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PRODUCTION OF STAR-GRAZING AND STAR-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 (as studied by Murray et al. in 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 semimajor axis, a fraction of its mass in planetesimals could impact the star. This process may be capable of enriching the metallicity of the star 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 ejected subsequently by the planet as it migrates further inward. This allows the planet to migrate a substantial fraction of its initial semimajor axis by ejecting planetesimals.

Key words: celestial mechanics, stellar dynamics — planets and satellites: general — stars: abundances — solar system: formation — solar system: general

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; Spangler et al. 1999; Robberto et al. 1999), suggests 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 been detected in these disks also, suggesting that there is asteroidal and cometary material in these disks (Malfait et al. 1998; Waelkens et al. 1996; Pantin, Waelkens, & Malfait 1999). The detection of planets orbiting nearby solar-type stars (e.g., Mayor & Queloz 1995; Marcy & Butler 1998) and dusty disks surrounding some of these stars (e.g., Trilling & Brown 1998) further supports a connection between rocky disk material and planets. Many stars with known extrasolar planets have enhanced metallicities (Gonzalez 1998; Gonzalez, Wallerstein, & Saar 1999), establishing an as yet unexplained link between planet formation and enhanced stellar metallicities.

The small orbital semimajor 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., Lin, Bodenheimer, & Richardson 1996; Ward 1997; Trilling et al. 1998). 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 1995). 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 large convective envelopes for nearly the entire time interval over which planets are expected to be accreted, incorporation 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 (Wisdom 1985; Ferraz-Mello & Klafke 1991; Farinella et al. 1994; Moons & Morbidelli 1995; Beust & Morbidelli 1996; Gladman et al. 1997; Migliorini et al. 1998). This would happen at a later time ($\gtrsim 10^7$ years; Murray et al. 1998) than planet-star collisions in 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 thin so that the metals will remain trapped in the convection zone rather than mixing into the entire star. In this way, orbital migration via ejection of planetesimals could explain more naturally 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 Δ[Fe/H] ~ 0.1 dex. For a planet to migrate a significant fraction of its initial semimajor axis, roughly *its* mass of planetesimals must be ejected from the system (Murray et al. 1998). We expect that some fraction of the bodies ejected or impacting the star would originate from the inner regions of the system and be asteroidal or rocky. For a Jupiter-mass planet migrating ($M_J = 310\ M_\oplus$), this implies that some fraction of the rocky material left in the inner stellar system would be incorporated into the star. However, for a Jupiter-mass of planetesimals to remain after the planet formation, the gaseous protoplanetary disk would have to have been far more massive. This is a concern for the planetary migration scenario involving ejection of planetesimals.

This paper concentrates on the mechanism for producing star-grazing planetesimals explored by Beust & Morbidelli (1996) to account for the transient absorption lines observed against β 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 (e.g., Beust et al. 1996; Beust & Morbidelli 2000). Mean-motion resonances (such as the 3:1 and 4:1) with one large, moderately eccentric planet can pump eccentricities to unity. Though secular resonances are also capable of driving particles to extremely high eccentricities (Levison, Duncan, & Wetherill 1994), since they are present in systems with more than one massive object and are more complicated, we concentrate here on mean-motion resonances with one major planet. In § 2, using averaged Hamiltonians, we consider the range of planetesimal and planet eccentricities required for a given resonance to produce a star-impacting body. In § 3, we estimate—using numerical integration—the efficiency of these resonances to produce extremely high-eccentricity particles during the migration of a giant planet. 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 semimajor axes.

2. WHEN CAN STAR-IMPACTING PLANETESIMALS BE PRODUCED?

During the migration of a major planet, mean-motion resonances will sweep through the disk of planetesimals. The maximum eccentricity reached by particles librating in a resonance is extremely sensitive to the eccentricity of the planet (Moons & Morbidelli 1995; Yoshikawa 1990; Beust & Morbidelli 1996). We expanded on the work of Beust & Morbidelli (1996) to determine what range of planet eccentricity is required to pump particle eccentricities to unity. We created contour plots numerically from the Hamiltonian averaged over time (as done by Yoshikawa 1990 and Beust & Morbidelli 1996). 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 Figure 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.[1] Few of the extrasolar planets with semimajor axis larger than $\sim$0.05 AU (where tidal forces can circularize the orbit) have eccentricities lower than 0.1.

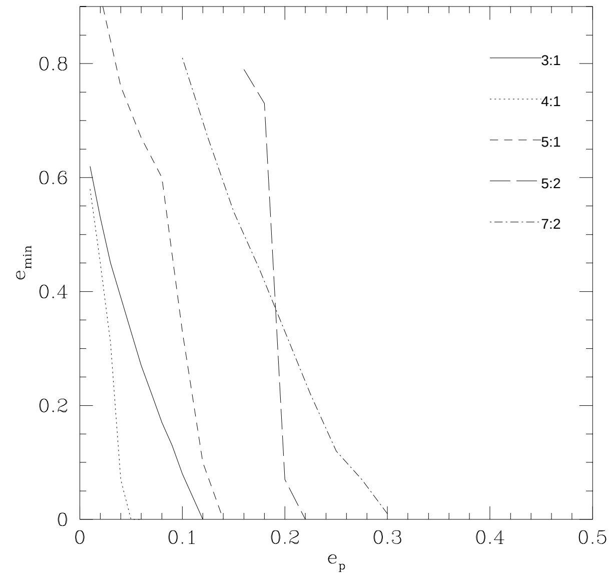

FIG. 1.—Minimum eccentricity (e_{min}) that can be pumped to a star-impacting orbit ($e = 1$) for a range of planet eccentricities (e_p). Each line corresponds to a different mean-motion resonance and was computed using an averaged Hamiltonian. Planetesimals with orbits that become planet-crossing (or cross the Hill sphere radius) are more likely to be ejected from the system rather than impact the star. So we restrict ourselves to resonances distant enough from the planet that high eccentricities can result in stellar impacts rather than a crossing of the Hill sphere. The eccentricities of many extrasolar planets (see the reference to Marcy 1999 in footnote 1 of the text) are sufficiently high that resonances capable of causing star-grazing or star-impacting planetesimals are likely to exist in many of these extrasolar planetary systems.

This implies that resonances capable of causing star-grazing or star-impacting planetesimals are likely to exist in many 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 integrated the orbits of particles (using a conventional Burlisch-Stoer numerical scheme) during the slow migration of a major planet. All particles were massless except for the star and one planet with an eccentricity e_p, which remained constant throughout the integration. During the integration, we forced the semimajor axis of the planet to drift inward at a rate given by the dimensionless parameter

$$D_a = \frac{da}{dt}\frac{P}{a} \tag{1}$$

for P the period of the planet and a its semimajor axis. D_a was fixed during the integration, resulting in $(da/dt) \propto a^{-1/2}$. Particles were placed in the plane of the planet's orbit and given a semimajor axis so that they were within a few resonance widths of the middle of the 3:1 or 4:1 resonance. For each particle, the initial argument of perihelion and mean anomalies were chosen randomly. Massless particles were integrated until they crossed the Hill sphere radius of the planet and were ejected to semimajor axes larger than the planet or were driven to high eccentricity ($e > 0.995$) and so impacted the star. This required between a few times 10^5 to 10^6 periods measured in units of the initial orbital period of the planet. We chose an eccentricity

[1] See G. Marcy, 1999, Masses and Orbital Characteristics of Extrasolar Planets, at http://cannon.sfsu.edu/~gmarcy/planetsearch.

limit to represent impact since it is independent of the stellar radius and particle semimajor axis. We found that particles that reached this eccentricity (0.995) were far more likely to subsequently impact the star than be ejected by the planet, even if this limiting eccentricity did not actually represent a collision with the star. The radius of closest approach to the center of the star is $q = (1 - e)a$. For a solar-type star with radius $R_* = R_\odot = 7 \times 10^{10}$ cm, our eccentricity limit corresponds to a collision with the star for $a < 1$ AU. 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 semimajor axes for a run (denoted N8) are shown in Figure 2. Almost at all times particles were 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 be caught later on in another resonance. For example, we observe that particles not removed by the 3:1 may be caught later on 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 ones, cause jumps in the semimajor axis as the particle crosses the resonance. However, only the 3:1 and 4:1 are strong enough (and have 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 Figure 2*a* 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, a planetesimal will graze the star and so be sublimated by it. Thus we would predict that a migrating planet would cause continuing production of "falling evaporative bodies," as was proposed to explain the transient absorption lines observed against β Pictoris and other stars (e.g., Crawford et al. 1994; Beust & Morbidelli 1996; Grady et al. 1996; Lagrange et al. 1996). We see in our simulations that more than one resonance can cause stargrazers. The high-eccentricity region of a resonance is associated with a particular angle between the periastrons of the planet and the planetesimal, and this angle differs for each resonance (e.g., Moons & Morbidelli 1995). If stargrazers 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 blueshifted event on β Pictoris (Crawford, Beust, & Lagrange 1998). However, Beust & Morbidelli (2000) have explored this possibility (outside the context of planetary migration) and found that absorption events caused by the 3:1 and 4:1 resonances are difficult to distinguish based on their redshift distribution.

Even though the 3:1 and 4:1 resonances can pump eccentricities to unity, in every simulation (see Table 1) we find particles which pass through these resonances that are not pumped to high eccentricities and are removed from the system by an impact with the star. These particles can be ejected later by the planet. If these resonances cleared a hole as they were swept through the disk, then the mechanism for orbital migration via ejection of planetesimals would not provide a good explanation for the extremely small semimajor axes of the extrasolar planets. Here we find that 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 sweep through the disk. If the density of planetesimals is high enough, a planet migrating as a result of ejection of planetesimals can still migrate to within its original

TABLE 1

NUMERICAL INTEGRATIONS

Run (1)	$\epsilon(t=0)$ (2)	ϵ_p (3)	M_p/M_* (4)	Resonance (5)	da (6)	D_a (7)	$N_{\rm imp}$ (8)	$N_{\rm ej}$ (9)
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	3×10^{-7}	6	4
M8	0.1	0.3	10^{-3}	3:1	0.03	3×10^{-6}	3	7
M7	0.3	0.1	10^{-3}	3:1	0.03	10^{-6}	5	5
M9	0.1	0.3	3×10^{-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	3×10^{-7}	8	2
N8	0.1	0.3	10^{-3}	4:1	0.02	3×10^{-6}	6	4
N7	0.1	0.1	10^{-3}	4:1	0.008	10^{-6}	9	1
N9	0.1	0.3	3×10^{-3}	4:1	0.008	10^{-6}	5	5
N10......	0.3	0.3	10^{-3}	4:1	0.02	3×10^{-6}	4	6
N11......	0.05	0.3	10^{-3}	4:1	0.02	3×10^{-6}	7	3
N12......	0.05	0.3	10^{-3}	4:1	0.02	10^{-6}	7	3

NOTE.—Col. (1): Run number. Col. (2): Initial eccentricity of particles. Col. (3): Eccentricity of the planet. Col. (4): Ratio of the planet mass to the stellar mass. Col. (5): Particles were placed just within this mean-motion resonance. Col. (6): Distance that particles were placed from the initial location of the resonance in units of the initial planet semimajor axis. Col. (7): Dimensionless orbital migration rate (see text). Col. (8): Number of particles eventually impacting the star ($N_{\rm imp}$) out of 10 particles integrated. Col. (9): Number of particles eventually ejected by the planet ($N_{\rm ej}$) 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	I	E	I	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	3:1	2:1
N8	E	I	E	E	I	I	I	I	I	E
	8:3	10:3	8:3	8:3	3:1	4:1	3:1	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	I	E	E	I	I	I
	4:1	10:3	7:2	3:1	7:2	7:2	8:3	3:1	3:1	4:1

Note.—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. The suspected resonance affecting the particle prior to ejection or impact is listed immediately below.

(at formation) 3:1 or 4:1 mean-motion resonances. This would allow a planet to migrate a substantial fraction of the planet's semimajor axis by ejecting planetesimals.

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 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, we found that weaker resonances such as the 4:1 or 7:2 did not strongly affect the particles; however, the 3:1 was still strong enough to cause impacts.

In a self-consistent calculation or simulation, the transfer of energy between the planet and planetesimals causes the migration of the planet. When particles are trapped in a resonance, their semimajor axes decrease, and this causes the planet to gain energy rather than lose it (as should be taking place when the planet is migrating inward). However, for these particles we found that the decrease in semimajor axis before impact was typically less than 30% of the particles' initial semimajor axis. Ejected particles cause the planet to lose an amount of energy proportional to the inverse of their initial semimajor axes. This implies that the energy gained by the planet from trapped particles should be small compared with that lost from those ejected. We do not expect that energy gained from trapped particles will prevent the migration of a planet.

The transfer of angular momentum and energy between the planet and planetesimals should cause the planet to vary in eccentricity rather than remain fixed, as is assumed in the simulations presented here. As long as the planet eccentricity does not drop below $e_p \sim 0.1$, where the strongest resonances would cease to produce star-grazers, we expect our simulations are at least qualitatively correct. To calculate the angular momentum and energy transfer between the planet and planetesimals, we would need to know how long particles are likely to be trapped in each resonance and the amount of angular momentum exchange that occurs during ejection. This suggests that a self consistent simulation is required to estimate the eccentricity evolution of the planet.

3.1. *Survival until Impact*

In our integrations we can estimate the timescale for the eccentricity to reach $\gtrsim 0.995$. 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 a solar radius from the Sun to be ~ 30 cm. This estimate is based on a simple sublimation model (described in Flammer

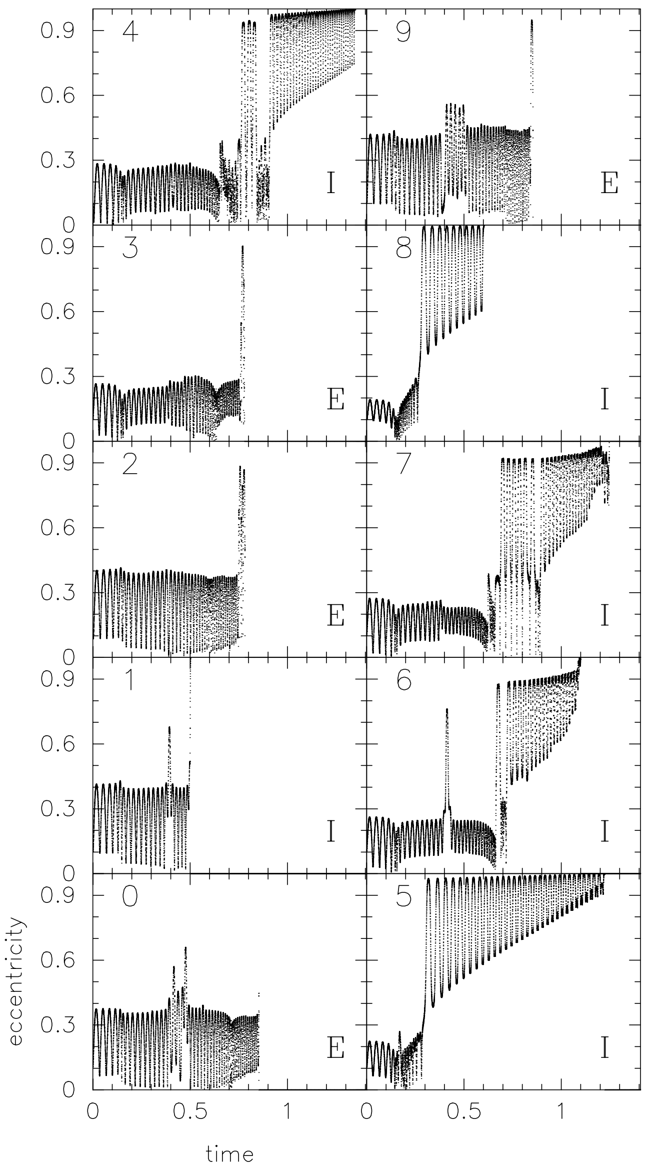

FIG. 2*a*

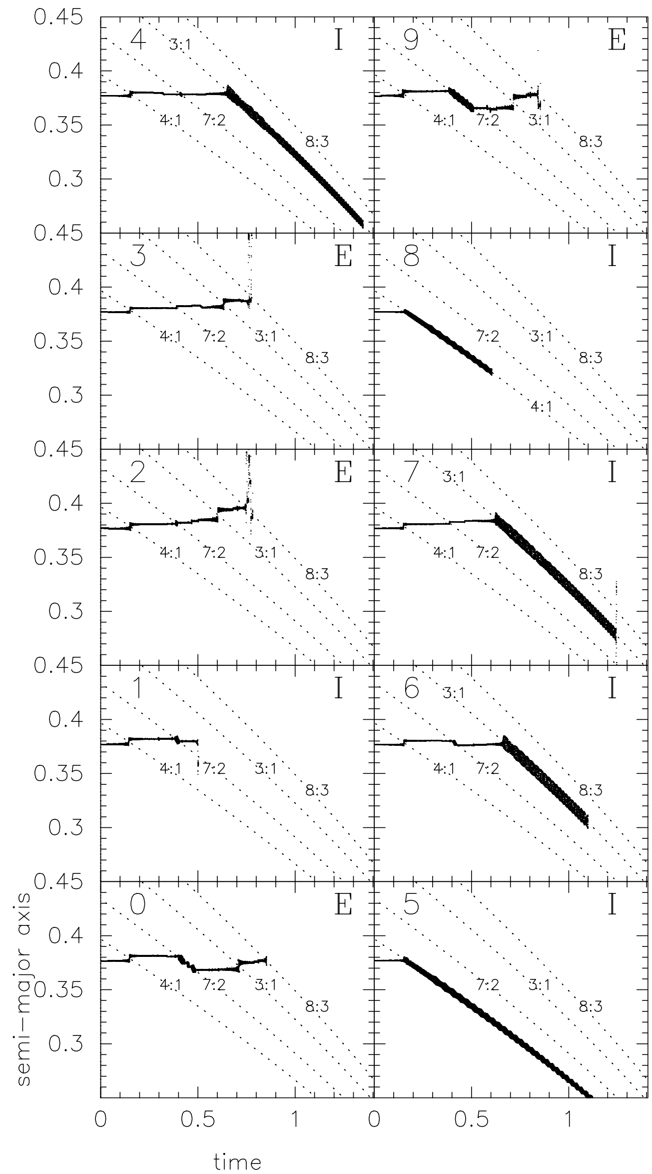

FIG. 2*b*

FIG. 2.—(*a*) Eccentricities as a function of time for 10 particles as part of the N8 integration (see Table 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 semimajor axes just within the 4:1 resonance. Particle numbers are labeled on the upper left-hand corner 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 should 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. On the lower right-hand corner 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. (*b*) Particle semimajor axes (in units of the planet's initial semimajor axis) as a function of time for the same 10 particles. The location of various resonances are shown as dotted lines and are labeled. While some particles spend time trapped in resonances such as the 3:1 and 4:1, others are not. On the upper right-hand corner of each box, the fate of the particle is shown. Ejection or impact occurs during the influence of a resonance. Four particles were ejected during this simulation, and the remaining six impacted the star.

1991), except that we use a vapor pressure and latent heat of sublimation typical of rocky material such as silicates instead of water ice. If the planetesimal makes 10^4 such close passages, then a kilometer-sized body will be completely evaporated by a solar-type star. For particles making multiple close approaches, only large bodies $\gtrsim 1$ km will survive until impact. If most of the disk mass is contained in the largest bodies (as predicted by many theories of planetesimal and planet growth; see references in Lissauer & Stewart 1993), then most of the mass trapped in resonances such as the 3:1 and 4:1 will become incorporated into the star. When migration is relatively quick, the mechanism explored here could be a way to increase the metallicity of the star, despite the fact that the lower mass bodies may not survive until impact.

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 periastron only if the density of the object is lower than the mean density of the star (e.g., Sridhar & Tremaine 1992; Asphaug & Benz 1996). The mean density of the Sun is $\rho \sim 1.4$ g cm^{-3}, so that for a solar-type star all but the least dense asteroids should remain intact and so should survive until impact. For lower mass main-sequence stars (which are denser), however, denser objects could be fragmented during close passages prior to impact. For higher mass stars, such as β 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 that pass through mean-motion resonances of a major, moderate-eccentricity, migrating planet. We confirm that the 3:1 and 4:1 resonances can pump the particle eccentricities to unity 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 β Pictoris may be quite young (2×10^7 yr; Barrado y Navascues et al. 1999). If orbital migration occurs commonly during this timescale, then a multiobject (or multifiber) survey in young clusters should detect transient absorption features caused by evaporating bodies similar to those seen in β 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 semimajor axis via ejection of planetesimals.

For the faster migration rates, we estimate that kilometer-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. This migration process may be capable of increasing the metallicity of the star. Planet migration should occur on a 10^7 yr 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 semimajor axis, the planet must eject on the order of its mass in planetesimals (Murray et al. 1998). If the material ejected is rocky, then the original protostellar disk would have had $\gtrsim$30–100 times this mass in gas and volatiles (we use a gas-mass ratio based on Jupiter's from Guillot, Gautier, & Hubbard 1997). Future work on planet formation should determine if this amount of material could be 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; Levison & Duncan 1994). This suggests another possible link between star-grazers and impactors and orbital migration.

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