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Dynamics of disks with planets

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Abstract. We review several theories of origin and evolution of the recently discovered extrasolar planetary systems. The properties of these systems were unexpected. This motivated theorists to extend and revise many preexisting theories. Important extensions include migration of bodies and planetary eccentricity pumping by planet-planet interaction, and primordial disk-planet interaction. Progress in observational techniques might allow us to find which of these two types of interaction is mainly responsible for the observed variety of orbits and exoplanet masses. New insights into the formation of our own system can be gained by asking why Jupiter and Saturn are not larger, closer to the sun and/or do not follow noticeably elliptic orbits.

Scenarios of planet migration in disks may change markedly on account of a new mode of migration, which does not have a predetermined direction in a given protoplanetary disk, provided it has zones of low and high density. We present the first simulations of planets undergoing a rapid (runaway) migration. Migration can be inward or outward, depending on the initial disk density distribution. The process is driven by corotational gas flows and orbital libration of underdense disk gas, rather than the previously considered Lindblad resonances or disk viscosity. With characteristic time scale $<$100 orbital periods in realistically dense disks, runaway migration can be stopped by density gradients, e.g., at the inner boundary of the magnetically inactive 'dead zone' of a protoplanetary disk, located from 0.1 to a few AU from the star.

1. Prior expectations

The extrasolar planetary systems have been anticipated long before they were discovered. Greek atomism of Leucippus and Democritus (cf. Dick 1982) has lead to prediction of other "worlds" (planetary systems with their moons and suns) and, importantly, their evolution (formation in a rotating, turbulent nebula; fractionation of dust), and diversity (worlds with no moons, multiple suns etc.) The oldest and the newest concepts regarding "other worlds" are thus remarkably similar.

The 'standard model' of solar system formation from 1980s served by default (Copernican principle) as a theory of extrasolar systems. In this model, planetary systems form from the protoplanetary disks (also known as primitive solar nebulae, protostellar accretion disks, or T Tauri disks). Planetesimals, comet-sized primitive rock+ice (or only rock) containing bodies, form from dust, accumulate in orbit via binary collisions, and in less than 1 Myr form protoplanets. In $<$100 Myr terrestrial planets are assembled in the inner solar system. Outside the ice condensation boundary, at a distance of several AU from the sun, protoplanets grew quicker and larger because of the availability of water ice, and grew up to a mass of several Earths, gathering around them a massive hydrogen+helium envelopes. In the formation scenario most supported by ground-based observations and spacecraft flybys, called "core-accretion" or "core-instability" scenario, the primitive atmosphere becomes unstable and accretes onto the core without mixing, when the core mass exceeds 7 and 10 Earth masses, a value in line with core mass estimates from Jupiter to Neptune (see reviews in Mannings et al. 2000).

Jupiter was thought to have been born: (i) at or near its present location, because of ice boundary location, (ii) on a circular orbit ($e \approx 0$), due to circular motion of the protoplanet and the disk, and (iii) with mass determined by the process of tidal gap opening in a viscous disk with parameter $\alpha \sim 10^{-2}$.

2. The new worlds

2.1. Dusty disks

The standard model of planet formation agrees with numerous observations of circumstellar disks. Many dusty disks known as Vega-excess systems (because of infrared radiation detected by satellite IRAS around Vega, much exceeding the flux from the star itself) are good, if not exact, analogues of an early solar system. An A-type star β Pictoris was first imaged to reveal an extended, edge-on dust disk. This system, and many others thereafter, were recognized as truly planetary systems, grinding planetesimals and meteoroids to dust (Artymowicz 1997). The name 'replenished disks' describes their nature well. The observed amount of dust in β Pic, which could tightly cover the orbit of Uranus and weighs as much as several Moons, must have been resupplied thousands of times during the star's lifetime (20-100 Myr), partly owing to erosion-enhancing dynamical effects of radiation pressure on dust. There is evidence that protoplanet-sized or larger bodies hide in the disk. The strongest ones include: the warp in the inner 100 AU zone of the disk (Heap 2000), the need to perturb comets/asteroids from the disk to the immediate vicinity of the star, where they are seen spectroscopically as gas-and-dust shedding bodies. (For review see Lagrange et al. 2000).

Several transitional disks, of approximately 5-10 Myr of age, have recently been imaged (Koerner et al. 1998, Weinberger et al. 1999). Situated evolutionary between gas-rich solar nebulae and the gas-poor replenished dust disks, these disks (e.g., in HR 4796A and HD 141569A) show evidence of features such as gaps and inner clearings, which may be due to planets (this happens in simulations presented below) or, alternatively, due to dust migration in optically thin disks with gas (Takeuchi & Artymowicz 2001).

2.2. Exoplanets

The first extrasolar planetary system was found in an unlikely place: around a millisecond pulsar PSR1257+12 (Wolszczan and Frail 1992). Belief in the ubiquity of planets was strengthened and searches might have been stimulated by its discovery but, ironically, the orbital structure was too similar to that of the inner solar system to prepre us for what was to be discovered around normal stars. Theoretical expectation (Boss 1995) that the solar and extrasolar systems share the basic blueprint (giants outside a

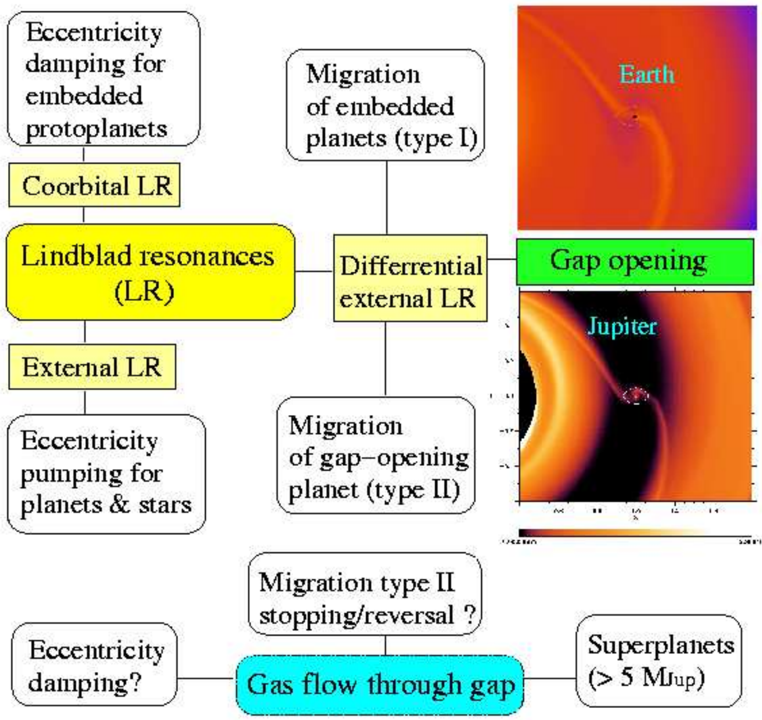

Figure 1. Theoretical concepts and effects of disk-planet interaction.

few-AU radius, terrestrial planets inside) provided no guidance to the discovery of the extrasolar giant planets.

Mayor and Queloz (1995) discovered the first 4-day period giant planet at a distance of only 0.05 AU from 51 Pegasi. Currently, more than 100 exoplanet candidates are known from radial velocity studies (Schneider 2002, Marcy et al. 2002). Statistical conclusions are possible at this stage (although serious modeling of the observational biases is acutely needed for confirmation of finer points):

• Planetary companions (with $a < 3$ AU and at least Saturn's mass) exist around at least $\sim$7% of normal stars.

• "hot Jupiters" (minimum masses $m > 0.1 m_J$, semi-major axes $a < 0.1$ AU) exist around 0.7% of sun-like stars.

• Eccentric planets abound. There is a clear e–P correlation (Marcy et al. 2002) resembling closely that of the PMS and main-sequence close binary stars (cf. Mathieu 1994). Orbits with $a < 0.1$ AU tend to have $e \approx 0$. There is a weak direct correlation of e with $m \sin i$.

• Very massive planetary companions are found with the frequency $dN \sim m_i^{-0.9}\, dm_i$, i.e., the logarithm of mass has a very flat distribution up to the minimum mass $m_i = m \sin i > 10 m_J$ (10 Jupiter masses).[1] This decreasing tail of planet-like bodies over-

[1]The unknown inclination of the orbit i does not allow unique mass determination, and yields only the minimum mass $m \sin i$ of a system. This mass, assuming randomly oriented orbits, is on the average $\langle 1/\sin i \rangle = \pi/2$ times smaller than the true mass.

laps with a low-mass tail of massive companions (stars or brown dwarfs with mass 13 to 80 m_J), but details of where this happens are unclear owing to poor statistics.

3. Theories

3.1. Planet-planet interaction and other perturbations

Eccentricity-inducing star-planet interactions take place during flyby's frequently occurring in dense open clusters (Laughlin & Adams 1999), especially if the planet is far away from its host star ($a > 10$ AU). On the other hand, such a perturbation cannot explain the eccentricities of short-period (hot) planets. Of course, planets in known binary systems, such as 16 Cyg B, can also be strongly affected (Holman & Wiegert 1999). Eccentricity and orbital inclination can undergo anticorrelated, large swings known as the Kozai effect (e.g., Lin et al. 2000). Strong mutual gravitational perturbations between the forming planets distort their orbits up to a high $e \approx 0.9$ or cause escapes (e.g., Weidenschilling & Marzari 1996). But the models of N-body interactions depend strongly on the initial configuration of bodies. To avoid making arbitrary assumptions about the initial state, Levison et al. (1998) simulated numerically the bottom-top accumulation of a swarm of protoplanets in the outer solar system, including the gas accretion from disk in a simple parametric way (non-selfconsistent). They presented statistics of the computed masses and eccentricities (migration in disks was not modeled), with a wide range of eccentricities including high ones, without a pronounced correlation with planet's mass. A slight anti-correlation may even exist, due to a tendency of any N-body systems toward energy equipartition (here, of the epicyclic motion associated with elliptic orbits). Thus, at least in a rough way, standard accumulation scenario may explain the statistics of eccentric exoplanets but, surprisingly, requires an extra mechanism for damping e (artificially included in a subset of Levison et al. calculations) in order to routinely produce low-eccentricity, solar-like systems. We feel that the best candidate for such a mechanism is the disk-planet interaction.

3.2. Disk-planet interaction

There are two key processes underlying much of the orbital evolution in disks. The first one is Lindblad Resonance (LR), where a planet launches a spiral wave in disk. The second unifying concept is mass flow through gaps, which will be elaborated in sect. 3.6.

Lindblad resonances and their manifestations are shown in Fig. 1. Lower (upper) part of the diagram describes the behavior of protoplanets which do (do not) open gaps. The condition of LR requires that the (disk) fluid element moves periodically through the rigidly rotating pattern of the perturbing potential with a period equal to its natural radial oscillation frequency, called epicyclic frequency (≈Keplerian angular frequency in a typical solar nebula). If the perturbing body's orbit has $e > 0$, a double Fourier decomposition of potential is carried out and the response of the disk is obtained by linear sum over harmonics (a theory valid for small protoplanets). Pioneered by Goldreich & Tremaine (1979, 1980), the LR theory was generalized by Artymowicz (1993) to handle point-like perturbers embedded in disks by computing the so-called torque cutoff at high azimuthal wave numbers of the potential.

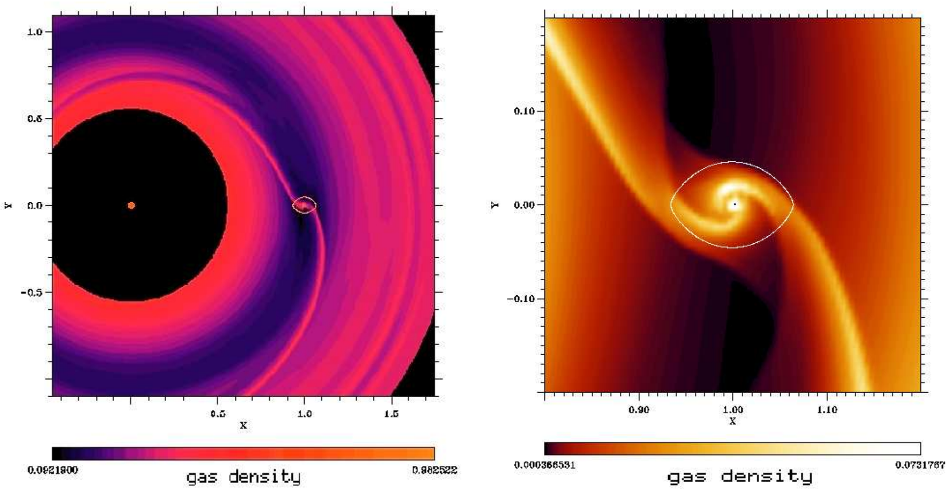

Figure 2. Left panel: a 25-Earth mass protoplanet opens a gap in the surrounding solar nebula (viscosity parameter $\alpha = 0.006$, thickness ratio $z/r = 0.05$). Gas density, in arbitrary units, is color-coded. Right panel: the same as left panel, but a 1 Jupiter-mass protoplanet (and a zoomed view). Notice the shock waves (wakes) between the disk and the Roche lobe of a planet. White ovals around planets mark the Roche lobe of Jupiter.

3.3. Gap opening

We mentioned in sect. 2.2 that in the standard theory gap opening was held responsible for limiting the mass of a giant planet. Indeed, the viscous gap opening criterion (Lin & Papaloizou 1979, one of two criteria of Lin & Papaloizou 1993), $\mu \approx 40Re$, is satisfied by a 0.4–1 m_J planet residing in a standard solar nebula with Reynolds number[2] $Re \approx 10^5$.

One problem is that the standard gap criterion disagrees with some numerical simulations (Artymowicz 2000). Figure 2 (left panel) shows the offending Neptune-class planet that exerts gap-opening torques in the surrounding disk simulated by PPM (Piecewise Parabolic Method). The density ratio inside/outside the gap is of order 1:10. Unexpectedly, the standard viscous criterion predicts a 2.5 times larger mass is needed for this, and an additional "thermal" one a 5 times larger mass (i.e., standard criteria require $\sim$100 Earth, i.e. Saturn mass, for gap opening in the simulated disk). More work on gap-opening criteria is clearly needed to find when gaps become observable and how far the planetary cores migrate within the disk, the question to which we now turn.

3.4. Distances: the puzzle of warm Jupiters

There are some empirical indications that solid material migrated long way through the solar system, perhaps before inclusion in planetary cores. An unexpectedly uniform

[2]Reynolds number can be estimated via the spectroscopically observed accretion rates of gas onto the PMS stars (this gives viscosity parameter $\alpha \sim 10^{-2}$, cf. review by Calvet et al. in Mannings et al. 2000; we have $Re^{-1} = \alpha(z/r)^2$, where $z/r \approx 0.05$ is the disk opening ratio.

abundance relative to solar of heavy elements including such volatiles as N_2, Ar, and Kr, was found by Galileo probe in Jupiter's atmosphere (Owen et al. 1999). However, if Jupiter formed from material that condensed at its present location then gases like Ar and N_2 should be depleted by 4 orders of magnitude, because they do not solidify or get trapped in clathrates at the temperature characteristic of Jupiter zone (Owen and Bar-Nun 1995). Planetesimals, which were incorporated into Jupiter or perhaps the whole core of Jupiter, appear to have been assembled outside the orbit of Neptune.

On the other hand, the final structure of our system does not suggest global migration of giant planets. For instance, migration of a giant protoplanet through the inner solar system destroy beyond repair or replacement the delicate system of growing proto-terrestrial planets.

But most exoplanetary systems seem to have a different history, involving global migration. Since it is difficult to imagine sufficient amounts of both the rocky material (needed for cores in core-accretion scenario) and the nebular gas for in-situ giant planet formation within a small fraction of AU from the star, it is generally thought that the hot Jupiters, or at least their solid cores formed much further out in the disk and migrated inwards (Lin et al. 1996). Customary distinction is made between migration type I, in which the protoplanet is embedded in disk gas, and migration type II, where the planet is centered in the disk gap.

Using semi-analytical formulae for the LR torques (Artymowicz 1993), Ward (1997) presented a unified theory of migration type I and II. It predicts large *inward* migration rates, on time scales (for migration from 5 AU) of only 10^4–10^5 yr. Observationally, for a while it seemed that exoplanets migrate but preferentially stop close to the stars surviving as "hot Jupiters" (Lin et al. 1996). Since then, however, so many "warm Jupiters" were discovered, smoothly distributed over all observable distances ($<$3 AU) that the existence of any *strong* stopping effect near the star bacame unnecessary.

Currently, a major question is why the migrating exojupiters so often do **not** migrate all the way in, but appear to stop at intermediate radii. One solution is suggested by the recent calculations of the rapid mode of migration dominated, not by LRs, but by corotational torques (cf. section ??? below).

3.5. Eccentricities: the puzzle of elongated orbits

The planets of υ And, and several other systems, exhibit an unnatural (anti-equipartition) dependence of e on m, the most massive superplanet ($\sim$10 m_J) having the largest mean eccentricity. This could indicate the influence of a disk during the formation period, or alternatively a contrived N-body interaction resulting in the loss of yet another, larger hypothetical superplanet.

Gravity of the disturbed disk(s) transfers energy and exerts feedback torques on the perturber (planet), thus causing a coupled orbital evolution of a and e in accordance with LR theory (Goldreich & Tremaine 1980, Artymowicz et al. 1991; Artymowicz 1993; see also Fig. 1). Therefore, significant migration necessarily implies significant eccentricity pumping or dumping. Artymowicz (1992) proposed that a sufficiently wide disk gap leads to eccentricity pumping by external Lindblad resonances in disk, and damping otherwise. The mass flowing from the disk onto a planet through a disk gap or from one side of the disk to the other provides an extra torque and energy transfer route, but these effects are more model-dependent (hence question marks following the outcomes presented in Fig. 1).

Eccentricity evolution is independent of the origin of affected bodies. While it is true that stars (brown dwarfs) and radial-velocity companions have similar eccentricity distributions, this does not at all mean that the former are small brown dwarfs, only that both types of objects may have their e pumped by the ubiquitous protostellar disks (for a diverging opinion see Black 1997). The crossover mass for eccentricity damping/excitation depends on disk parameters in a still poorly studied way. We estimate that the most important disk parameter is its Reynolds number, which varies by 2 orders of magnitude among the observed protostellar disks. This should result in exoplanetary systems exhibiting a transition from low to high e over a range of $m \sin i$ from 1 to 10 (or 20) Jupiters. Current searches do not yet yield reliable statistics of sub-Saturnian companions, whose eccentricities should be low if disk-planet interaction is of lasting importance in planet formation. It is also not yet known theoretically how large e might be generated (Papaloizou et al. 2001 obtain $e \sim 0.2 - 0.3$ in their models).

3.6. Masses: the puzzle of superplanets

Superplanets (a loose term for companions roughly 5 to 20 m_J) might, in principle, be small brown dwarfs (forming directly from collapsing molecular cloud) rather than planets (understood to be objects grown in a two-stage accretion process in protoplanetary disks). Why not adopt a definition of a brown dwarf based on mass ($>$13 times Jupiter's perhaps) and just call massive superplanets brown dwarfs? One reason *not* to do it is that naming a body brown dwarf may falsely suggest we know how it formed. A growing number of systems (like υ And, HD 168443, Gl 876) will surely be found, in which companions have very different masses and would have to be called stars/planets despite the apparently common origin.

The reasoning behind an idea of a disk viscosity-based mass limit for Jupiter (Lin & Papaloizou 1993) included an assumption that the gap is empty and impermeable. We have seen above that gaps are cleared somewhat earlier than previously expected. That would lead to a final planetary mass *smaller* than computed from the standard viscous criterion, and thus to problems with the explanation of massive exoplanets. However, gap impermeability has been questioned by Artymowicz & Lubow (1996). Lubow and Artymowicz (2000) summarized the remarkable permeability of almost-empty gaps around binary stars to gas flows from circumbinary disks. Non-axisymmetric flows (and accompanying wakes around the planet growing in a disk, seen in Fig. 2) are a very robust phenomenon and are *not* restricted to eccentric binary systems or stellar mass ratio systems. In fact, a Jupiter in a standard minimum mass solar nebula (with viscosity $\alpha > 10^{-3}$) would double in mass in less than 1 Myr (Artymowicz et al. 1998; fig. 1 of Lin et al. 2000). Results of a number of different hydrodynamical codes, from SPH to ZEUS-type codes (Lubow et al. 1999, Bryden et al. 1999, Kley 1999) and PPM (fig. 2), are supporting a general conclusion: a protoplanetary disk must be extremely non-viscous ($\alpha < 10^{-4}$) to prevent Jupiter from growing further.

However, limiting mass by invoking low viscosity clashes with empirical requirements based on accretion rates (footnote 2 above). A typical disk with $\alpha \sim 10^{-2}$ and lifetime $>$1 Myr can form a 10 m_J (super)giant planet. Thus, either we do not understand correctly the accretion rates in T Tau disks, or for some reason our calculation do not capture the physics or timing of exoplanet formation (most of which are not superplanets, after all). This is a basic unsolved problem, which will grow more obvious if and when Neptune-class exoplanets are discovered in large numbers.

4. Back to Jupiter

We sketched some old and new theories accounting for the amazing variety of planets in nature. Some mechanisms, such as migration and eccentric instability of orbits, constituted an old (pre-1995) *prediction*. While new ingenious theories help us interpret exoplanets, we must not forget about planets close to home. The ice boundary lost its predictive power for the location of Jupiter, because of (i) smaller than previously thought jump in surface density of solids across the boundary, evidenced by a rather modest 25% to 50% mass percentage of ice in comets (previously thought of as only slightly dirty ice), and (ii) effectiveness of migration across any predefined boundary. The concept of viscosity-dependent mass limit was replaced by a more uncertain and much higher estimate of achievable planet mass. Finally, disks were intuitively thought of being able to circularize planetary orbits because of their "dissipative nature", a wrong idea since planets have large mass/area ratio and are oblivious to gas drag. This idea died (or should have died) when it was realized that eccentricities can easily result from gravitational interactions of many sorts. We tasted the knowledge (about the reasons for exoplanetary diversity) but lost a paradise (some paradigms about the solar system formation).

This loss is not a serious problem if we accept that planetary systems like our own, while abundant (up to 10^{20} may exist in the Universe, 10^6 new ones born every hour), are nonetheless not "typical". A natural explanation of properties of Jupiter, Saturn, Uranus and Neptune is provided by the late timing of their formation with respect to the dissipation of the primordial solar nebula. For instance, early photoevaporation of the solar nebula by nearby massive stars might provide the explanation of why these planets, if they formed in the sequence mentioned above, captured decreasing amounts of nebular gas.

5. A rapid migration mode

It is a common knowledge that forming planets induce a structure (e.g., gaps) in the surrounding disk. If theory described in this section is correct, then there is an opposite link as well: preexisting radial disk structure (e.g., the dense non-magnetized zones) are very special places, saving planets from early demise due to inward migration.

5.1. Corotational flows and migration

Several reviewers of disk-planet interaction in the recent volume known affectionately as PPIV (Mannings et al. 2000) emphasised that less is known about CRs (corotational resonances) than LRs (Lindblad resonances), and maybe therein lies a salvation from the curse of rapid inward migration that, among others, endangers the survival of planetary cores, as well as large protoplanets in disks. We have studied this possibility in 2-dimensional fully nonlinear disk models with embedded and freely evolving planets. The results, to be presented in detail elsewere (Artymowicz & Peplinski 2004), do indeed provide a glimpse of what might be a radically changed picture of planet migration.

Corotational region an annulus around the planet's orbit of width comparable with the Roche lobe size. There, the gas from the disk can librate, i.e. corotate on the average with the planet, on the horseshoe and tadpole orbits or similar (both being closed in the frame uniformly rotating with a circular motion of the planet, but tadpole being closer to the L4, L5 triangular equilibrium Lagrange points). As we have already discussed, it can also flow between the inner and outer disk parts. Theory of corotational resonances exists (Goldreich & Tremaine 1979), but cannot be applied to the situation we study, where a rapid migration of a planet influences the flow pattern of gas around the planet and destroys any symmetry of the flow (inwar bound vs. outward bound).

Corotational region torques can be one whole order of magnitude stronger than those due to LRs, if the disk has substantial radial gradient of surface density. In the extreme case of a planet interacting with a one-sided disk (for instance a hot jupiter in a magnetically created inner disk cavity around a magnetized star has only an outer disk to interact with), LRs produce a negative torques on the planet. It is equal and opposite to the increase of the angular momentum by a gas parcels making close approaches to the planet. This phenomenon can be described in terms of impulse approximation (Lin & Papaloizou 1993).

If, however, the gas parcel is able to make a U-turn on a horseshoe-type orbit (w.r.t. planet) then it would lose orbital separation from the star (and the angular momentum) 10 time more efficiently (depending on the Roche lobe size, CR region is about 5 times the Roche lobe radius), and hence generate a much more efficient *outward* migration of a planet. Similarly, if the gas ends up on the planet itself, a smaller but still large, positive contribution to migration rate results.

Figure 3 shows two snapshots from a simulation of a migrating jupiter. Initial position of the planet is in the middle of a smooth transition between a dense inner disk and a low-density outer disk. This arrangement causes a strong, negative corotational torque connected with the outward flow of gas along a U-turn path, recorded in the left panel on the figure. After just 10 orbits, the planet spirals visibly inward (right panel has a smaller star-planet separation, at the same pixel scale in both panels). It continues at a steady rate, despite the fact that it now travels through an initially zero-gradient disk region. This process is not unlike the “sinking satellite” drift in the dynamics of galactic mergers.

An oppositely directed, outward migration through a disk with initial zero surface density gradient can be initiated if the dense disk is initially placed outside, rather than inside the orbit of the planet (Figure 4). Again, as in the previous calculation, an underdense region is found near the planet, in the direction of motion in case of inward migration and vice versa. This region is populated with orbits approximately closed in the frame corotating with the planet, thus trapping the initial amount of gas on such orbits in libration with the planet. The trapped gas is underdense, compared with the disk region into which the planet migrates. We tentatively identify the driving force (or, more specifically, torque) for the rapid migration with the azimuthal asymmetry of the gas density in front and behind the planet, also causing an asymmetric gas distribution near and withing the crucial Roche lobe region. It is straightforward to see that the sign of the torque generated by the asymmetry always supports migration (negative torque in fig. 3, positive in fig. 4). If the trapped region is an engine of migration, it is a curious one for it seems to run on vacuum (or, at least, underdense gas).

5.2. Implications of rapid migration

The migration presented in Figs. 3 and 4 is frighteningly rapid, perhaps deserving a name ”runaway migration”. In our simulations, the disk had the surface density typical of a solar nebula only twice as dense as the minimum solar nebula at the location of Jupiter. Inner, unform disk at the initial unperturbed density would have a mass of 4

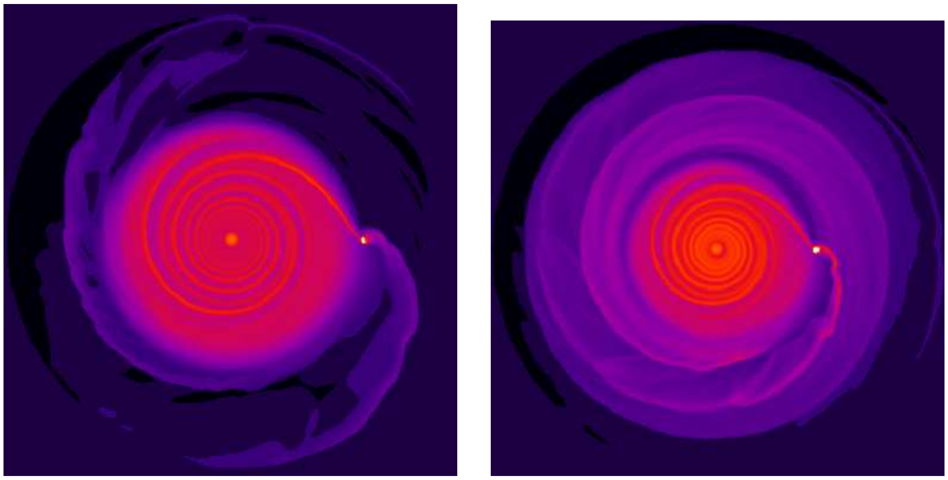

Figure 3. Cartesian-grid PPM simulation of an inward-migrating jupiter. *Left panel:* Surface density after 2.4 orbital periods. Planet was initially located at the outer edge of the disk. *Right panel:* The same, after 10 orbital

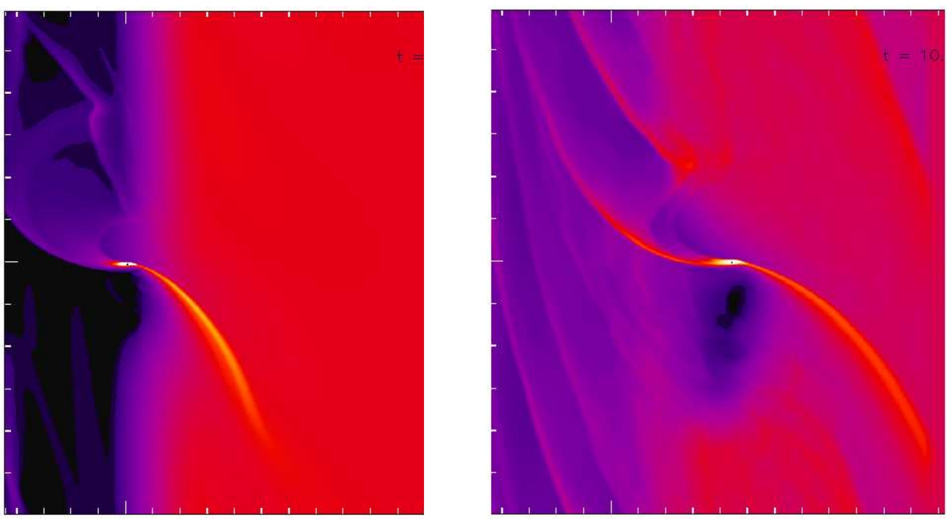

Figure 4. Corotating polar grid calculation of a migrating planet (small dot in white surrounding areas) using PPM hydrodynamics. Horizontal axis shows radius marked with 0.1a ticks. Vertical axis represents azimuthal angle, with 30 degree tick spacing. *Left panel:* Surface density around a Jupiter-mass protoplanet, after 1 orbital period in a solar nebula initially located mostly outside the planet. *Right panel:* The same after 10 orbital periods. Notice outward migration (to the right) and formation of underdense region behind the planet (below it, in our figure.)

Jupiters. Orbital radius changed on time scale of about 30 orbital periods. (Large variation of this quantity can be obtained for different starting radii and different nebulae.) Instead of curing the migration problem of the standard LR-based theory, corotational flows only seem to exacerbate the problem! There is, however, a silver lining. The rapid migration mode is very sensitive to the radial structure of the disk, and should be stopped/reversed if appropriate density gradients are encountered. This suggests that perhaps it is time to abandon the simple models of the protoplanetary disk utilizing power laws of radius, and consider a more realistic non-uniform radial disk structure. The latter can be caused by the insufficient ionization of the bulk of matter in the so-called dead zone, where magnetorotational instability ceases, and the resultant large effective viscosity of gas leads to its buildup. The dead zones in protoplanetary disks may appear anywhere from 0.1 to 10 AU from the star, and may not be time-stationary (Balbus & Hawley 2000, Armitage et al. 2001). That is where most of the known exoplanets reside, perhaps not by coincidence. The inner edge of the dead zone provides a favored place for an inwardly migrating planet to stop, or even reverse the migration. This could have important implications for the scenarios of planet formation.

Anther novel result, that the protoplanets can migrate outwards almost as easily as inwards, simply due to initial conditions, can also have important applications to transitional disks with apparent gaps at large radii. Although it is unlikely that such gaps are caused by planets forming as far as hundreds of AU away from stars, planets could, in principle, migrate there from the inner several AU. Could this be the correct explanation of the tantalizing gap-like region with spiral structure in HD 141596A, recently imaged with the Advanced Camera for Surveys onboard HST (Clampin et al. 2002)?

As a caveat, we stress that our calculations so far were limited to 2-dimensional disk models, and need to be verified in 3 dimensions, as well as include better disk thermodynamics (PPM models of Artymowicz and Peplinski (2004) assume a locally polytropic gas with a prescribed temperature profile, and do not calculate radiation transfer explicitly.)

6. Disk fragmentation: alternative to core accretion?

A percieved problem of long formation timescales for giant planets in the standard core-accretion scenario has prompted a second look at an old idea of rapid giant gaseous planet formation by disk fragmentation (Boss 2001 and references therein). However, the long timescale problem may not exist (e.g., Lissauer 2001), and/or would be easily curable by adopting a sufficient mass of the disk (smaller than required for fragmentation). The disk fragmentation model, in turn, has its own problems. Notice, for instance, that existing models typically begin with disk configurations which are known in advance(!) to be *unstable* to axisymmetric perturbations, but lack convincing proof of why and how the disk would find itself in such precarious state. We know that the approach to an unstable configuration would have to occur rapidly to be successful, on orbital time scale. Disks are known to defend themselves from a slowly approaching Safronov-Toomre gravitational instability, e.g., when their mass is being augmented slowly. Like the observed galactic disks and correctly modeled protostellar disks, by launching mass-transferring open spiral waves they tend to stay close to but on the safe side of the instability (Laughlin & Bodenheimer 1994, Nelson 2000). Core accretion may, after all, still the best bet. Better understanding of migration will result in new formation scenarios, giving a better fit to observed variety of exoplanets.

7. Concluding remarks

Exciting discoveries have been made revealing the existence and diversity of planetary systems around stars, from dusty disks made of planet-building rocks (crushed to sand and dust), to the giant and supergiant planets causing a detectable stellar wobble. It is still too early to conclude how exoplanets normally form, or even what kind of planetary systems constitute the norm.

Some of our prior theories of Jupiter formation have been questioned, as an indirect effect of the discovery of exoplanets. In this paper, too, we challenged the received wisdom of disks effectively repelling planets (Corotational flows have the opposite effect, thus tending to keep planets inside disks longer, where they have abetter chance to grow and survive).

This turmoil in the world of theory will surely be resolved in due time, contributing to a better understanding of both the solar and the extrasolar systems. A surmised unified, future theory will likely rest upon the familiar fundament of the accumulation of solid planetesimals and planets in a solar-type nebula, a model which right now finds beautiful confirmation in the observations of the evolutionary descendants of such nebulae, the transitional and replenished dust disks around a significant fraction of normal stars.

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References

Armitage, P. J., Livio, M., & Pringle, J. E., 2001, MNRAS, 324, 705-711

Artymowicz, P., Clarke, C., Lubow, S.H., & Pringle, J.E. 1991, ApJ, 370, L35-L39

Artymowicz, P., 1992, PASP, 104, 769-774

Artymowicz, P., 1993, ApJ, 419, 155-165

Artymowicz, P., 1997, Ann. Rev. Earth Planet Sci., 25, 175-219

Artymowicz, P., & Lubow, S.H. 1996, ApJ, 467, L77-L81

Artymowicz, P., Lubow, S. H., and Kley, W., 1998, in Planetary systems - the long view, Eds. Celnikier, L. et al., Editiones Frontieres, pp. 381-389

Artymowicz, P. 2000, in From Extrasolar Planets to Cosmology: The VLT Opening Symposium, Eds. J. Bergeron, A. Renzini, Springer Verlag, pp. 391-398

Artymowicz, P., & Peplinski, A., 2004, in preparation

Balbus, S., & Hawley, J., 2000, Space Sci. Rev., 92, 39-54

Black, D., 1997, ApJ, 490, L171

Boss, A., 1995, Science, 287, 360

Boss, A., 2002, proceedings of IAU Symp. 202, Manchester, UK, ASP Publications, in print

Bryden, G., Chen, X., Lin, D.N.C., et al. 1999, ApJ, 514, 344-367

Clampin, M., Krist, J. E., Ardila, D. R., Golimowski, D. A., et. al., 2002, ApJ, submitted

Dick, S.J., 1982, Plurality of Worlds, Cambridge U. Press

Duquennoy, A. & Mayor, M. 1991, A&A, 248, 485-524

Goldreich, P., & Tremaine, S. 1979, ApJ, 233, 857

Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425

Heap, S., Lindler, D., Lanz, T., et al., 2000, ApJ, 539, 390

Holman, M.J., & Wiegert, P.A., 1999, AJ, 117, 621

Kley, W. 1999, MNRAS, 303, 696-710

Koerner, D. W., Ressler, M. E., Werer, M. W., Backman, D. E. 1998, ApJ, 503, L83-L87

Lagrange, A-M., Backman, D., & Artymowicz, P., 2000, in Protostars and Planets IV, eds. V. Mannings et al. (Tucson: Univ. Arizona Press), 703-730

Laughlin, G., & Adams, F., 1999, ApJ, 508, L171

Laughlin, G., & Bodenheimer, P., 1994, ApJ, 436, 335

Levison, H.F., Lissauer, J.J., & Duncan, M.J., 1998, AJ, 116, 1998-2014

Lin, D.N.C., & Papaloizou, J.C.B. 1979, MNRAS, 186, 799-830

Lin, D.N.C., & Papaloizou, J.C.B. 1993, in Protostars and Planets III, eds. E.H. Levy and J.I. Lunine (Tucson: Univ. Arizona Press), 749-835

Lin, D.N.C., Bodenheimer, P., & Richardson, D.C. 1996, Nature, 380, 606-607

Lissauer, J.J., 2001, Nature, 409, 23

Lubow, S.H., & Artymowicz P., 2000, in Protostars and Planets IV, eds. V. Mannings et al. (Tucson: Univ. Arizona Press), 731-755

Lubow, S.H., Seibert, M., & Artymowicz P., 1999, ApJ, 526, 1001-1012

Mannings, V., Boss, A. & Russell, S. (eds.), 2000, Protostars and Planets IV,(Tucson: Univ. Arizona Press), 1400 pp.

Marcy, G., et al. 2001, www.exoplanets.org

Mathieu, R. D., 1994, ARA&A, 32, 465-530

Mathieu, R. D., Ghez, A. M., Jensen, E.L.N., & Simon, M. 2000, in Protostars and Planets IV, eds. V. Mannings et al. (Tucson: Univ. Arizona Press), 703-730

Mayor M., Queloz, D., 1995, Nature, 378, 355-359

Nelson, A., 2000, ApJ, 537, L65-L68

Owen, T., & Bar-Nun, A., 1995, Icarus, 116, 215-226

Owen, T., Mahaffy, P., Niemann, H.B., Atreya, S., et al., 1999, Nature, 402, 269-270

Papaloizou, J.C.B., Nelson, R.P. & Masset, F., 2001, A&A, 366, 263-275

Schneider, J., 2001, www.obspm.fr/planets

Takeuchi, T., & Artymowicz P., 2001, ApJ, 557, 990-1006

Ward, W.R., 1997, ApJ, 482, L211-L214

Weidenschilling, S.J., Marzari, F., 1996, Nature, 384, 619-621

Weinberger, A. J., Becklin, E. E., Schneider, G., Smith, et al., 1999, ApJ, 525, L53-L56

Wolszczan A., Frail D.A. 1992, Nature, 355, 145-147