Production of star-grazing and impacting planetesimals via orbital migration of extrasolar planets

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ABSTRACT

During orbital migration of a giant extrasolar planet via ejection of planetesimals (Murray et al. 1998), inner mean motion resonances can be strong enough to cause planetesimals to graze or impact the star. We integrate numerically the motions of particles which pass through the 3:1 or 4:1 mean motion resonances of a migrating Jupiter mass planet. We find that many particles can be trapped in the 3:1 or 4:1 resonances and pumped to high enough eccentricities that they impact the star. This implies that for a planet migrating a substantial fraction of its semi major axis, a significant fraction of its mass in planetesimals could impact the star. This process may be capable of enriching the metallicity of the star, and at a time when the star is no longer fully convective. Upon close approaches to the star the surfaces of these planetesimals will be sublimated. Orbital migration should cause continuing production of evaporating bodies, suggesting that this process should be detectable with searches for transient absorption lines in young stars. The remainder of the particles will not impact the star but can be subsequently ejected by the planet as it migrates further inwards. This allows the planet to migrate a substantial fraction of its initial semi-major axis via ejection of planetesimals.

1. Introduction

In the standard scenario for solar system formation, solid material in the disk forms rocky or icy bodies called planetesimals. These then accumulate in certain regions to form planets. The moderate detection rate of dusty disks with IRAS and ISO in the far infrared, particularly surrounding younger stars (Aumann & Good 1990, Becklin et al. 1999, Beckwith et al. 1999), suggest that planet formation is often accompanied by the formation of belts (e.g., the Kuiper belt and possibly the Main asteroid belt). Recently spectral features of crystalline silicate material similar to those observed in comets have also been detected in these disks, suggesting that there is asteroidal and cometary material in these disks (Malfait et al. 1998, Waelkens et al. 1996, Pantin et al. 1999). The detection of planets orbiting nearby solar-type stars (e.g., Mayor & Queloz) and dusty disks surrounding some of these stars (e.g., Trilling & Brown 1998) confirms the connection

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between rocky disk material and planets. Notably stars with known extra-solar planets have enhanced metallicities (Gonzalez, Wallerstein, & Saar 1999; Gonzalez 1998), establishing an as yet unexplained link between planet formation and stellar metallicities.

The small orbital semi-major axes of many of the newly discovered extrasolar planets ($a < 0.1$ AU) is surprising. This has resulted in the proposal of two classes of planetary orbital migration mechanisms. One mechanism involves the transfer of angular momentum between a planet and a gaseous disk (e.g. Trilling et al. 1998; Lin, Bodenheimer & Richardson 1996). The other focuses on resonant interactions between planetesimals and the planet and the resulting ejection of the planetesimals (in extrasolar systems Murray et al. 1998, and in our solar system Fernandez & Ip 1984 and Malhotra 1993). The first mechanisms suffers from a fine tuning problem where only a small range of planet and disk masses would allow migration but not the destruction of planet by the star (Trilling et al. 1998). Metals from planets accreted by the star could account for the enhanced metallicities of the more massive stars with known planets. However because stars with masses comparable to the sun have convective envelopes for nearly the the entire time interval over which planets are expected to be accreted, encorporation of giant planets into the star should not be able to enhance the stars metallicity substantially (Laughlin & Adams 1997).

The second mechanism involving ejection of planetesimals (Murray et al. 1998) has some advantages over the first mechanism. Planetesimals affected by the inner resonances can be driven to extremely high eccentricities and so can impact the star (Beust & Morbidelli 1996; Gladman et al. 1997; Moons & Morbidelli; Wisdom 1985; Farinella et al. 1993; Migliorini et al. 1998; Ferraz-Mello & Klaflke 1991). This would happen at a later time ($\gtrsim 10^7$ years; Murray et al. 1998) than appropriate for the migration scenario involving a gaseous disk ($\sim 10^6$ years). Thus addition of rocky or metallic material will happen when the stellar convective envelope is small so that the metals will remain trapped in the convection zone, rather than mixing into the star. In this way orbital migration via ejection of planetesimals would more naturally explain the enhanced metallicities of stars with massive planets. As pointed out by Gonzalez (1998) adding $20 M_\oplus$ (earth masses) of asteroidal material to the convection zone of the star is sufficient to increase the enhanced metallicities of a solar type star by $\Delta[Fe/H] \sim 0.1$ dex. For a planet to migrate a significant fraction of its initial semi-major axis roughly its mass of planetesimals must be ejected from the system (Murray et al. 1998). Since in the inner solar system this material is expected to be asteroidal or rocky this could result in a significant fraction of a Jupiter mass planet ($M_J = 310 M_\oplus$) impacting and becoming incorporated into the star.

In this paper we concentrate on the mechanism for producing star grazing planetesimals explored by Beust & Morbidelli (1996) to account for the transient absorption lines observed against beta Pictoris (e.g., Crawford et al. 1994; Lagrange et al. 1996). In this context a star grazing planetesimal approaches within 10 stellar radii of the star. Mean motion resonances (such as the 3:1 and 4:1) with one large moderately eccentric planet, can pump eccentricities to 1.0. In §2 using averaged Hamiltonians we plot the range of planetesimal and planet eccentricities needed for a given resonance to produce a star impacting body. However the region of phase phase that
results in extremely high eccentricity orbits is not necessarily large since many particles with semi-major axes containing the resonance will not librate or will not librate to high eccentricities (e.g., as shown in the contour plots of Yoshikawa 1990; Yoshikawa 1991). As a planet migrates we expect many particles to have orbital elements such that they will not be caught in the active (or high eccentricity) part of the resonance. So in §3 we estimate via numerical integration the efficiency of these resonances to produce extremely high eccentricity particles. For a series of integrations we tabulate the numbers of particles which impact the star and those which eventually cross the Hill sphere of the planet and are ejected to large semi-major axes.

2. When can star impacting planetesimals be produced?

During the migration of a major planet, mean-motion resonances will be swept through the disk of planetesimals. Though secular resonances are also capable driving particles to extremely high eccentricities (Levison, Duncan & Wetherill 1994) they may not necessarily be swept through the disk. We also cannot necessarily assume that secular resonances are always strong in extra-solar systems (Beust & Morbidelli 1996) particularly as the innermost planet becomes more distant from its neighboring planets. So we concentrate here on mean motion resonances with one major planet.

The maximum eccentricity reached by particles librating in a resonance is extremely sensitive to the eccentricity of the planet (Beust & Morbidelli 1996; Yoshikawa 1990; Moons & Morbidelli). We expand on the work of Beust & Morbidelli (1996) to determine what range of eccentricities for a planet are required to pump particle eccentricities to 1. We created contour plots numerically from the Hamiltonian averaged over time (as in Beust & Morbidelli 1996 and Yoshikawa 1990). For each resonance we then determined what minimum initial particle eccentricity is needed for a particle to later reach the star (e = 1). We estimated this minimum eccentricity (shown in Fig. 1) for a range of planet eccentricities, $e_p$. These contour plots are only extremely weakly dependent on the planet mass. We see in Fig. 1 that past a planet eccentricity of 0.3 the 3:1, 4:1, 5:1, 5:2 and 7:2 resonances are all capable of driving low eccentricity particles to extremely high eccentricities. The eccentricities of the extrasolar planets are not restricted to extremely low values (Marcy 1999). This implies that resonances which are capable of causing star grazing or impacting planetesimals are likely to exist in almost all of these systems.

3. Simulation of particles in mean motion resonances during orbital migration

To estimate the efficiency of production of high eccentricity orbits we numerically integrate the orbits of particles (using a conventional Burlisch-Stoer numerical scheme) during the slow migration of a major planet. All particles are massless except for the star and one planet with an eccentricity $e_p$, which remains constant throughout the integration. During the integration
we force the semi-major axis of the planet to drift inwards at a rate given by the dimensionless parameter

\[ D_a = \frac{da}{dt} \frac{P}{a} \]  

for \( P \) the period of the planet and \( a \) its semi-major axis. \( D_a \) is fixed during the integration resulting in \( \frac{da}{dt} \propto \sqrt{a} \). Particles are placed in the plane of the planet’s orbit just within (a few resonance widths) the semi-major axis of either the 3:1 or 4:1 resonance. For each particle the angle of perihelion and the mean anomalies were chosen randomly. Massless particles were integrated until they were driven to high eccentricity (\( \epsilon > 0.995 \)) and so impact the star, or crossed the Hill sphere radius of the planet and were ejected to semi-major axes larger than the planet. This took between a few times \( 10^5 \) to \( 10^6 \) periods measured in units of the initial orbital period of the planet. In Table 1 we note the initial conditions, migration rates, planet masses and eccentricities (which remain fixed during the simulation), and final particle fates for a set of 10 particle integrations. In Table 2 we note the resonances operating on the particles in each simulation prior to impact or ejection.

A sample plot showing eccentricity and semi-major axes for a run (denoted N8) are shown in Fig. 2. Almost at all times particles are strongly affected by resonances. When a particle crosses the 3:1 or 4:1 resonance it may be trapped in a high eccentricity region of the resonance. Then the particle can be pumped to extremely high eccentricities and impact the star. We find that both the 3:1 and 4:1 resonances cause impacts. However if the particle does not remain trapped in the resonance it can later on be caught in another resonance. For example, we observe that particles not removed by the 3:1 may later on be caught in the 5:2 or 7:3 resonances and particles not initially affected by the 4:1 may subsequently be caught in the 3:1, 7:2 or 8:3 resonances (see Table 2). If the particle is trapped or strongly affected by a resonance nearer to the planet (such as the 8:3 resonance) then it has a higher chance of being ejected than hitting the star. In the slower migration rate simulations (N5, M5) we see that even minor resonances such as the 11:3, 10:3, 11:4 cause jumps in the semi-major axis as the particle crosses the resonance. However only the 3:1 and 4:1 are strong enough (and with large enough regions in phase space) that particles are trapped in them for long periods of time. These resonances are responsible for the majority of impacts.

In Fig. 2a we see that particles trapped in the 3:1 and 4:1 resonances can make multiple close approaches to the star. During a close approach the surface of a planetesimal will graze the star and so be sublimated it. Thus we would predict that a migrating planet would cause continuing production of ‘falling evaporative bodies’, as proposed to explain the transient absorption lines observed against beta Pictoris and other stars (e.g., Beust & Morbidelli 1996, Crawford et al. 1994, Lagrange et al. 1996, Grady et al. 1996). We see in our simulations that more than one resonance can cause star grazers. If star grazers are produced by more than one resonance then particles could approach the star from different angles with respect to the planet’s angle of perihelion. This might provide an alternative explanation for the occasional blue-shifted event on beta Pictoris (Crawford, Beust & Lagrange 1998).
Even though the 3:1 and 4:1 resonances can pump eccentricities to 1.0, in every simulation (see Tab. 1) we find particles which pass through these resonances that are not pumped to high eccentricities and so removed from the system by an impact with the star. These particles can later be ejected by the planet. While the 3:1 and 4:1 resonances can reduce the surface density in a disk of planetesimals, they do not create a hole as they are swept through the disk. If the density of planetesimals is high enough, a planet migrating as a result of ejection of planetesimals can migrate to within its original (at formation) 3:1 or 4:1 mean motion resonances. This would allow a planet to migrate a substantial fraction of the planet’s semi-major axis via ejection of planetesimals.

Particles which impact the star loose all their angular momentum to the planet which would reduce the planet’s eccentricity. During the time they are trapped in a resonance their semi-major axes decreases. This implies that the planet will gain energy. However the decrease in semi-major axis was typically less than 30% of the particle’s initial semi-major axes, so the energy gained by the planet from trapped particles should be small compared to that lost from ejected particles.

We did not find that the fraction of impacts was strongly dependent on the planet migration rate, initial particle conditions, or planet eccentricity. However more particles should be integrated to verify this. We would have expected that slower migration rates, more massive planets, lower eccentricity initial particle eccentricities, and higher planet eccentricities would result in an increase in the efficiency of trapping particles in resonances and so in producing impacts. However the number of resonances operating on each particle makes it difficult to predict the final states. For example when the migration rate is fast or the planet eccentricity is lowered then we found that weaker resonances such as the 4:1 or 7:2 did not affect the particles much, however the 3:1 was still strong enough to cause impacts.

3.1. Survival until impact

In our integrations we can estimate the timescale for the eccentricity to reach $\sim 0.995$. While some particles impact the star on a very short timescale (e.g., particle 1 in Fig. 2), others are slowly pumped to high eccentricities (e.g., particles 5,6,7, and 8 in Fig. 2). For the slower approaches the particle or planetesimal could make $\sim 10^4 - 10^5$ close passages to the star before impact. When the migration rate was slower particles typically experienced larger numbers of close passages before impact. We have estimated the mass loss from a rocky body during a free fall time at solar radius from the sun to be $\sim 30$ cm. If the planetesimal makes $10^4$ of such close passages then a km body will be completely evaporated by a solar type star. For particles making multiple close approaches only large bodies $\sim 1$km will survive until impact. Notably the size distribution of asteroids subsequent to Gyr timescale collisional evolution (Davis et al. 1985; Greenberg et al. 1978) is expected to be such that most of the integrated disk mass is contained in the largest bodies. When migration is relatively quick, this mechanism could be a way to increase the metallicity of the star, despite the fact that the lower mass bodies may not survive until
impact. Smaller bodies which will completely evaporate could manifest themselves as transient absorption features, a phenomenon which is observed on beta Pictoris and other stars (e.g., Crawford et al. 1994; Lagrange et al. 1996; Grady et al. 1996).

We now consider whether large bodies are likely to fragment upon close approach. If the object is strengthless then it is likely to fragment at periapse only if the density of the object is lower than the mean density of the star (e.g., Asphaug & Benz 1996; Sridhar & Tremaine 1992). The mean density of the sun is $\rho \sim 1.4 \text{ g cm}^{-3}$ so that on a solar type star all but the least dense asteroids should not fragment and so should survive until impact. On lower mass main sequence stars (which are denser), however, denser objects could be fragmented during close passages subsequent to impact. On higher mass stars, such as beta Pictoris, even cometary material will not be fragmented by the star during close passages.

4. Summary and Discussion

We have presented a series of numerical integrations of particles initially at low eccentricities which pass through mean motion resonances with a major moderate eccentricity migrating planet. We confirm that the 3:1 and 4:1 resonances can pump the particles eccentricities to 1.0 and so can cause particles trapped in them to impact the star or be evaporated by it. As a planet migrates through a disk of planetesimals we would expect continuing production of bodies undergoing close approaches to the star. This provides us with a possible observational test. A recent study finds that beta Pictoris may be quite young ($2 \times 10^7$ years; Barrado y Navascues et al. 1999). If orbital migration occurs commonly during this timescale then a multi-object (or multi-fiber) survey in young clusters should detect transient absorption features due to evaporating bodies similar to those seen in beta Pictoris and other stars.

Our integrations show that many particles which pass through these resonances will not be pumped to high eccentricities and so removed from the system by evaporation or by impact with the star. These particles can subsequently be ejected by the planet. This implies that a planet can migrate a significant fraction of its initial semi-major axis via ejection of planetesimals.

For the faster migration rates, we estimate that $\gtrsim 1$ km sized rocky bodies will survive heating from a solar type star during multiple close passages and so can become incorporated into the convection zone of the star. Because we expect that most of the mass will be in the most massive bodies, this migration process may be capable of increasing the metallicity of the star. Planet migration should occur on a $10^7$ year timescale (Murray et al. 1998) so we do not expect the star to be fully convective during migration. Metals dumped into the star should remain in the convection zone of the star. This scenario therefore offers a plausible explanation for the metallicity enhancements observed in stars with extrasolar planets (Gonzalez et al. 1999).

To migrate a significant fraction of its semi-major axis the planet must eject on the order of its mass (Murray et al. 1998) in planetesimals. If the material ejected is rocky then the original
proto-stellar disk would have had $\gtrsim 30$ times this mass in gas and volatiles. It is not inconceivable that this amount of material was left in and interior to a Jupiter mass planet after formation. However planetesimals exterior to the planet forced to high eccentricity by a secondary planet may also be ejected by a planet and so cause its migration. Some fraction of these particles will also impact the star (e.g., as seen in simulations of short period comets, \cite{Levison&Duncan1994}). This suggests another possible link between star grazers and impactors and orbital migration.

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Table 1. Numerical Integrations

| Run | $\epsilon(t = 0)$ | $\epsilon_p$ | $M_p/M_*$ | Resonance | $da$ | $D_a$ | $N_{imp}$ | $N_{ej}$ |
|-----|------------------|-------------|-----------|-----------|-----|------|----------|--------|
| M1  | 0.1              | 0.3         | $10^{-3}$ | 3:1       | 0.03| $10^{-6}$ | 3        | 7      |
| M5  | 0.1              | 0.3         | $10^{-3}$ | 3:1       | 0.015| $3 \times 10^{-7}$ | 6 | 4 |
| M8  | 0.1              | 0.3         | $10^{-3}$ | 3:1       | 0.03| $3 \times 10^{-6}$ | 3 | 7 |
| M7  | 0.3              | 0.1         | $10^{-3}$ | 3:1       | 0.03| $10^{-6}$ | 5 | 5 |
| M9  | 0.1              | 0.3         | $3 \times 10^{-3}$ | 3:1 | 0.03| $10^{-6}$ | 6 | 4 |
| N1  | 0.1              | 0.3         | $10^{-3}$ | 4:1       | 0.008| $10^{-6}$ | 8 | 2 |
| N5  | 0.1              | 0.3         | $10^{-3}$ | 4:1       | 0.004| $3 \times 10^{-7}$ | 8 | 2 |
| N8  | 0.1              | 0.3         | $10^{-3}$ | 4:1       | 0.02| $3 \times 10^{-6}$ | 6 | 4 |
| N7  | 0.1              | 0.1         | $10^{-3}$ | 4:1       | 0.008| $10^{-6}$ | 9 | 1 |
| N9  | 0.1              | 0.3         | $3 \times 10^{-3}$ | 4:1 | 0.008| $10^{-6}$ | 5 | 5 |
| N10 | 0.3              | 0.3         | $10^{-3}$ | 4:1       | 0.02| $3 \times 10^{-6}$ | 4 | 6 |
| N11 | 0.05             | 0.3         | $10^{-3}$ | 4:1       | 0.02| $3 \times 10^{-6}$ | 7 | 3 |
| N12 | 0.05             | 0.3         | $10^{-3}$ | 4:1       | 0.02| $10^{-6}$ | 7 | 3 |

Columns: (1) Run number; (2) Initial eccentricity of particles; (3) Eccentricity of the planet; (4) Ratio of the planet mass to the stellar mass; (5) Particles were placed just within this mean motion resonance; (6) Distance that particles were placed from the initial location of the resonance in units of the initial planet semi-major axis. (7) Dimensionless orbital migration rate (see text); (8) Number of particles eventually impacting the star ($N_{imp}$) out of 10 particles integrated; (9) Number of particles eventually ejected by the planet ($N_{ej}$) out of 10 particles integrated.
Table 2. Resonances operating prior to impact or ejection

| Run | Particle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----|----------|---|---|---|---|---|---|---|---|---|---|
| M1  |          | E | E | I | I | E | E | E | E | E | I |
|     | 5:2      | 5:2| 3:1| 3:1| 5:2| 5:2| 7:3| 7:3| 5:2| 3:1|   |
| M5  |          | E | E | I | I | E | I | E | I | E | I |
|     | 7:3      | 8:3| 3:1| 3:1| 3:1| 11:4| 13:5?| 3:1| 8:3| 3:1|   |
| M7  |          | E | E | I | I | E | E | E | I | E | E |
|     | 2:1      | 2:1| 3:1| 2:1| 5:2| 7:4| 7:3| 2:1| 2:1| 9:4|   |
| M8  |          | E | E | I | I | E | I | I | E | E | I |
|     | 5:2      | 8:3?| 3:1| 3:1| 5:2| 8:3| 3:1| 3:1| 5:2?| 3:1|   |
| M9  |          | I | I | I | I | E | I | E | E | E | I |
|     | 8:3      | 5:2| 3:1| 3:1| 3:1| 3:1| 5:2| 3:1| ? | 3:1|   |
| N1  |          | I | E | I | E | I | I | I | I | I | I |
|     | 7:2      | 8:3| 3:1| 8:3| 10:3?| 4:1| 3:1| 7:2| 4:1| 10:3?|   |
| N5  |          | I | E | I | I | I | I | I | I | I | E |
|     | 3:1      | 7:3| 5:2| 4:1| 10:3| 4:1| 7:2| 4:1| 3:1| 4:1|   |
| N7  |          | I | I | E | I | I | I | I | I | I | I |
|     | 2:1      | 3:1| 5:2| 3:1| 3:1| 3:1| 3:1| 3:1| 2:1|   |   |
| N8  |          | E | I | E | E | I | I | I | I | E |   |
|     | 8:3      | 10:3| 8:3| 8:3| 3:1| 4:1| 3:1| 4:1| 8:3|   |   |
| N9  |          | I | I | E | I | E | E | E | E | I | I |
|     | 4:1      | 7:2| 7:2| 4:1| 3:1| 3:1| 3:1| 3:1| 4:1| 4:1|   |
| N10 |          | E | I | I | E | I | E | E | I | E | E |
|     | 10:3?    | 7:2| 10:3?| 8:3?| 10:3?| 8:3?| 10:3?| 7:2| 10:3?| 5:2?|   |
| N11 |          | E | I | I | I | I | I | E | E | I | I |
|     | 10:3     | 3:1| 10:3?| 3:1| 8:3| 5:2| 8:3| 8:3| 8:3| 3:1|   |
| N12 |          | I | E | I | I | E | E | I | I | I | I |
|     | 4:1      | 10:3| 7:2| 3:1| 7:2| 7:2| 8:3| 3:1| 3:1| 4:1|   |

For each simulation (labeled on the left) the final state of each of 10 particles is listed. E refers to ejection by the planet and I refers to an impact with the star. Below this is listed the suspected resonance affecting the particle prior to ejection or impact.
Fig. 1.— Minimum eccentricity ($e_{\text{min}}$) that can be pumped to a star impacting orbit ($e = 1$) for a range of planet eccentricities ($e_p$). Each line corresponds to a different mean motion resonance. Orbits that become Jupiter crossing (or cross the Hill sphere radius) are more likely to be ejected from the system rather than impact the sun. So we restrict ourselves to resonances with semi major axis small enough that high eccentricities can result in stellar impacts rather than a crossing of the Hill sphere. The eccentricities of the extrasolar planets are not restricted to extremely low values (Marcy 1999). This implies that resonances which are capable of causing star grazing or impacting planetesimals are likely to exist in almost all of these extrasolar planetary systems.

Fig. 2.— a) Eccentricities as a function of time for 10 particles as part of the N8 integration (see Tab. 1). Time is given in units of $10^5$ periods where a period corresponds to the initial orbital period of the planet. The migration rate is $D_a = 3 \times 10^{-6}$, planet eccentricity $e_p = 0.3$, initial particle eccentricity $e_0 = 0.1$, and planet mass in units of the stellar mass, $M_p/M_* = 10^{-3}$. Particles were set initially with semi-major axes just within the 4:1 resonance. Particle numbers are labelled in the upper left of each panel. Particles 5 and 8 spend time trapped in the 4:1 resonance and impact the star. Particles 4, 6, and 7 spend time trapped in the 3:1 resonance and eventually impact the star. Prior to impact the surfaces of these particles would be evaporated by the star. Particles 0, 2, 3, and 9 are ejected when the 8:3 resonance causes them to cross the Hill sphere of the planet. Particle 1 impacts the star as a result of the 10:3 resonance.

b) Particle semi-major axes (in units of the planet’s initial semi-major axis) as a function of time for the same 10 particles. The location of various resonances are shown as dotted lines and are labelled. On the upper right of each box the fate of the particle is shown where E refers to ejection by the planet and I refers to an impact with the star. While some particles spend time trapped in resonances such as the 3:1 and 4:1 others are not. Ejection or impact occurs during the influence of a resonance. 4 particles were ejected during this simulation and the remaining 6 impacted the star.
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