($1.4 M_J$), we reiterate that our calculations represent an absolute lower limit on the total planetary mass of a system. Our solar system easily increases its planetary mass since the planets closer than Neptune have varying mass ratios larger than that of Neptune. Since stability is less dependent on mass ratio than spacing, fewer more massive planets exist, thus increasing total planetary mass in the solar system.

4 CONCLUSIONS AND DISCUSSION

In this paper we have made the assumption that bodies, both planetesimal and dust particles, within a dust disk clearing must be removed from the clearing within the age of the system via gravitational interactions with planets. This assumption is consistent with some scenarios for the early evolution of our solar system. This assumption is combined with a rough estimate for the timescale for instability in multiple planet systems to estimate the planet spacing required for instability. The result is an estimate for the number of planets likely to reside in debris disk systems that host disks with clearings. We find that the number of required planets is 3-6, between the dust disk clearing radius and the iceline, for the sample of disks studied by (Chen et al. 2006), assuming a planet mass ratio like that of Neptune. We find that the number of estimated planets is only weakly dependent on the assumed planet mass. At least $0.2 M_J$ total mass

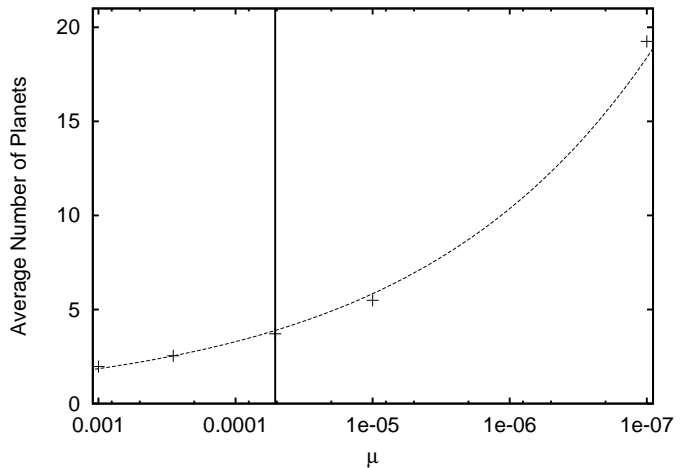


Figure 2. We consider the average number of planets for the systems in Table 1 for assumed mass ratios between 10^{-3} and 10^{-7} . The curved line, $\propto (\log_{10} \mu)^{-0.25}$, is a best fit line for the average number of planets in a system based on mass ratio. We find that the number of estimated planets is insensitive to the assumed planet mass ratio for planets sufficiently massive to effectively empty a clearing. If more massive planets are present then the total mass in planets could be an order of magnitude higher than listed in Table 1.

in planets is required in each system. The planets could be more massive and an order of magnitude more mass in planets could reside in these systems.

Our estimate neglects planets that lie within the iceline but planets could migrate or form closer to the star. The estimate for the planet spacing is based on integration of a 10-body system but our estimated planet number falls below 10. Further numerical experiments show that if the number of planets is decreased to five, a decrease in $\delta/\mu^{1/4}$ by ten percent results in the same instability timescale. The estimate for spacing is twice that for instability in a 10-body system but really we require an instability timescale for massless bodies in between massive bodies (e.g., as studied by Duncan et al. 1989). We have assumed that the planet/planet encounter timescale is related to a clearing timescale and this is not necessarily true as small, low mass objects do not feel forces on each other the way that large, massive bodies do. A more sophisticated treatment would require integration of a much larger number of particles and low mass as well as planetary mass bodies. We could also examine the effects of resonances on stability timescales and the phase space of systems with massive planets as was done by Chatterjee et al. (2007). Such an exploration could improve on the crude constraints on multi-planetary systems based on observations of debris disks that we have explored here. Here we have assumed that central clearing of debris and dust is primarily due to scattering by planets. However collisional cascade models for dust production in debris disks predict that the dust production rate drops with time and that the centers of disks evolve faster than their outer parts (e.g., Dominik & Decin 2003). It is possible that future observations and statistical studies may differentiate between collisional cascade evolution and planetary clearing models.

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Table 1. Stars with Dusty Disks with Clearings

Name	M_* (M_\odot)	R_{out} (AU)	R_{in} (AU)	L_* (L_\odot)	Age (Gyr)	N_p	$M_{p,total}$ (J_\odot)
γ Cas	4.0	72	16.5	250	0.11	3.2	0.17
HR 333	2.5	34	6.67	41	0.11	3.5	0.19
49 Cet	2.2	22	4.54	19	0.05	3.5	0.19
HR 506	1.2	21	1.35	1.7	0.3	5.8	0.31
γ Tri	2.6	31	7.65	54	0.17	3.0	0.16
τ^3 Eri	2.0	12	3.75	13	0.5	2.4	0.13
HR 1082	1.9	52	3.45	11	0.15	5.9	0.31
HR 1570	2.2	42	4.88	22	0.23	4.6	0.24
η Lep	2.3	10	5.70	30	0.18	1.2	0.06
HD 53143	0.8	4	0.72	0.48	0.97 ^a	3.5	0.19
HR 3314	2.5	27	6.83	43	0.19	2.9	0.16
HD 95086	1.7	30	2.85	7.5	0.016 ^b	5.5	0.29
β UMa	2.7	53	9.32	80	0.34	3.6	0.19
β Leo	2.0	19	3.90	14	0.05	3.5	0.19
HD 110058	?	20	3.29	10	0.016 ^b	4.2	0.22
γ Boo	2.2	23	4.77	21	0.27	3.3	0.18
α CrB	2.7	33	9.61	85	0.30	2.6	0.14
HD 139664	2.7	15	1.97	3.6	0.48	4.2	0.23
HD 146897	1.5	17	2.23	4.6	0.005 ^b	4.9	0.26
HR 6297	1.8	21	3.45	11	0.42	3.8	0.20
HR 6486	1.7	14	2.71	6.8	0.24	3.5	0.19
HR 6532	3.0	47	10.05	93	0.2	3.3	0.17
78 Her	2.6	23	7.44	51	0.05	2.5	0.13
γ Oph	2.5	27	6.50	39	0.19	3.0	0.16
HR 6670	1.5	13	2.11	4.1	1.6	3.6	0.19
HD 181327	1.9	20	1.64	2.5	1.4	5.0	0.27
HD 191089	1.8	14	1.83	3.1	1.6	4.1	0.22
HR 8799	1.6	8	2.57	6.1	0.59	2.3	0.13
SUN	1.0	30	1.04	1.0	4.6	6.6	0.36

The stellar masses (M_*), outer disk radii (R_{out}), Luminosity (L_*), and stellar ages are given for the sample discussed and studied by Chen et al. (2006). ^aAge of HR 53143 from Zuckerman & Song (2004). ^bAge of HR 95086, HD 146897 from deZeeuw et al. (1999). Note as can be seen from Table 1 of Chen et al. (2006) there are discrepancies between available age estimates. The rightmost two columns are calculated using Equations 6 and 3 and show the estimated number of planets residing between the iceline and the clearing edge (at R_{out}). The iceline radius R_{in} is estimated using equation 5. Each planet is assumed to have the mass ratio of Neptune. The number of planets, N_p , is estimated assuming that the planets are sufficiently close together that all interplanetary debris has suffered a close encounter with a planet within the lifetime of the system. The total mass in planets $M_{p,total} = N_p \mu M_*$ is a lower limit for the total mass in planets residing in the system. Our own solar system is included to emphasize this point. As is the case in our Solar System, if more massive planets are present, then more mass could be present in planets between the dust disk and the iceline even though the planets must be further apart.