Impact of planet–planet scattering on the formation and survival of debris disks

F. Marzari

Dept. of Physics, University of Padova, 35131 Italy

Accepted .....; Received ..... ; in original form ........

ABSTRACT
Planet–planet scattering is a major dynamical mechanism able to significantly alter the architecture of a planetary system. In addition to that, it may also affect the formation and retention of a debris disk by the system. A violent chaotic evolution of the planets can easily clear leftover planetesimal belts preventing the ignition of a substantial collisional cascade that can give origin to a debris disk. On the other end, a mild evolution with limited steps in eccentricity and semimajor axis can trigger the formation of a debris disk by stirring an initially quiet planetesimal belt. The variety of possible effects that planet–planet scattering can have on the formation of debris disks is analysed and the statistical probability of the different outcomes is evaluated. This leads to the prediction that systems which underwent an episode of chaotic evolution might have a lower probability of harboring a debris disk.

Key words: planetary systems; planets and satellites: dynamical evolution and stability

1 INTRODUCTION
Most of the belts of dust or debris that have been detected around many main sequence stars like HR4796A (Jura 1993), AU Mic (Kalas, Liu & Matthews 2004), HD107146 (Williams et al. 2004), as well as our sun, are thought to originate from a ring of planetesimals, leftover of the planet formation process. If a population of large solid bodies have formed within the protoplanetary disk, as predicted by the core–accretion model, at later stages of the system evolution, when the star has reached its mature state, they may collide creating smaller and smaller "debris" dust grains. The collisional cascade of these remnant planetesimals effectively replenish the dust population long after it would have normally dispersed because of P-R drag, further collisions or interaction with planets (see Wyatt (2008) for a review). The constant refilling of dust due to cratering and fragmentation within the planetesimal belt maintains at present what we observe as a debris disk surrounding the star. To produce dust by collisions, the disk must be stirred enough to ignite the collisional cascade. Different mechanisms have been proposed to activate a planetesimal belt and these include stellar flybys, self stirring and planet stirring (see Matthews et al. 2004 for a review). On the other hand, the planetesimal belt must survive in order to continuously replenish the dust disk and, as a consequence, a smooth and limited evolution of the planets after their formation is required. Planet migration caused by tidal interaction with the gas of the native protoplanetary disk (Papaloizou et al. 2007) or planetesimal–driven migration (Murray et al. 1998, Levison et al. 2007) both may lead to changes in the planetesimal orbital distribution but, in most cases, they would not totally clear remnant planetesimal belts from the system. Even a mildly violent evolution, such as that suggested for our solar system by the Nice model (Tsiganis et al. 2005) and characterized by a significant outward migration of Neptune and Uranus driven by close encounters with Saturn, possible sculpted the Kuiper belt but did not cleared it out.

Different is the scenario in those extrasolar systems harboring planets in highly eccentric orbits. The leading mechanism for explaining why extrasolar planets have very elliptic trajectories is planet–planet scattering (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Marzari & Weidenschilling 2002; Jurić & Tremaine 2008; Nagasawa, Ida & Bessho 2008; Raymond, Armitage & Gorelick 2009, 2010; Marzari 2011; Nagasawa & Ida 2011; Raymond et al. 2011, 2012; Beaugé & Nesvorný 2012), hereinafter P-P scattering. Often called the Jumping Jupiters” model, it assumes that two or more massive giant planets form from the disk around a solar–type star. Mutual gravitational perturbations among the planets excite their eccentricities leading to dynamical instability and crossing orbits. Repeated close encounters between the planets cause an extended period of chaotic evolution characterized by major changes in the orbital configuration. The most likely outcome is the ejection of one (or more) planet on a hyperbolic trajectory, leaving one (or more) planets on a stable eccentric and inclined orbit.
The orbit of the inner survivor is closer to the star than the innermost starting orbit, since it supplies orbital energy to the ejected planet(s).

During the chaotic evolution preceding the ejection of one planet on a hyperbolic trajectory, the planets roam around the system on eccentric and inclined orbits for an extended period. An important question concerning the final aspect of these systems is: can planetesimal belts formed prior to the onset of instability survive this violent phase? In other words, is the probability of detecting debris disks the same in planetary systems which underwent P–P scattering compared to those in which this kind of dynamical evolution did not occur? If indeed P–P scattering tends to clear planetesimal belts then we would expect a lower rate of debris disk detections around stars with planets on eccentric orbits. On the other hand, if the chaotic evolution of planets does not clear potential planetesimal belts, it would leave them in a dynamically excited state sufficient to trigger the collisional cascade needed to form the dust disk. In this case, all systems which underwent P–P scattering would have stirred planetesimal disks and the debris disk statistics would be richer.

While Bonsor, Raymond & Augereau (2013) investigated the short-lived production of exozodiacal dust just after a P–P scattering event due to an increase of mass scattered in inner orbits from outer Kuiper belts and Raymond & Armitage (2013) studied the formation of mini–Oort clouds, here the impact of the chaotic phase on the long term survivial of debris disks is explored. Initially unstable planetary systems populated by three planets on circular orbits and by a non–excited swarm of leftover planetesimals, it would leave them in a dynamically excited state sufficient to trigger the collisional cascade needed to form the dust disk. In this case, all systems which underwent P–P scattering would have stirred planetesimal disks and the debris disk statistics would be richer.

The survival of an asteroid belt or of a Kuiper belt in a planetary system where P–P scattering occurred depends on 1) how long and wild is the evolution of the planets prior the ejection of one of them and 2) on the final architecture of the system i.e. where the outer planet is placed at the end of the chaotic behavior. Both these aspects may be very different and, since the evolution is fully chaotic, cannot be predicted a priori. In the next sections different final outcomes will be discussed ranging from dispersal of the belt, partial excitation and almost no effect. This last case is typical of those systems where P–P scattering leads to the ejection of one planet on a very short timescale. A statistical prediction of the impact of the different outcomes on the presence of debris disks will be given in the next section on the basis of the outcome of a large number of P–P scattering test events.

3 Chaotic Evolution of the Planets: Effects on the Planetesimal Remnant Population

The survival of an asteroid belt or of a Kuiper belt in a planetary system where P–P scattering occurred depends on 1) how long and wild is the evolution of the planets prior the ejection of one of them and 2) on the final architecture of the system i.e. where the outer planet is placed at the end of the chaotic behavior. Both these aspects may be very different and, since the evolution is fully chaotic, cannot be predicted a priori. In the next sections different final outcomes will be discussed ranging from dispersal of the belt, partial excitation and almost no effect. This last case is typical of those systems where P–P scattering leads to the ejection of one planet on a very short timescale. A statistical prediction of the impact of the different outcomes on the presence of debris disks will be given in the next section on the basis of the outcome of a large number of P–P scattering test events.

3.1 Planetesimal dispersal: no debris disks

In Fig.1 the final orbital distribution of an initial quiet planetesimal belt extending from 30 to 60 AU is shown after the end of the chaotic evolution of the planets. One body is ejected on a hyperbolic trajectory and the two surviving planets are left on stable eccentric orbits both inside the initial location of the belt. The P–P scattering phase has lasted 2.1 Myr and in this period about 95% of the planetesimals are ejected out of the system. Those which are still orbiting the star are in a highly excited state with eccentricities reaching almost 1, inclinations up to 90° and a few also on
retrograde orbits. Most of them, due to their high eccentricity, are doomed to encounter the outer planet, which is also on a highly eccentric orbit, and be ejected out of the system later on. Only a few planetesimals located beyond 50 AU do not interact with the planets and may survive for a long time. However, their number density is much lower than the initial one and it appears unlikely that they can activate a significant collisional cascade able to create and maintain a debris disk also because of their large dispersion in eccentricity and inclination. This farther decreases the volume density preventing an intense collisional activity.

A second event which may prevent the formation of a debris disk after a P–P scattering phase is the insertion of the outer planet into a highly eccentric orbit. This outcome is illustrated in Fig.2 where the outer planet, whose semimajor axis is moved to about 72 AU at the end of the chaotic phase, has an eccentricity of ~0.8 that allows it to cover a wide range in radial distance. The initial planetesimal belt, located in this case between 1 to 30 AU, is stirred up during the P–P scattering phase which lasts about 0.9 Myr and when the planets are injected in their final orbits it is destined to be fully cleared. Even this kind of dynamical outcome is adverse to the formation of a debris disk in the system. This second kind of P–P scattering evolution is lethal also for a potential Kuiper Belt since the planet reach extends well beyond 100 AU clearing any leftover planetesimal belt initially present in the system.

### 3.2 Planetesimal stirring: activation of debris disks

The cases described in the previous section are characterized either by an extended period of chaotic evolution or by the insertion of the outer planet in a highly eccentric orbit. However, the P–P scattering may occur on a short timescale and the final eccentricity of the surviving planets may be low. In this case, the chaotic evolution of the planets is an important source of velocity stirring able to ignite the collisional cascade leading to a debris disk without clearing the belt. This behavior is illustrated in Fig.3 where an initial Kuiper Belt is efficiently stirred up during the P–P scattering phase. The chaotic evolution of the planets, prior the ejection of one of them, is limited in semimajor axis and it is shown in Fig.4. The two surviving planets are left on low eccentricity orbits allowing a debris disk to form and be refilled. A somewhat more excited belt is produced in the case illustrated in Fig.5. The initial planetesimal ring is stirred up by encounters with the planets and finally a stirred belt is formed extending from about 20 AU and beyond. High velocity collisions are dominant and dust is produced.

The type of evolution described in this section is characterized by a mild chaotic evolution of the planets with contained changes in eccentricity and semimajor axis. It is highly favorable to the development of a debris disk from a planetesimal belt, better if located in the outer regions of the system. It excites the planetesimal trajectories leading to high velocity impacts with a consistent rate of dust production able to refill the debris disk. Different degrees of stirring are possible and they depend on the timespan of the planet chaotic evolution and on the final orbital elements of the planets.
The P–P scattering phase is shorter and the outer planet is inserted in a highly eccentric orbit. Its gravitational perturbations will fully clear any planetesimal belt located within 130 AU preventing the formation of a significant debris disk.

Figure 3. Activation of a debris disk by stirring a belt of planetesimals in the outer regions of the system. The P–P scattering in this case does not clear the planetesimal ring but it excites higher values of eccentricity and inclination triggering a high dust production rate. In this case $a_2 = 3.93$ AU and $a_3 = 6.23$ AU.

Figure 4. Evolution of the planets during the P–P scattering phase that has lead to the excitation of the belt illustrated in Fig. 3. The semimajor axes of the planets never jump beyond 20 AU and the outer planet achieves a low final eccentricity.

Figure 5. An excited planetesimal belt is created at the end of the P–P scattering phase ($a_2 = 3.90$ AU and $a_3 = 5.93$ AU). The green dots, representing planetesimals that do not cross the planet orbits, extend beyond 20 AU.
ers it is only stirred up leading to the activation of a debris disk. Due to the chaotic nature of the evolution of planets in crossing orbits, it is not possible to predict a priori the effects on planetesimal belts of the P–P scattering phase. However, it is possible to have a rough glimpse at the frequency with which the different cases can occur. To achieve this goal, the initial configuration with 3 planets on unstable orbits has been replicated with the same criteria adopted to generate the initial orbital elements described in Sect. 2. Due to the strong chaotic nature of the planet evolution after the first close encounter, the choice of a limited range of values for $K_1$ and $K_2$ but random values for all other orbital elements allow to span the whole spectrum of possible final dynamical states of the system once fixed $a_1$ and the masses of the planets. To cover a wider scenario of possible systems, we have performed three additional statistical simulations where also different masses and wider initial orbits have been considered. These models are motivated by the presence of a significant number of exoplanets with masses beyond that of Jupiter. In spite of a decreasing trend beyond 1 $M_J$, there is a consistent number of bodies with masses of 2 and 3 $M_J$ on eccentric orbits which may have been involved in a P–P scattering event. It is also impossible, at present, to predict the orbital distribution of a multi-planet system before the onset of a P–P scattering phase since it depends on the initial density of the protoplanetary disk, the amount of orbital migration of the planets during their growth, if the P–P scattering event occurs in presence or not of the disk gas and on many additional factors. For these reason, a different initial architecture for the 3-planet systems is studied with the whole system moved outwards in semimajor axis setting $a_1 = 5$ AU. In these statistical simulations, each system is numerically propagated until one planet is ejected. The orbital elements of the surviving planets are recorded in order to test the frequency with which the different outcomes occur. 2000 3-planet systems are integrated in each different case.

In Fig. 6a, we show the final distribution of the outer planet semimajor axis vs. eccentricity for the case with $m_1 = m_2 = m_3 = 1 M_J$ (case a). The color coding gives the timespan of the P–P scattering phase which is important in determining the amount of dispersal of the planetesimal belt. In this plot we can draw a rough separation between highly perturbing systems, that possibly inhibit the formation of a dusty disk, and those where, on the contrary, the mild perturbations favor the formation of a disk. The green dots mark those systems where the timespan of the chaotic evolution is shorter than $1 \times 10^6$ and the aphelion is lower than 30 AU. The majority of these systems should activate potential leftover Kuiper–like belts and have debris disks, at least populating the outer region of the system. All the other systems are potentially hostile to the survival of any planetesimal belt and should not posses debris disks. It is noteworthy that the large majority of systems (76%) belong to this second category and are expected not to harbor a debris disk since its potential precursors have been eroded away by the perturbations of the planets either during an extended chaotic phase or because the outer planet is on a highly eccentric orbit. In Fig. 6b the masses of the planets are set to $m_1 = 1 M_J$, $m_2 = 2 M_J$, and $m_3 = 3 M_J$, respectively. For this initial configuration (case b) we observe an increase of systems which may harbor debris disks since the fraction of planets on outer and eccentric orbits is lower compared to the standard case a) with 3 equal mass planets. In model b) 62% of the planetary systems are hostile environments for the formation of a debris disk, a lower percentage compared to case a). When the planet masses are set to $m_1 = 2 M_J$, $m_2 = 1 M_J$, and $m_3 = 3 M_J$ (Fig. 6c) the situation is somewhat intermediate between case a) and b) with the number of systems potentially adverse to debris disk development up to 71%. The most critical scenario is that shown in case d) where the planets, all with the same mass equal to $M_J$, are shifted on wider orbits ($a_1 = 5 A_U$). It is noteworthy in this case the proliferation of systems with the outer planet on a wide and eccentric orbit and, as a consequence, 87% of the systems appear to be hostile to the formation of a debris disk.

5 DISCUSSION AND CONCLUSIONS

A large fraction of extrasolar planetary systems harbor planets on highly eccentric orbits and relatively small semimajor axes. The most promising mechanism to explain this finding is that the planetary system had an additional planet which was ejected after a period of dynamical instability. The P–P scattering phase that precedes the ejection of one planet on a hyperbolic trajectory naturally leads to the onset of highly eccentric and inclined orbits for the surviving planets explaining observations. On the long term, the inner planet, if close to the star, would have its orbit circularized by stellar tides. The outer one would preserve its high eccentricity.

An important question concerning these systems is the fate of remnant planetesimal belts, leftover of the planet formation process, and their capability of forming and maintaining debris disks in spite of the P–P scattering event. Two conditions are strongly unfavorable to the survival of these belts: an extended period of chaotic behavior before the ejection of one planet and the insertion of the outer surviving planet in a highly eccentric orbit. In the first case the prolonged chaotic evolution of the planets characterized by large steps in semimajor axis and eccentricity bring them frequently within the belt where they excite and scatter a large fraction of the planetesimals that populate it. When finally the P–P scattering comes to an end, most of the belt is cleared and the chance of forming a debris disk is very low due to the large orbital dispersion of the surviving planetesimals. In the second case, when the outer planet is ejected in a high eccentricity orbit, it spans a wide range of radial distance scattering out of the system every body it encounters on its path. It disperses even potential Kuiper Belts if the eccentricity is high enough.

If the chaotic evolution evolve on a short timescale and the outer planet ends up on a orbit which is not too eccentric, then planetesimal belts can survive the P–P scattering event and are left in an excited state which easily activates the collisional cascade leading to a debris disk. The disk can either be related to an asteroid belt or, more frequently, to a Kuiper Belt.

In a minority of cases, the P–P scattering will occur on such a short timescale that the planets will not have the time to excite the belt during the chaotic evolution and, unless the outer planet is in a very eccentric orbit, the belts in the system will not be stirred up. In this case, other dynamical
mechanisms are required to trigger high velocity collisions, similar to those in systems where P–P scattering did not occur (Matthews et al. 2014).

A statistical exploration of the P–P scattering event in terms of timespan of the chaotic evolution and orbital elements of the outer surviving planet shows that the fraction of events leading to a highly perturbing configuration depends on the dynamical architecture of the 3 planets prior the onset of the chaotic phase. A different mass distribution among the planets or their shift to wider orbits may either enhance or reduce the number of cases potentially hostile to the survival of a planetesimal belt. In particular, if the planets enter the chaotic phase when they are far from the host star, like in the case d) described in Section 4, then the erosion of remnant planetesimal belts is expected to occur in the vast majority of cases. A general conclusion, that can be drawn from the statistical analysis performed in Section 4, is that from about 60 to 90% of systems which underwent a period of P–P scattering potentially cleared their leftover planetesimal belts. This suggests that planetary systems where at least one planet has been discovered on a highly eccentric orbit, probable outcome of a P–P scattering period, should have a lower rate of debris disks.

The analysis presented here needs to be extended to other different initial configurations for the planets. Systems with only 2 initial planets or with more than three should be investigated to give more stringent predictions about the fate of planetesimal belts and debris disks.

ACKNOWLEDGMENTS

We thank an anonymous referee for his useful comments and suggestions.

REFERENCES

Beaugé C., Nesvorný D., 2012, ApJ, 751, 119
Bonsor A., Raymond S. N., Augereau J.-C., 2013, MNRAS, 433, 2938
P–P scattering and the formation of debris disks

Chatterjee S., Ford E. B., Matsumura S., Rasio F. A., 2008, ApJ, 686, 580
Everhart E., 1985, in Dynamics of Comets: Their Origin and Evolution, Proceedings of IAU Colloq. 83, held in Rome, Italy, June 11-15, 1984. Edited by Andrea Carusi and Giovanni B. Valsecchi. Dordrecht: Reidel, Astrophysics and Space Science Library. Volume 115, 1985, p.185, Carusi A., Valsecchi G. B., eds., p. 185
Jura M., 1991, ApJL, 383, L79
Juric M., Tremaine S., 2008, ApJ, 686, 603
Kalas P., Liu M. C., Matthews B. C., 2004, Science, 303, 1990
Levison H. F., Morbidelli A., Gomes R., Backman D., 2007, Protostars and Planets V, 669
Marzari F., 2010, Formation and Evolution of Exoplanets, R. Barnes Editor, WILEY-VCH, 223
Marzari F., 2014, MNRAS, 442, 1110
Marzari F., Weidenschilling S. J., 2002, Icarus, 156, 570
Matthews B. C., Krivov A. V., Wyatt M. C., Bryden G., Eiroa C., 2014, ArXiv e-prints
Murray N., Hansen B., Holman M., Tremaine S., 1998, Science, 279, 69
Nagasawa M., Ida S., 2011, ApJ, 742, 72
Nagasawa M., Ida S., Bessho T., 2008, ApJ, 678, 498
Papaloizou J. C. B., Nelson R. P., Kley W., Masset F. S., Artyomovicz P., 2007, Protostars and Planets V, 655
Rasio F. A., Ford E. B., 1996, Science, 274, 954
Raymond S. N., Armitage P. J., 2013, MNRAS, 429, L99
Raymond S. N., Armitage P. J., Gorelick N., 2009, ApJL, 699, L88
Raymond S. N., Armitage P. J., Gorelick N., 2010, ApJ, 711, 772
Raymond S. N. et al., 2011, A&A, 530, A62
Raymond S. N. et al., 2012, A&A, 541, A11
Tsiganis K., Gomes R., Morbidelli A., Levison H. F., 2005, Nat, 435, 459
Weidenschilling S. J., Marzari F., 1996, Nature, 384, 619
Williams J. P., Najita J., Liu M. C., Bottinelli S., Carpenter J. M., Hillenbrand L. A., Meyer M. R., Soderblom D. R., 2004, ApJ, 604, 414
Wyatt M. C., 2008, ARAA, 46, 339

This paper has been typeset from a TeX/\LaTeX file prepared by the author.