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Resonant Planets: From Stability to Violent Upheaval

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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.

1. Introduction

Currently, there are twenty-six detected multi-planet extrasolar systems[†]. 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) . Several scenarios for producing such configurations have been suggested. Two gap-opening planets, if formed in close enough proximity, will clear out the intervening annulus of gas and so 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 mean-motion resonance is a very likely outcome (Lee & Peale 2002; Kley et al. 2004). Differential migration will also tend to take place between gap-opening bodies co-evolving with the gas disk, and non-gap-opening bodies undergoing type I migration. Ward 1997); when the latter catch up to the former, capture into mean-motion resonances is again a likely result, as suggested by Hahn & Ward (1996) and demonstrated by Thommes (2005). 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, which has been a

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[†]`http://www.exoplanets.org, http://exoplanet.eu/`

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 ($\sim 5 - 10$ 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 Myrs 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 which 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 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 §3., we demonstrate that this can lead to Solar System-like outcomes. We explore another scenario, with more closely-spaced Jovian planets, in §4., and find that large gas giant eccentricities can be produced in the ensuing instability. We discuss our results in §5..

2. Making and Breaking 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. We begin by constructing a version of the Solar System in which all the giant planets are (i) locked in MMRs with each other, and (ii) packed within, approximately, the current Jupiter-Saturn region. We want to do this in a way which 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, adding to the code accelerations to model the radial migration and eccentricity damping due to gravitational interaction with the gas disk, in both the type I and type II regimes. Details are given in Thommes et al. (2008).

We begin with a Jupiter-mass planet (310 $M_\oplus$) 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. A Uranus and Neptune-mass planet are placed at 15 and 25 AU, respectively. (Thommes 2005).

We adopt a gas disk scale height like that in as in the model of Hayashi (1981). We take the gas surface density to be of the form

$$\Sigma_g(r) = \Sigma_{g,\mathrm{AU}} \left(\frac{r}{1\mathrm{AU}}\right)^{-1} e^{-t/10^6\mathrm{yrs}} \tag{1}$$

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.

By themselves, these resonant systems are likely to remain essentially "frozen" in the configuration with which they emerge from the gas (numerical simulations confirm that, even after removal of the "gas", all are completely stable for at least 10^9 yrs). 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 planetesimal very likely drove divergent migration of the giant planets in the early Solar System (Fernandez & Ip 1984; Hahn & Malhotra 1999; Gomes et al. 2004). 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).

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 individual planetesimals have a mass of 0.035 $M_\oplus$. The planetesimals are distributed with a surface density

$$\Sigma_{\mathrm{plsml}} = \Sigma_{\mathrm{plsml,AU}} \left(\frac{r}{1\mathrm{AU}}\right)^{-1}. \tag{2}$$

We perform a set of 30 simulations, linearly varying $\Sigma_{\mathrm{plsml,AU}}$ from 4 to 16 $\mathrm{g\,cm^{-2}}$. Each runs to 3×10^8 years. In all but two of the simulations, the orbits of the giant planets undergo significant dynamical changes. Fig. 1 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. Similarly 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 shakeup 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,

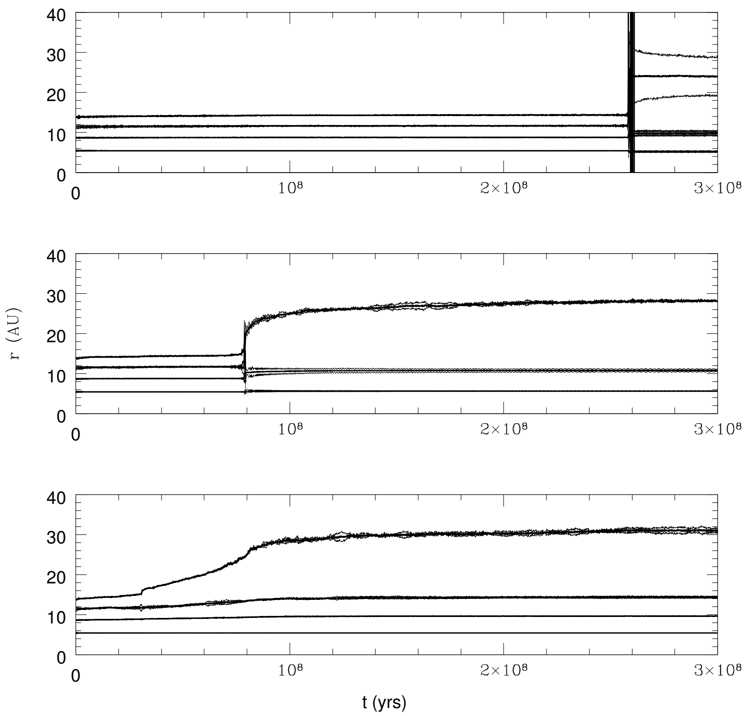

Figure 1. Three simulations out of a set of 30, showing the evolution of an initially compact, resonant-locked version of the Solar System, as described in §2., interacting with an outer planetesimal disk. Semimajor axis as well as peri- and apocenter distance are plotted as a function of time. In the first two panels, one of of the Uranus/Neptune mass planets is abruptly ejected after 2.6×10^8 years and 8×10^7, respectively. In the last panel, although the ice giants clearly receive a kick at 3×10^7 years, 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.

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 it is much later that the instability sets in; it happens when Uranus and Neptune divergently cross their 7:5 MMR and receive an impulsive increase in their eccentricities. With Saturn and Jupiter nearby, this eccentricity increase turns out to be sufficient to initiate a chain reaction of instability.

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. Though 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.

3. 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 will 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 Eq. 2, we now let $\Sigma_{\rm plsml,AU}$ range from 4 to 8 $\rm g\,cm^{-2}$. Having noted that all instances of strong scattering in §2. 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. Snapshots of the simulations at this time are shown in Fig. 2. 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, though 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 which 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 ~ 40 AU, and are undergoing little or no migration: runs 3, 9, 11, 12, 13, 14, 15, 19 fall into this category.

4. A More Compact System

We now explore the evolution of a planetary system from a different initial configurations, though 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. Fig. 3 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.: 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 eccentricities ($\gtrsim 0.2$). 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.

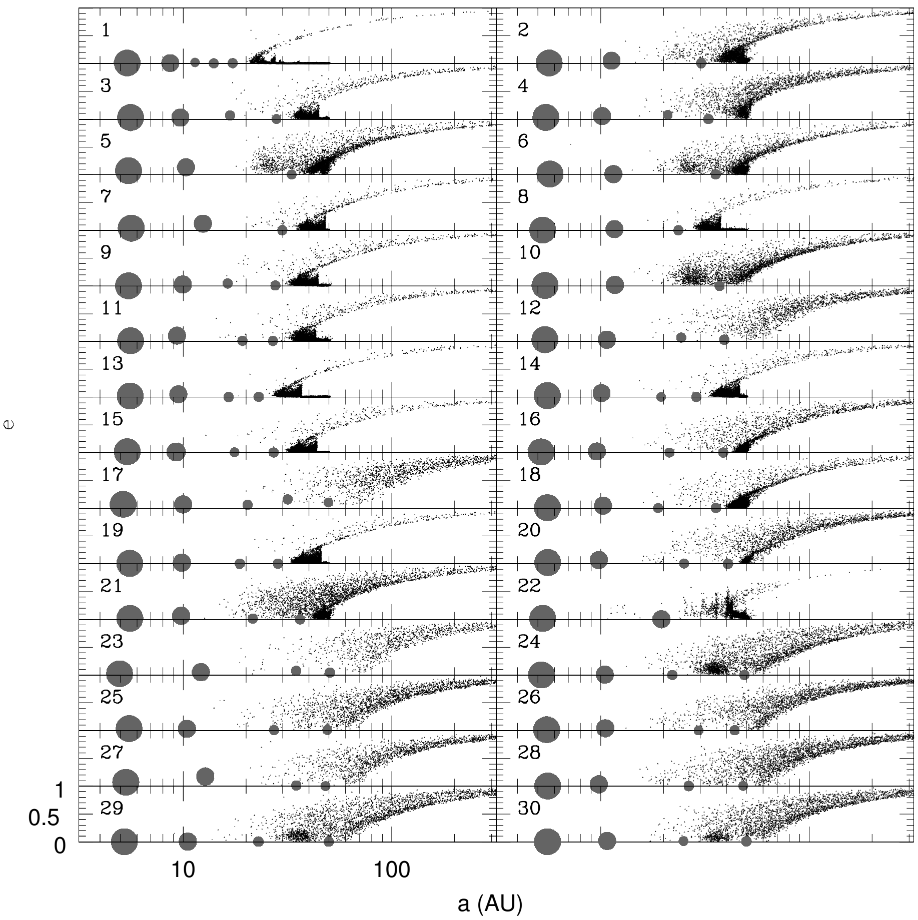

Figure 2. The state of the 30 simulations in §3. at their stopping time of 200 Myrs. Eccentricity vs. semimajor axis (averaged over the last 10^6 yrs) is plotted for the planets (gray, size $\propto$ physical size) and the planetesimals. Initial planetesimal disk surface densities are given by Eq. 2, with $\Sigma_{\rm plsml,AU}$ linearly increasing from 4 to 8 $\rm g\,cm^{-2}$ between Run 1 and Run 30.

5. 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 to 10^7 years), 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 by driven be 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 com-

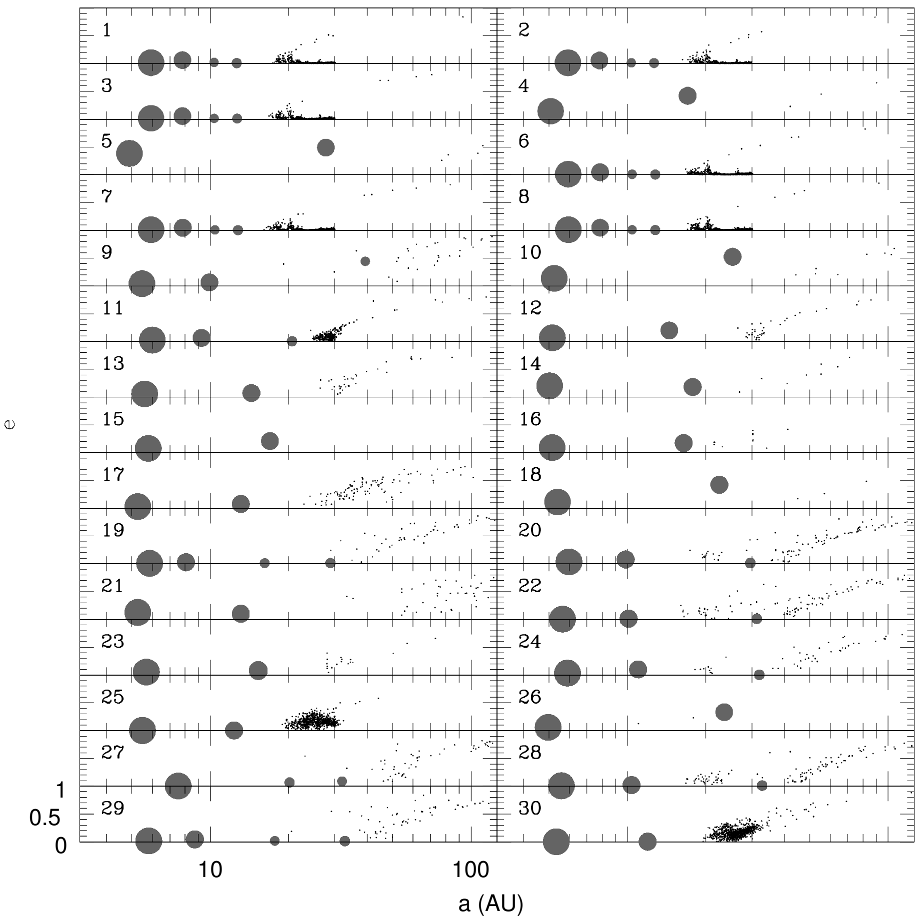

Figure 3. The state of the 30 simulations in §4. at their stopping time of 300 Myrs. Initial conditions are as in §2. but with Jupiter and Saturn beginning in a 3:2 instead of a 2:1 MMR. Eccentricity vs. semimajor axis (averaged over 10^6 yrs) is plotted for the planets (gray, size $\propto$ physical size) and the planetesimals. Initial planetesimal disk surface densities are given by Eq. 2, with $\Sigma_{\rm plsml,AU}$ linearly increasing from 4 to 8 $\rm g\,cm^{-2}$ between Run 1 and Run 30.

pact 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".

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 a MMR (the 2:1). Also, no planets are initially in resonance 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 years (and in principal arbitrarily long) depending on how far the inner edge of the planetesimal disk is from the outermost planet. In the simulations presented here, instability generally sets in on a timescale $\lesssim 10^8$ years; 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.

Although we have by no means undertaken an exhaustive parameter study, 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 three orders of magnitude. This implies that in these systems, we are actually observing the signatures of transient events. 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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