FROM MEAN MOTION RESONANCES TO SCATTERED PLANETS: PRODUCING THE SOLAR SYSTEM, ECCENTRIC EXOPLANETS, AND LATE HEAVY BOMBARDMENTS

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ABSTRACT

We show that interaction with a gas disk may produce young planetary systems with closely spaced orbits, stabilized by mean motion resonances between neighbors. On longer timescales, after the gas is gone, interaction with a remnant planetesimal disk tends to pull these configurations apart, eventually inducing dynamical instability. We find that this can lead to a variety of outcomes; some cases resemble the solar system, while others end up with high-eccentricity orbits reminiscent of the observed exoplanets. A similar mechanism has been previously suggested as the cause of the lunar late heavy bombardment. Thus, it may be that a large-scale dynamical instability, with more or less cataclysmic results, is an evolutionary step common to many planetary systems, including our own.

Subject headings: planetary systems: formation — solar system: formation

1. INTRODUCTION

Currently, there are 26 detected multiplanet extrasolar systems.[4] Of these, at least eight (Udry et al. 2007) contain a pair of planets in a likely mean motion resonance (MMR), wherein the planets' periods are maintained in an integer ratio (Murray & Dermott 1999). The stable locking of two bodies into such resonances requires a dissipative process that induces convergent migration between the pair. Indeed, gravitational interaction with the gas nebula likely causes extensive migration in a young, forming planetary system (Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Ward 1997; see also Papaloizou et al. 2007 for a review); the establishment of MMRs is thus thought to be a consequence of this early evolution. Several specific scenarios have been suggested. The observed resonant exoplanets are all massive enough that they likely formed a fairly deep gap in their parent disk, thus being more or less locked into the disk's viscous evolution in what is referred to as type II migration. Two gap-opening planets, if formed in close enough proximity, will clear out the intervening annulus of gas and thus end up in a common gap (Bryden et al. 2000; Kley 2000) or, if the inner disk accretes faster than the planets migrate, at the inner edge of a disk cavity. Subsequent capture into a MMR is a very likely outcome (Lee & Peale 2002; Kley et al. 2004). Differential migration will also tend to take place between gap-opening bodies, coevolving with the gas disk, and non–gap-opening bodies, which usually migrate more rapidly (type I migration; Ward 1997); when the latter catch up to the former, capture into MMRs is again a likely result, as suggested by Hahn & Ward (1996) and demonstrated by Thommes (2005). A resonantly captured smaller body may subsequently grow into a gas giant, providing another pathway to a pair of Jovian planets in an MMR. In general, planet-disk interaction in a young planetary system may result in multiple planets, both gas giants and smaller, locked in MMRs.

Such a picture leads naturally to the notion of planetary systems emerging from the gas disk era with crowded, compact architectures. This, in turn, has been a recurring theme in formation models of planetary systems. Thommes et al. (1999, 2002) developed a model of giant planet formation in the solar system wherein Uranus and Neptune originated in the same region (∼5–10 AU) as Jupiter and Saturn. Proto-Jupiter's acquisition of a massive gas envelope then destabilized the closely spaced system. The ensuing scattering, combined with dynamical friction from the remaining outer planetesimal disk, then delivered the planets to their current orbits. The model of Gomes et al. (2005) begins with a similarly compact configuration but requires it to be stable until the time of the late heavy bombardment (LHB), a cataclysmic event 700 Myr after the initial formation of the solar system, as implied by the Moon's cratering record (Tera et al. 1974; Hartmann et al. 2000 and references therein). The instability that places the planets on their final orbits is then simultaneously invoked as the cause of the LHB. Also, models for reproducing the eccentricity distribution of the observed extrasolar planets by planet-planet scattering of course require the planets to start out close enough to each other for instability to ensue (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997; Chatterjee et al. 2007; Juric & Tremaine 2007).

Here we combine these two notions and begin, in § 2, by constructing a model of a compact, resonantly locked planetary system, as might plausibly be left behind by a dissipating gas disk. Simulating the post-gas evolution, we then add an outer planetesimal disk beginning just beyond the outermost planet (§ 3). Scattering of planetesimals induces planet migration, albeit on a much longer timescale than in the presence of a gas disk; this eventually drives the system to instability. In § 4 we demonstrate that this can lead to solar system–like outcomes. We explore two other scenarios, with more closely spaced Jovian planets, in §§ 5.1 and 5.2, and find that large gas giant eccentricities can be produced in the ensuing instability. We discuss our results in § 6.

2. A COMPACT, RESONANTLY LOCKED SOLAR SYSTEM

Thommes (2005) performed simulations of growing protoplanets exterior to a Jupiter-mass planet and showed that a variety of resonant configurations can result. The protoplanets end up occupying different exterior low-order resonances, and sometimes multiple planets end up sharing the same resonance; individual outcomes are stochastic. Here we wish to begin by constructing a version of the solar system in which all the giant

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planets are (1) locked in MMRs with each other and (2) packed within, approximately, the current Jupiter-Saturn region.

We want to do this in a way that mimics the action of planet-disk interactions. We perform simulations with SyMBA (Duncan et al. 1998), an N-body integrator optimized for near-Keplerian systems. SyMBA uses the symplectic mapping of Wisdom & Holman (1991) with the addition of an adaptive time step to resolve close encounters between pairs of bodies. Bodies are merged when their separation is less than the sum of their physical radii. We add to the code accelerations to model the radial migration and eccentricity damping due to gravitational interaction with the gas disk. For type I migration, we use the result of Tanaka et al. (2002):

$$t_{\text{migr}} \equiv \frac{r}{|\dot{r}_{\text{migr}}|}$$
$$= (2.7 + 1.1\beta)^{-1} \left(\frac{M}{M_*}\right)^{-1} \left(\frac{\Sigma_g r^2}{M_*}\right)^{-1} \left(\frac{H}{r}\right)^2 \Omega^{-1} \quad (1)$$

for a mass M body orbiting a mass M_* star at radius r, embedded in a gas disk with surface density Σ_g and scale height H. Ω is the Keplerian angular velocity and $\beta = -d \log \Sigma_g / d \log r$. For eccentricity damping, we use

$$t_e \equiv \frac{e}{|\dot{e}|} = \frac{1}{C_e} \left(\frac{M}{M_*}\right)^{-1} \left(\frac{\Sigma_g r^2}{M_*}\right)^{-1} \left(\frac{H}{r}\right)^4 \Omega^{-1} \quad (2)$$

with $C_e \sim 1\text{--}10$ (Ward 1989, 1993; Artymowicz 1993; Papaloizou & Larwood 2000). The corresponding acceleration applied within the code is $\boldsymbol{a} = a_\phi \hat{\phi} + a_r \hat{r}$, where

$$a_\phi = -\frac{v_\phi}{2 t_{\text{migr}}}, \quad (3)$$

and

$$a_r = -2 \frac{\boldsymbol{v} \cdot \boldsymbol{r}}{r^2 t_e}. \quad (4)$$

We then model type II (gap-opening) planets in a very simple way, as in Thommes (2005): We choose a radius r_{gap} for the center of the gap and a fractional gap "width" w, then for a type II planet with semimajor axis a, apply an azimuthal acceleration a'_ϕ as follows:

$$a'_\phi = \frac{a - r_{\text{gap}}}{|a - r_{\text{gap}}| + wa} a_\phi. \quad (5)$$

Since a_ϕ is negative, a'_ϕ is negative at $a > r_{\text{gap}}$, positive at $a < r_{\text{gap}}$, and falls off to zero as $a \to r_{\text{gap}}$. Therefore, if our "gap-opening" planet is displaced in its semimajor axis from the gap midpoint, it experiences a restoring torque toward $a = r_{\text{gap}}$. Although the eccentricity evolution of gap-opening planets is uncertain, for simplicity we calculate the eccentricity-damping part of the acceleration in the same manner:

$$a'_r = \frac{a - r_{\text{gap}}}{|a - r_{\text{gap}}| + wa} a_r. \quad (6)$$

We begin with a Jupiter-mass planet (310 $M_\oplus$) centered in its simulated gap at 5.5 AU. A Saturn-mass body (95 $M_\oplus$), which is treated as being in the non–gap-opening regime, begins at 10 AU. Uranus- and Neptune-mass planets are placed at 15 and 25 AU, respectively. It should be noted that this configuration
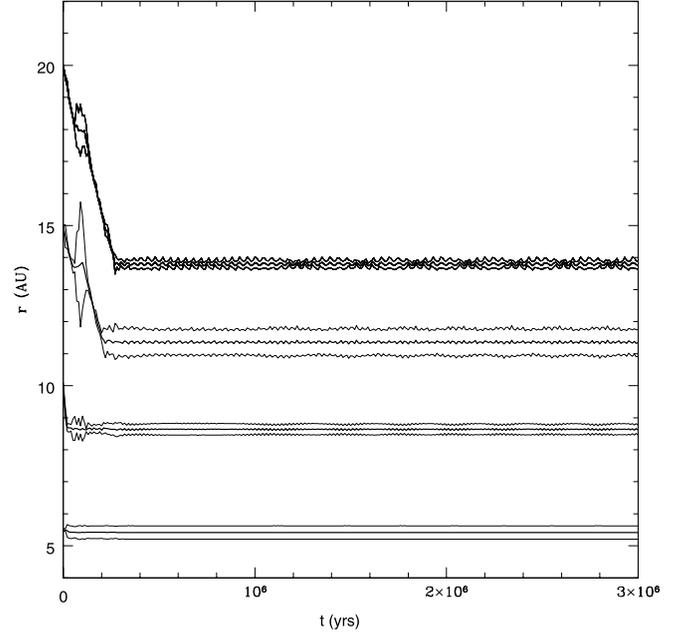

FIG. 1.—Planetary migration due to simulated planet-disk interaction resulting in the establishment of a resonantly locked version of the solar system. For each planet, pericenter distance, semimajor axis, and apocenter distance are plotted as a function of time (all three being coincident for zero eccentricity). Jupiter and Saturn end up in a 2 : 1 MMR, Saturn and Uranus in a 3 : 2 MMR, and Uranus and Neptune in a 4 : 3 MMR. Note that for simplicity the system's initial spacing is chosen to be (probably) artificially large, in order to facilitate an orderly rather than stochastic resonance capture process; see text.

is not meant to necessarily reflect the initial state of the planetary system; rather, it is chosen as a simple way to allow one planet after another to migrate into resonance in an orderly manner. A more likely scenario—one that avoids a prohibitively long formation timescale—is that the planets originated much closer to Jupiter and Saturn (Thommes et al. 1999, 2002). They would then have tended to be captured into resonance as they grew, in a rather more stochastic process involving planets "hopping" from resonance to resonance until a stable configuration is reached (Thommes 2005).

We adopt a gas disk scale height of

$$H(r) = 0.047 (r/1 \text{ AU})^{5/4} \text{ AU} \quad (7)$$

as in the model of Hayashi (1981). We take the gas surface density to be of the form

$$\Sigma_g(r) = \Sigma_{g,\text{AU}} \left(\frac{r}{1 \text{ AU}}\right)^{-1} e^{-t/10^6 \text{ yr}}, \quad (8)$$

where the time-dependent exponential part models the observed dissipation of T Tauri gas disks on a Myr timescale (Haisch et al. 2001). The outcomes show the same behavior described in Thommes (2005): Higher surface mass densities produce stronger migration and thus tend to lock bodies in closer MMRs. At the same time, the value of the damping coefficient C_e controls the ratio between migration and eccentricity damping and thus affects the equilibrium eccentricity the bodies reach after being locked in resonance. For 200 g cm$^{-2} \lesssim \Sigma_{g,\text{AU}} \lesssim 1300$ g cm^{-2} and $C_e = 1$, we obtain a stable configuration in which Jupiter and Saturn are in a 2 : 1 MMR, Saturn and Uranus are in 3 : 2, and Uranus and Neptune are in 4 : 3, all with eccentricity $\lesssim 0.05$. An example is shown in Figure 1, illustrating the stability of the system once the resonance locks have been achieved. It should

be pointed out that these low eccentricities result because eccentricity damping is applied to *all* the planets, under the assumption that all of them are within the disk. In contrast, when damping is only applied to one of a pair of resonant planets—as would happen when the inner migrates within a disk cavity—the eccentricities of both will become large unless damping on the outer is very strong (Lee & Peale 2002; Thommes & Lissauer 2003). A limitation of this prescription is that it does not capture the effect of the azimuthally symmetric part of the disk's gravitational potential on the embedded planets, which would be to induce orbital precession. We perform separate tests in which we impose large differential precession in pairs of resonant planets, at a level far higher than would plausibly arise in a protostellar disk; however, no effect on the stability of the resonances is apparent. This suggests that disk-induced precession has a negligible effect on resonance dynamics and can indeed be safely left out.

3. BREAKING APART A RESONANTLY LOCKED SOLAR SYSTEM

We numerically evolve different versions of this system (differing in the initial orbital angles of the planets) to 10^9 yr, with the planet-disk interaction falling off exponentially with a 10^6 yr *e*-folding time, uniformly at all radii, to simulate in a simple way the dispersal of the gas disk; all remain completely stable. Resonant capture due to disk-induced migration thus provides a natural way of producing planetary systems that are not only close-packed but also long-lived. In contrast, comparably compact but nonresonant versions of this system require significant fine-tuning to assemble if they are not to go unstable on timescales $\ll 10^6$ yr.

By themselves, then, these resonant systems are likely to remain essentially "frozen" in the configuration with which they emerge from the gas. However, in reality, our systems would have an important additional component, namely, the remnant outer planetesimal disk, where significant planet growth did not have time to occur before the disappearance of the gas (Thommes et al. 2003). Scattering of leftover planetesimals very likely drove divergent migration of the giant planets in the early solar system as follows (Fernandez & Ip 1984; Hahn & Malhotra 1999; Gomes et al. 2004): Planetesimals from the inner disk edge are perturbed onto orbits that cross the planets. Planetesimals are then scattered from planet to planet until they are ejected. When the innermost planet is much more massive than the others (as is Jupiter), it is most efficient at ejecting planetesimals. In the process, the massive planet loses angular momentum and migrates inward by a small amount, while the smaller outer planets, as they pass the planetesimals inward, undergo a net gain in angular momentum and migrate outward. For given planetary masses, the rate of migration increases with the surface density of planetesimals; at a high enough density, "runaway" migration may even result (Gomes et al. 2004). The numerous Kuiper belt objects in exterior MMRs with Neptune—including Pluto and its fellow "Plutinos" in the 3 : 2 resonance—are thought to be the result of resonant capture during this migration. It is reasonable to expect that this same mechanism would act to pull apart our resonantly locked planets. How would this affect the dynamics of the system? To investigate, we perform a series of simulations, taking the resonant system assembled in the previous section and adding an outer planetesimal disk. The disk initially extends from 15.3 AU (1.5 AU beyond the outermost planet) to 30 AU. The rather small extent of the disk is motivated by the models of Levison & Morbidelli (2003) and Gomes et al. (2005). These invoke an initially compact planetesimal disk, truncated at ~30 AU, with the present-day Kuiper belt consisting of bodies
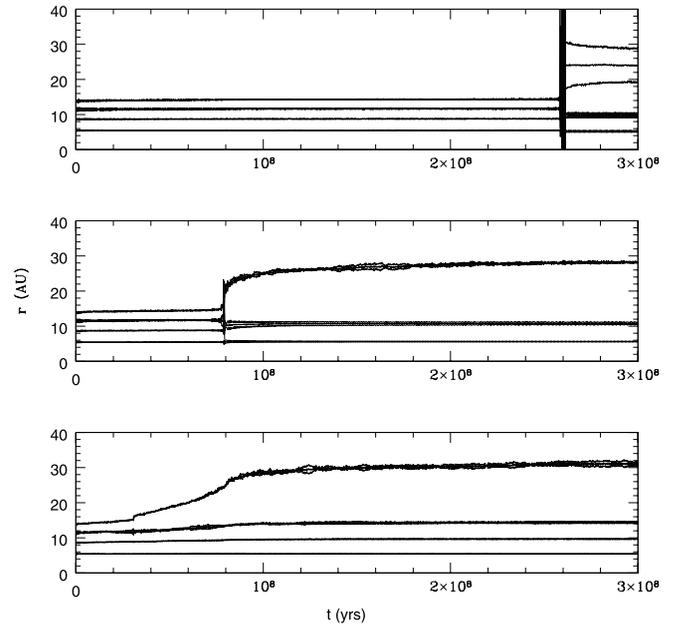

FIG. 2.—Three simulations of a set of 30, showing the evolution of an initially compact, resonant-locked version of the solar system, as described in § 2, interacting with an outer planetesimal disk. Semimajor axis as well as peri- and apocenter distance are plotted as a function of time. In the first two panels, one of the Uranus/Neptune mass planets is abruptly ejected after 2.6×10^8 and 8×10^7 yr, respectively. In the last panel, although the ice giants clearly receive a kick at 3×10^7 yr, strong scattering does not take place, and the planets primarily just evolve by scattering planetesimals. Neptune does not stop until it reaches the outer planetesimal disk edge at 30 AU.

later transported outward, and Neptune's migration through the planetesimal disk having been stopped simply by reaching the outer disk edge. The individual planetesimals have a mass of $0.035\ M_\oplus$, much larger than physically realistic planetesimals but small enough compared to the giant planets that the key effects we are interested in—planetesimal-driven migration and dynamical friction—are adequately modeled. Planetesimals are treated as "second-class" particles, which interact fully with the four planets but not with each other. The planetesimals are distributed with a surface density

$$\Sigma_{\text{plsml}} = \Sigma_{\text{plsml, AU}} \left(\frac{r}{1\ \text{AU}} \right)^{-1}. \qquad (9)$$

We perform a set of 30 simulations, linearly varying $\Sigma_{\text{plsml, AU}}$ from 4 to 16 g cm^{-2} (corresponding to a total planetesimal disk mass of about 14–55 $M_\oplus$, made of 400–1600 planetesimals). Each runs to 3×10^8 yr. In all but two of the simulations, the orbits of the giant planets undergo significant dynamical changes. Figure 2 shows three representative cases. The evolution is particularly dramatic in the first two of these, both of which undergo a scattering event that results in the ejection of one of the Uranus/Neptune-mass bodies. This behavior—a long period of slow, quiescent evolution followed by abrupt instability—is reminiscent of what occurs in the scenario of Gomes et al. (2005). There, an instability is triggered when Jupiter and Saturn, migrating divergently, cross their 2 : 1 MMR. Divergent resonance passage cannot result in resonant capture but does give a "kick" in eccentricity to the two bodies involved, with closer and lower order resonances having a stronger effect (Dermott et al. 1988; Chiang et al. 2002). Gomes et al. (2005) show that the abrupt increase in Jupiter and Saturn's eccentricity in a compact version of the solar system can cause Uranus and Neptune to be strongly scattered.
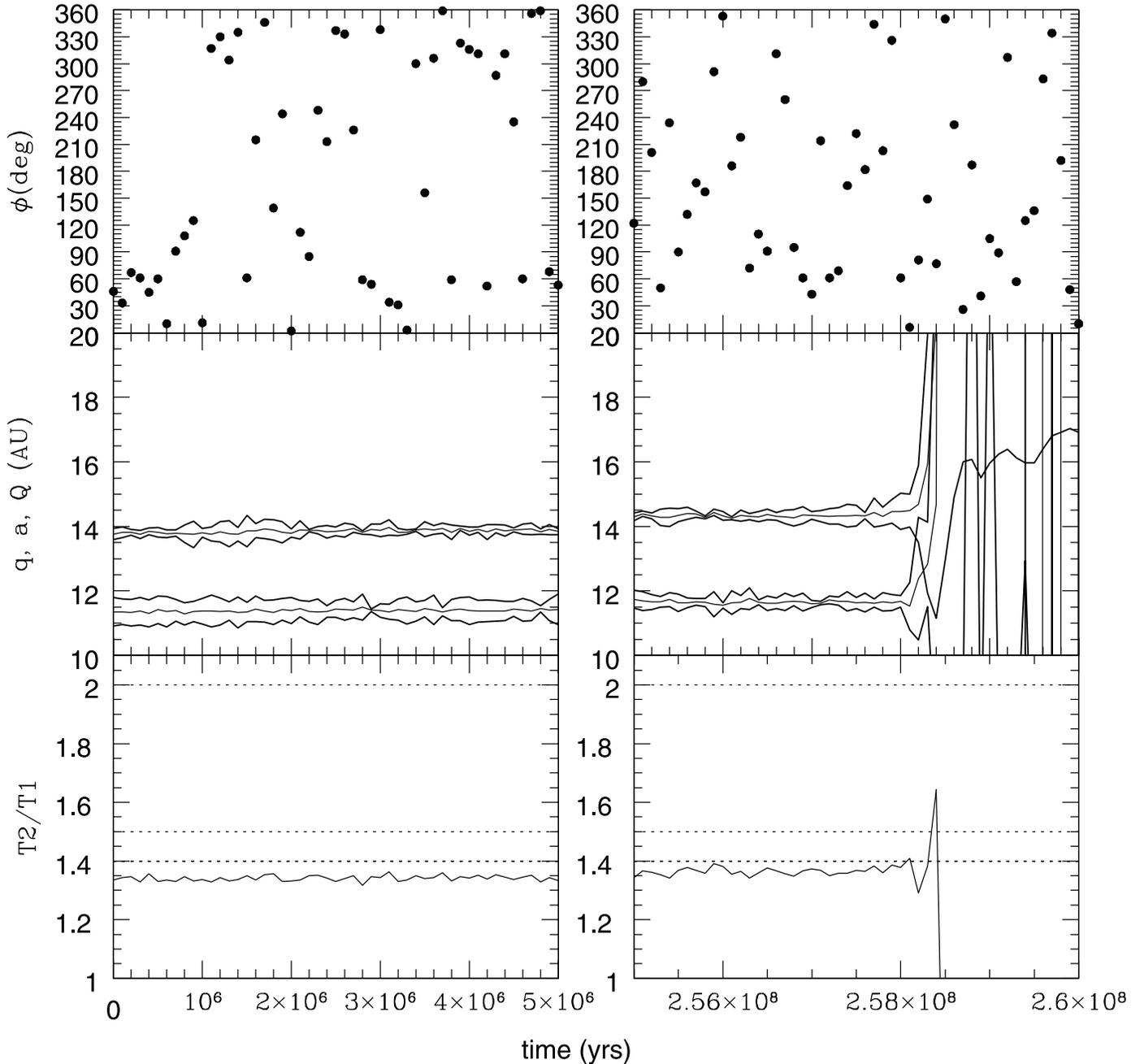
Fig. 3.—Closer look at the evolution of the outer two ice giants in one of the simulations of § 3, showing ϕ_1, one of the 4 : 3 resonance angles (*top*), the pericenter (*q*), semimajor axis (*a*), and apocenter (*Q*) distances of the two planets (*middle*) and their period ratio (*bottom*) for the first 5 Myr, and around the time the system becomes unstable. This happens as the two planets cross their 7 : 5 MMR ($T_2/T_1 = 1.4$).

Similar to the model of Thommes et al. (1999) this can propel them toward their wider current orbits, while dynamical friction with the planetesimal disk serves to damp their eccentricities. This large-scale shake-up of the solar system also provides a plausible source for the late heavy bombardment, by causing the terrestrial region to suffer a sudden increase in the flux of small bodies, both cometary (from the outer disk) and asteroidal (putative bodies perturbed from thus far stable orbits in the asteroid belt).

However, this process cannot be the one responsible for the instabilities we find here, for a simple reason: Jupiter and Saturn are *already* in a 2 : 1 MMR. In fact, we find that they do not leave this resonance until the moment the instability sets in. Thus, the trigger for the instability must be something else. Figure 3 gives a

closer look at what happens. Uranus and Neptune are initially in a 4 : 3 MMR, as assembled in § 2. Interaction with the planetesimal disk pulls them apart, and they soon leave the resonance, signified by the 4 : 3 resonance angles,

$$\phi_1 = 4\lambda_2 - 3\lambda_1 - \tilde{\omega}_1 \text{ and } \phi_2 = 4\lambda_2 - 3\lambda_1 - \tilde{\omega}_2 \quad (10)$$

(see, e.g., Murray & Dermott 1999) switching from libration to circulation, where λ are the planets' instantaneous longitudes, $\tilde{\omega}$ their longitudes of pericenter, and 1, 2 denote the inner and outer planet, respectively. This happens after only ∼2 Myr, but the system continues to be stable. It is much later that the instability sets in, and it happens when Uranus and Neptune divergently cross their 7 : 5 MMR and receive an impulsive increase in their

eccentricities. This increase is not by itself large; separate simulations with only Uranus and Neptune and artificially imposed migration on a similar timescale to what is induced by planetesimal scattering show that Δe is always far below 0.1 for both planets. If the system consists only of these two planets, no instability results, as can be seen by considering the Hill stability criterion for the minimum separation of a pair of equal-mass ($M/M_* = \mu$) eccentric planets:

$$\frac{\Delta a}{a} \gtrsim \sqrt{\frac{8}{3}\left(e_1^2 + e_2^2\right) + 9\mu^{2/3}}, \qquad (11)$$

where $\Delta a/a$ is the fractional orbital separation (Gladman 1993). For Uranus/Neptune mass bodies orbiting a solar mass star, $\mu \approx 5 \times 10^{-5}$, and for the $7:5$ resonance, $\Delta a/a = (7/5)^{2/3} - 1 = 0.25$; assuming $e_1 \approx e_2$, the pair remains stable unless e_1 and e_2 are excited to 0.1 by the resonance passage.

However, with Saturn and Jupiter nearby, this modest eccentricity increase turns out to be sufficient to initiate a chain reaction of instability, with both ice giants crossing the gas giants' orbits. One of the ice giants is ejected from the system. At the same time, Jupiter and Saturn receive a sufficiently strong kick that they are knocked out of their $2:1$ MMR, scattering each other and ending up about 1 AU farther apart with higher eccentricities, ≈ 0.04 and 0.06, respectively.

A very similar evolution takes place for about a third of the simulations. The trigger for instability is the divergent passage of Uranus and Neptune through either their $7:5$ or $3:2$ MMR, and the kick in eccentricity this interaction administers to both planets. Although the exact outcomes vary stochastically from simulation to simulation, there is a clear overall correlation with the planetesimal disk surface density, with higher disk densities decreasing the strength of the scattering. This is because higher mass disks produce faster planetesimal-driven migration, resulting in faster passage through MMRs and thus a weaker impulse for Uranus and Neptune. At the same time, dynamical friction with the disk is stronger, so that whatever eccentricity the planets do manage to pick up is damped more effectively. As a result, none of the cases with $\Sigma_{\mathrm{plsml,\,AU}} \gtrsim 8$ g cm^{-2} result in scattering. Instead, all of them display variants of the behavior seen in the bottom panel of Figure 2: The outermost planet migrates outward through the planetesimal disk at low eccentricity, not stopping until it arrives near the original outer edge of the disk (30 AU). These bodies are in fact undergoing runaway or "forced" migration, as detailed in Gomes et al. (2004).

Snapshots of all 30 simulations at their completion time of 3×10^8 yr are shown in Figure 4. Insofar as we are looking for an analog to the solar system, the outcomes reveal somewhat of a "catch-22": All of the cases in which strong scattering occurs lose one of the ice giants. On the other hand, in the cases with higher disk masses, in which planetesimal-driven migration dominates, the absence of an abrupt instability does away with the desirable late heavy bombardment part of the picture. Also, when the ice giants' orbital evolution is predominantly the result of migration, the mechanism works much less efficiently for the inner of the two ice giants. Therefore, Uranus is systematically placed at too small an orbital radius in the end, a dilemma pointed out by Gomes et al. (2004). This effect is clearly visible in Figure 4.

4. SOLAR SYSTEM–LIKE OUTCOMES

We have demonstrated that interaction with an outer planetesimal disk will tend to eventually pull apart a compact, resonant version of the solar system. For lower mass planetesimal disks, the most important part of this evolution is usually an abrupt instability triggered when Uranus and Neptune, having left their original MMR, encounter a more distant one. For higher disk masses, this instability tends to be suppressed or absent, and the giant planets' orbits evolve by planetesimal-driven migration alone. We focus on the former scenario. To this end, we conduct another set of simulations and begin by choosing a lower range of disk masses. Again distributing the planetesimals as per equation (9), we now let $\Sigma_{\mathrm{plsml,\,AU}}$ range from 4 to 8 g cm^{-2}. An added consequence of adopting such a relatively low disk mass is that planetesimal-driven migration is more likely to be in the "damped" regime (Gomes et al. 2004), wherein migration stops by itself after a few AU. Thus, an outer disk edge at $\sim$30 AU should no longer be critical to stopping Neptune at the right place. To test this, we extend the outer disk edge to 50 AU. The disk masses thus range from about 31 to 63 $M_\oplus$. Having noted that all instances of strong scattering in § 3 resulted in the loss of one of either Uranus or Neptune, we simply add an extra Neptune-mass ice giant in Neptune's exterior $4:3$ MMR. With initial exploratory runs giving encouraging results, we increase the fidelity of the simulations by decreasing the planetesimal masses to 5×10^{-3} $M_\oplus$ (less than half a lunar mass), so that the lowest mass planetesimal disk is modeled with $\approx$6200 particles and the highest mass one with $\approx$12,500. Due to the significantly increased computational cost, we only run to 2×10^8 yr. Snapshots of the simulations at this time are shown in Figure 5.

All except one of the simulations (run 1) undergoes a scattering instability within this time. In most cases, this is the result of the inner and middle ice giants crossing the $7:5$ or $3:2$ MMR as they diverge, although in some cases it is the middle and outer. The important point is that even with this different initial configuration, it continues to be the small outer planets that served as the trigger for the instability.

Eight of the outcomes resemble the solar system in the sense that two ice giants are left with low eccentricities inside $\sim$ 40 AU and are undergoing little or no migration: runs 3, 9, 11, 12, 13, 14, 15, and 19 fall into this category. Another four cases, runs 4, 16, 18, and 21, look like reasonable solar system analogs but are still undergoing substantial migration and are thus likely to end up with their Uranus and Neptune significantly more widely spaced than in the solar system if their evolution is followed beyond 2×10^8 yr. Finally, runs 23 and higher have a sufficiently massive disk that planetesimal migration subsequent to the instability has driven the outermost planet to end up at or near the original outer disk edge at 50 AU. It is also worth noting that of the solar system–like outcomes above, all except run 12 end up with at least a part of their outer disk largely pristine. Thus, an additional depletion mechanism, such as collisional grinding (e.g., Stern & Colwell 1997; Davis & Farinella 1997), would need to act in order to reproduce the inferred low mass of the present-day Kuiper belt, $\lesssim 0.1$ $M_\oplus$.

5. OTHER INITIAL CONDITIONS

5.1. A More Compact System

We now explore the evolution of a planetary system from a few other initial configurations, although for simplicity we keep the solar system giant planets as our "building blocks." We begin with a resonant system assembled in the same way as in § 2, except that Jupiter and Saturn start between a $2:1$ and $3:2$ period ratio. As a result, the two gas giants are captured into the $3:2$ MMR. We again add an outer planetesimal disk. We revert to the coarser, smaller disk of § 3, made up of 0.035 $M_\oplus$ planetesimals and with an outer edge at 30 AU. Another set of 30 simulations (to 3×10^8 yr) is performed, with the same range of
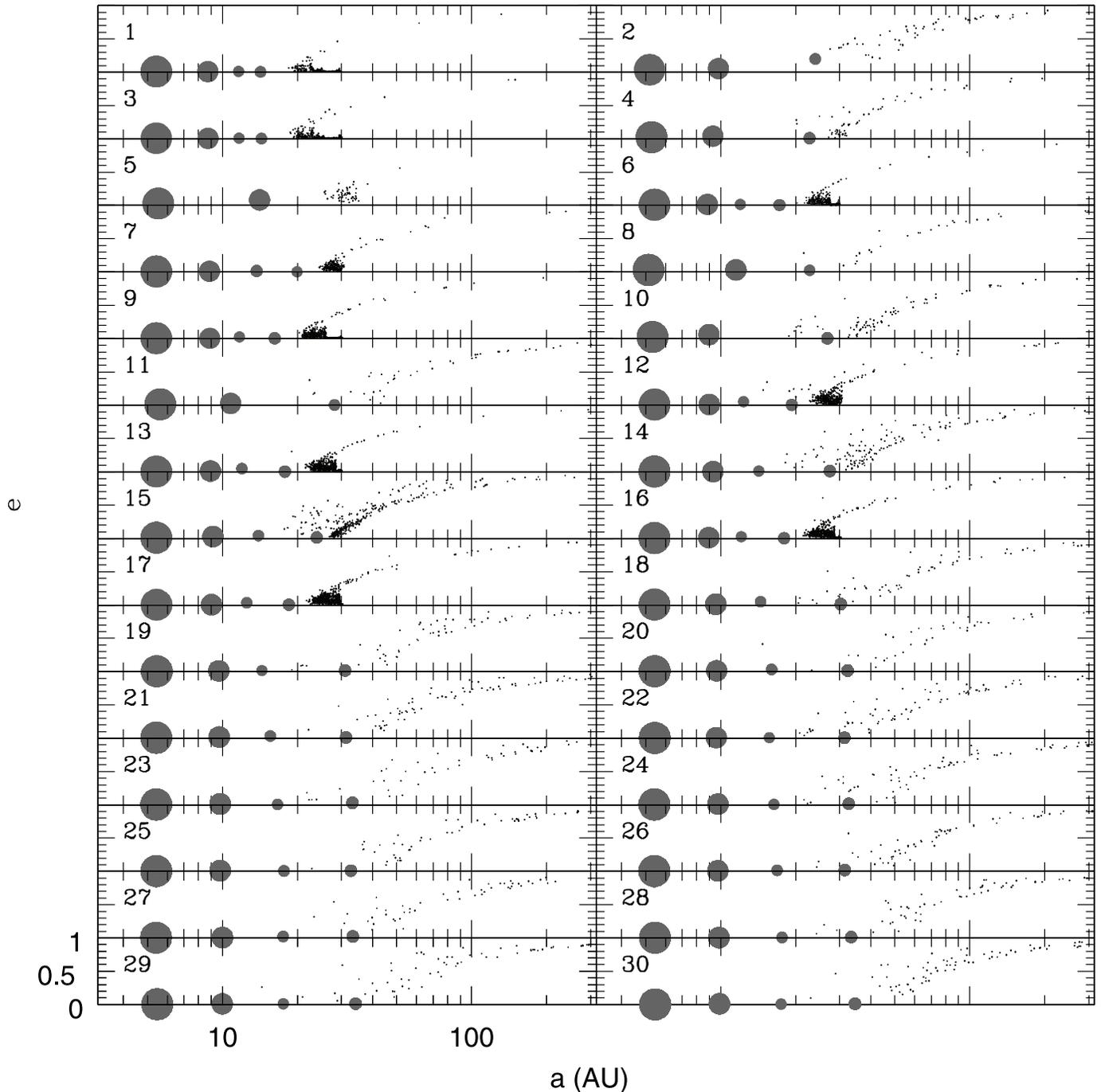
Fig. 4.— State of the 30 simulations in § 3 at their stopping time of 300 Myr. Eccentricity vs. semimajor axis (averaged over the last 10^6 yr) is plotted for the planets (*gray circles*, *size proportional to physical size*) and the planetesimals. Initial planetesimal disk surface densities are given by eq. (9), with $\Sigma_{plsml, AU}$ linearly increasing from 4 to 16 g cm^{-2} from runs 1 to 30. Broadly speaking, the systems evolve in one of three ways: (1) Almost no change in the giant planet orbits over 300 Myr (runs 1 and 3); (2) divergent migration of the outer planets, resulting in sudden instability and scattering when they cross their 7 : 5 or 3 : 2 MMR (runs 2, 4, 5, 7, 8, 10, and 11); (3) divergent migration in which resonance crossing does not destabilize the system, in the sense that no orbits cross (all remaining runs).

disk surface densities as in § 3. Figure 6 shows that we now obtain a number of systems in which one or both gas giants have eccentric orbits. This is in sharp contrast to the simulations performed in §§ 3 and 4; there, although the instability typically administers a strong enough kick to throw the gas giants out of resonance, they never acquire large eccentricities. However, with the two largest planets now starting out in the closer 3 : 2 MMR, the situation changes, and they strongly scatter each other in several cases. In almost a quarter of the runs—4, 5, 10, 12, 14, 18, and 26—one or both gas giants end up with substantial eccen-

tricities ($\gtrsim 0.2$). In one case, run 27, Saturn is lost from the simulation. However, this is not the result of an ejection; it happens when the planet crosses the inner simulation domain boundary at 2 AU and so constitutes a rather artificial result. Also worth noting is that Saturn is in some cases scattered to a significantly larger semimajor axis, as high as ≈ 30 AU.

5.2. *Reversing Jupiter and Saturn*

The model of Gomes et al. (2005) requires Jupiter and Saturn to migrate apart and cross their 2 : 1 MMR, something that is
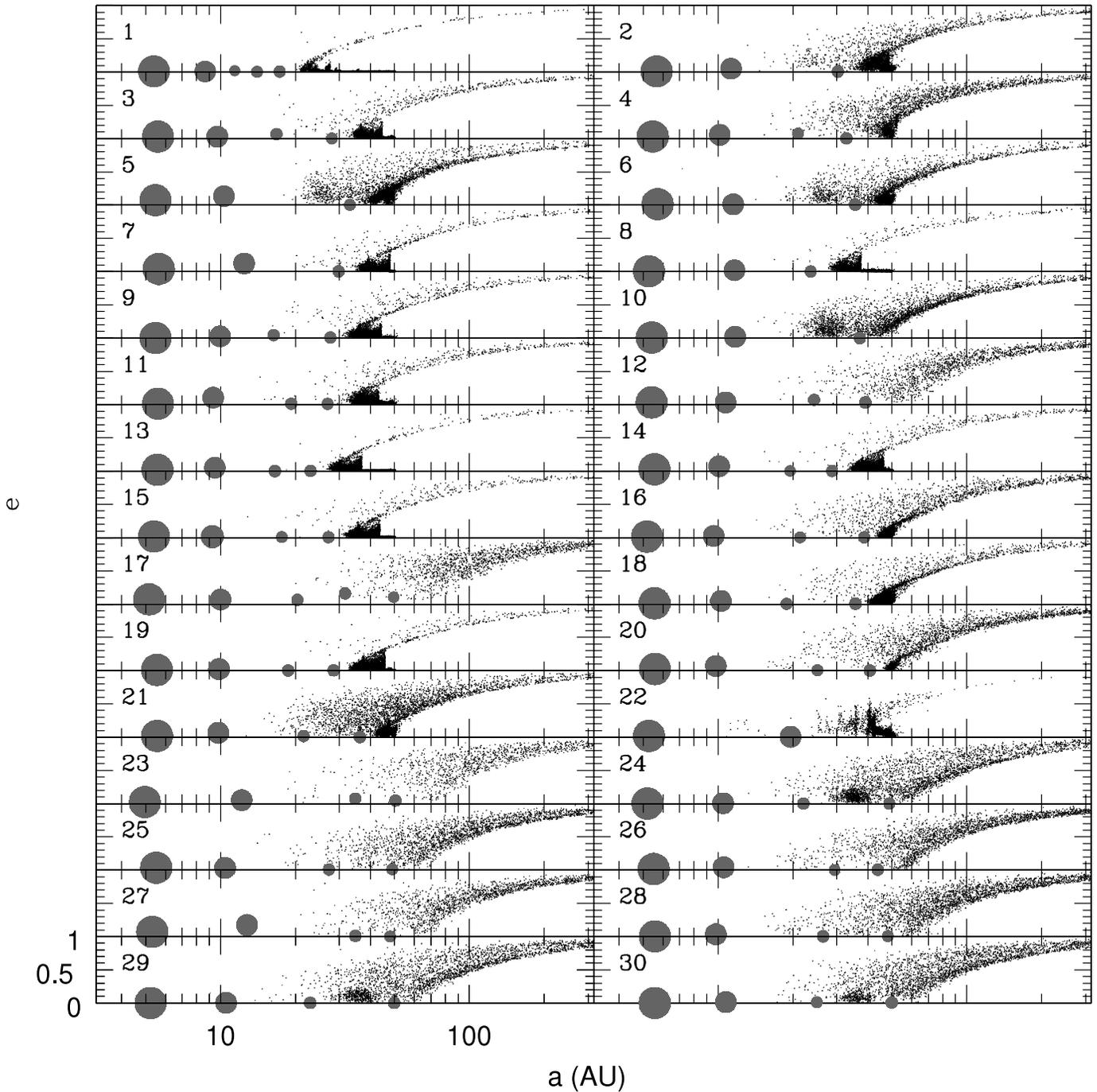
F$_{IG}$. 5.—State of the 30 simulations in § 4 at their stopping time of 200 Myr. Eccentricity vs. semimajor axis (averaged over the last 10^6 yr) is plotted for the planets (*gray circles, size proportional to physical size*) and the planetesimals. Initial planetesimal disk surface densities are given by eq. (9), with $\Sigma_{plsml, AU}$ linearly increasing from 4 to 8 g cm^{-2} between runs 1 and 30.

only possible because the inner gas giant, being more massive, is more efficient at ejecting planetesimals. In contrast, the instability mechanism we have examined here only requires the divergent migration of the small outer Uranus/Neptune-mass planets and thus ought to function independently of the gas-giant mass ratio. As a demonstration, we assemble the resonant configuration of § 5.1 above, except that we reverse the ordering of Jupiter and Saturn, making the latter the innermost planet. The results are shown in Figure 7. In contrast to the previous sets of simulations, here *all* have undergone strong scattering within 300 Myr. The higher yield of instability is the result of the smal-

ler outer planets now having a (3 times) more massive neighbor. This lowers the threshold for how strong a perturbation to the outer planets' orbits is needed in order to trigger global instability. In comparison to the previous set of simulations in § 5.1, we also produce a larger fraction of cases—one-half—in which at least one of the gas giants ends up with an averaged eccentricity ≳0.2 (runs 1, 3, 6, 7, 8, 9, 10, 11, 14, 15, 16, 19, 22, 24, and 27). In one of these cases (run 1) Saturn is ejected from the system, and in another (run 3) it acquires a semimajor axis of almost 100 AU. Among the remaining lower eccentricity outcomes, there are two instances (runs 12 and 28) of a physical collision,
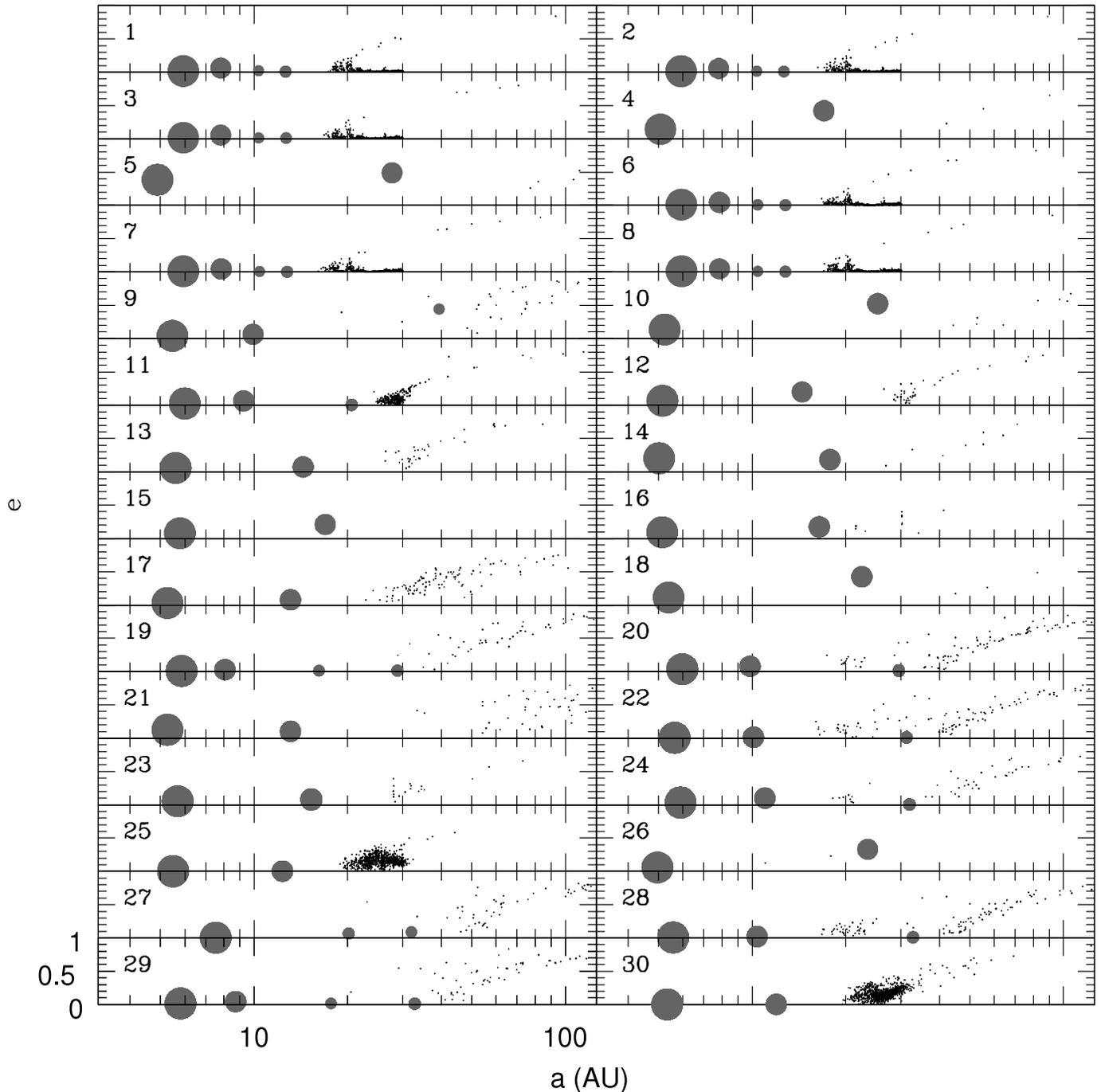
FIG. 6.— State of the 30 simulations in § 5.1 at their stopping time of 300 Myr. Initial conditions are as in § 3 but with Jupiter and Saturn beginning in a 3 : 2 instead of a 2 : 1 MMR. Eccentricity vs. semimajor axis (averaged over 10^6 yr) is plotted for the planets (*gray circles, size proportional to physical size*) and the planetesimals. Initial planetesimal disk surface densities are given by eq. (9), with $\Sigma_{plsml, AU}$ linearly increasing from 4 to 8 g cm^{-2} between runs 1 and 30.

and thus a merger, between the two gas giants. In another two cases (runs 5 and 23) Saturn is removed when it crosses the inner boundary.

6. DISCUSSION AND CONCLUSIONS

We have shown that migration in a young protoplanetary disk can readily produce systems of planets in which each member is locked in a mean motion resonance (MMR) with its neighbors. Due to the stabilizing effect of the resonances, even tightly packed configurations, with period ratios of adjacent planets ranging from 2 : 1 to 4 : 3, are stable over timescales long compared to the gas disk lifetime (10^6–10^7 yr), even after the dissipational

effect of the gas is removed. We have then gone on to show that at later times such configurations can be destabilized, frequently in a catastrophic manner involving strong planet-planet scattering. This requires divergent planet migration, which can be driven by the interaction with an outer planetesimal disk. The actual trigger is a pair of planets crossing a mutual MMR, which for diverging orbital periods produces eccentricity excitation but not capture.

A key feature we find is that in a compact system of Jupiter/Saturn-mass inner planets combined with much smaller Uranus/Neptune-mass outer planets, the latter alone can serve as the trigger for global instability, a case of the "tail wagging the dog."

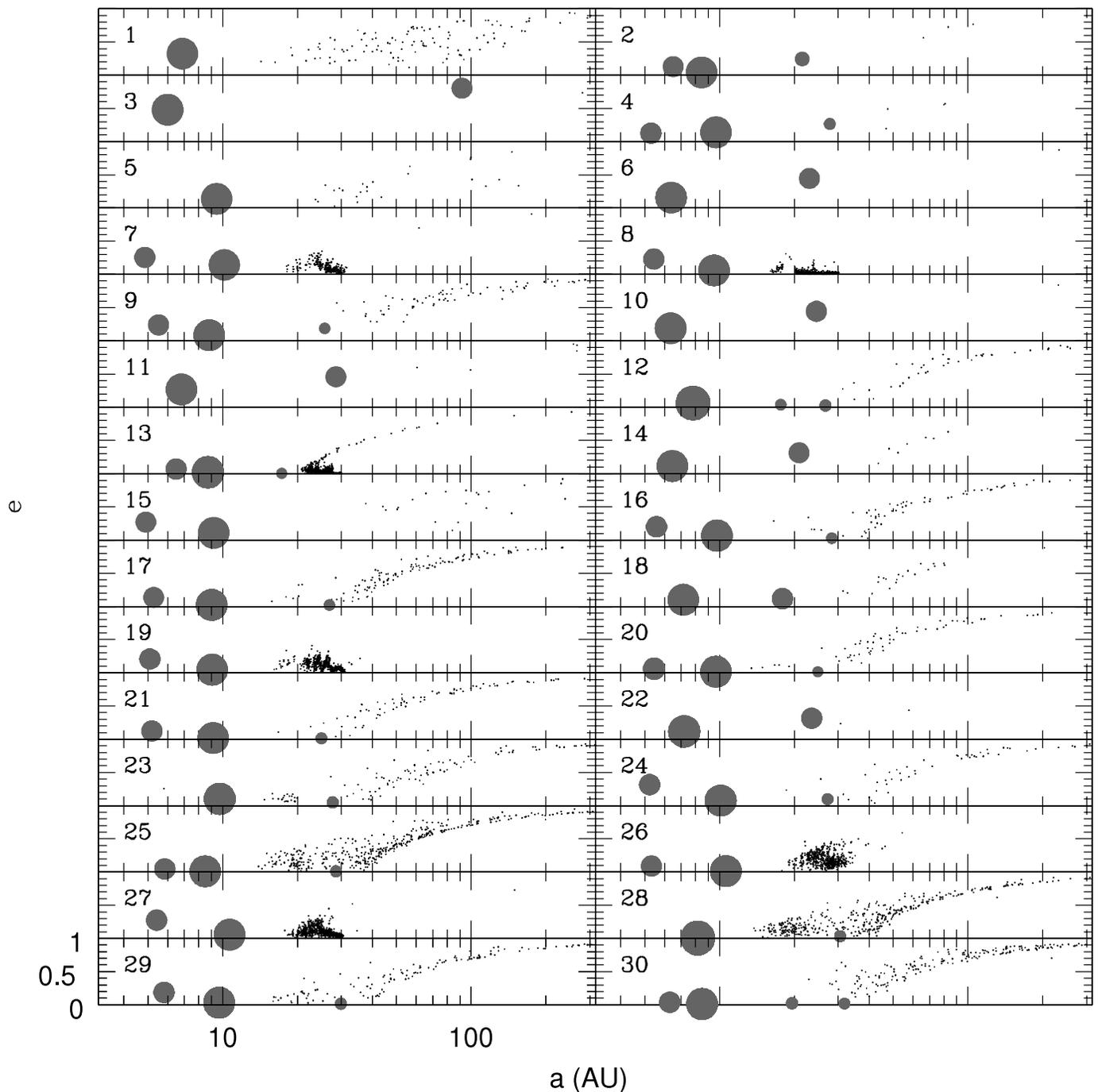Fig. 7.—State of the 30 simulations in § 5.2 at their stopping time of 300 Myr. Initial conditions are as in § 5.1 but with Jupiter and Saturn reversed, so that Saturn is the innermost planet. Eccentricity vs. semimajor axis (averaged over 10^6 yr) is plotted for the planets (*gray circles, size proportional to physical size*) and the planetesimals. Initial planetesimal disk surface densities are given by eq. (9), with $\Sigma_{\mathrm{plsml,\,AU}}$ linearly increasing from 4 to 8 g cm^{-2}.

Reverse resonance crossing was invoked as the trigger for the scattering of Uranus and Neptune, and simultaneously for the late heavy bombardment, in the model of Gomes et al. (2005), but in contrast, they require the largest planets, Jupiter and Saturn, to cross an MMR (the 2 : 1). Also, no planets are initially in resonance.[5] The problem is that planetesimal-induced migration moves the less-massive Uranus and Neptune much faster than it does Jupiter and Saturn, yet at the time of resonance crossing, the

system still needs to be compact enough that the ice giants have a high probability of being scattered. In order that they cross the resonance quickly enough, Jupiter and Saturn must therefore start out just a bit closer than the 2 : 1. Thus, the system must have emerged from the gas disk in a rather finely tuned configuration, made even more precarious by the lack of any stabilizing MMRs between the closely packed planets. However, notwithstanding this issue, Gomes et al. (2005) demonstrate that the onset of planetesimal-driven migration can be delayed by at least 10^9 yr (and in principle, arbitrarily long), depending on how far the inner edge of the planetesimal disk is from the outermost planet. It is this feature—the ability to initiate an instability after

[5] As we were writing this paper, it was brought to our attention that a new version of their model also begins with the giant planets in MMRs (Morbidelli et al. 2007).

a long delay—that makes this mechanism a good candidate for triggering the late heavy bombardment. In the simulations presented here, instability generally sets in on a timescale $\lesssim 10^8$ yr; since we perform many simulations, we avoid a prohibitive computational cost by placing the inner disk edge close enough to produce a relatively rapid onset of migration.

Our goal here has not been to undertake a thorough parameter study of outcomes produced by the breakup of resonant planetary systems; rather, we have tried to present a few interesting cases—simply from mixing and matching the solar system giant planets—to illustrate the key features of this mechanism and to serve as a jumping-off point for future work. We have identified one pathway for producing systems that resemble the solar system, beginning with a moderately compact set of planets: Jupiter and Saturn in a 2 : 1 MMR, and three exterior resonant Uranus/Neptune-mass planets, at least one of which is usually lost when the system becomes unstable. We find that if Jupiter and Saturn start in a closer 3 : 2 MMR, strong scattering between the two gas giants can occur when instability sets in. In almost one-quarter of this set of simulations, either Saturn, or both Jupiter and Saturn, are left with substantial eccentricities as a result. Instability continues to take place—in fact, the fraction of cases left with an eccentric gas giant rises to one-half—when the orbits of Jupiter and Saturn are switched. Therefore, this mechanism also provides a pathway to producing the sort of high eccentricities possessed by a large fraction of observed exoplanets. Planet-planet scattering was proposed as a way of generating eccentricities as far back as the discovery of the first exoplanets (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997), and recent results on reproducing the observed exoplanet eccentricity distribution in this way look promising (Chatterjee et al. 2007; Juric & Tremaine 2007). The scenario we develop here amounts to a means of systematically producing scattering from an initially stable configuration. Again, however, it should be emphasized that we have only considered a few specific cases; the inclusion of a planetesimal disk renders the problem more dynamically complex (and much more computationally expensive) than a few-body scattering problem. Thus, significantly more work is required in order to extract from this model an eccentricity distribution that can be directly compared to observations. Likewise, we cannot say much about the semimajor axis distribution, except to note that in starting with the gas giants between ∼5 and 10 AU, we do not produce any close-in giant planets (although our simulations have an inner boundary at 2 AU, there are only very few instances of a gas giant crossing it). This is consistent with earlier findings that planet-planet scattering by itself is probably not able to account for hot Jupiters (Ford et al. 2001). On the other hand, in a number of cases the lower mass gas giant is scattered far outward, in one instance acquiring a semimajor axis of nearly 100 AU.

Also requiring more investigation are the conditions under which a young planetary system will become resonantly locked. Although we find in § 2 that capture happens robustly over a wide variety of disk densities, it is worth remembering that our modeling of the disk-planet interactions is still quite simplified.

The key quantity in determining how readily resonant groups of planets can be assembled is the ratio of the eccentricity damping and migration timescales, t_{migr}/t_e. The larger this quantity, the more the eccentricity damping protects a pair of convergently migrating planets against scattering each other before they can be safely locked into a resonance. This in turn allows more "precarious" configurations to be assembled. Although we have used a relatively conservative prescription for the strength of the eccentricity damping, there is no guarantee that this is correct. Furthermore, the above ratio is proportional to $(H/r)^{-2}$; i.e., it has a strong dependence on the assumed scale height profile of the disk, with thinner disks favoring eccentricity damping relative to migration. This we have not varied, and simply used the "standard" model of Hayashi (1981). Given how little we actually know about protostellar disk conditions, this is perhaps the biggest source of uncertainty in the ratio t_{migr}/t_e. For now, the best we can do is to explore the behavior for a range of ratios, which we leave for future work.

With the above qualifications, our results suggest the possibility that the violent breakup of close-packed, resonantly locked planets is an evolutionary step that has occurred in many planetary systems. The exoplanets observed to be in MMRs would then represent simply the survivors of a much larger primordial resonant population. The late heavy bombardment in our own solar system may have actually resulted from a relatively gentle version of such a breakup, with more violent outcomes recorded in the high eccentricities common among observed exoplanets. Indeed, recent *Spitzer* observations suggest that extrasolar versions of the LHB could be commonplace. Wyatt et al. (2007) find that 2% of Sun-like stars exhibit hot dust in what corresponds to the terrestrial planet region; for most of these, the luminosities exceed model predictions for quasi-steady state disk evolution by more than 3 orders of magnitude. This implies that in these systems, we are actually observing the signatures of transient events. It has been suggested that collisions of larger bodies result in episodic dust production in debris disks (Rieke et al. 2005). However, Wyatt et al. (2007) demonstrate that individual collisions are almost certainly not efficient enough to produce the observed dust overabundances and conclude that a large-scale dynamical instability is a more likely explanation. Furthermore, they show that observing this phenomenon in 2% of systems means there is a good chance that such a cataclysmic event occurs at some point during the lifetime of *all* Sun-like stars. More observations as well as modeling are required to explore this intriguing possibility.

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