The race is not to the swift

Megan K Pickett and **Andrew J Lim** examine the role of spirals in protoplanetary disks and the formation of gas giant planets, and find that slower may be better than faster, if planets are to endure.

Abstract

One of the outstanding questions in solar system astrophysics is the formation of most of the planetary mass, i.e. Jupiter. The problem is of increased interest and importance with the accelerating discovery of extrasolar planets; by mid-2003, more than 100 'exoplanets' are known. All of these objects are presumably gas giants like Jupiter. Given the relatively high abundance of stars with planets (~10% of surveyed stars) after about a decade of dedicated searches, it would seem that Jupiters are commonplace. In this review we discuss the two leading ideas for gas giant planet formation: the traditional core-accretion scenario and the recently revived gravitational instability model. Given the severe flaws of the core-accretion model, particularly regarding time scale, we here focus on how gravitational instabilities, by transforming the early solar system gas disk into a complex network of spirals and spiral fragments, may have given rise to Jupiter and its extrasolar kin. Much of this work is necessarily numerical, employing sophisticated, extremely high-resolution, modern hydrodynamics codes run on high-speed computing platforms. Though we have learned much about the relevant physical processes at work in the early solar system, gravitational instabilities remain an uncertain but promising route to gas giant formation.

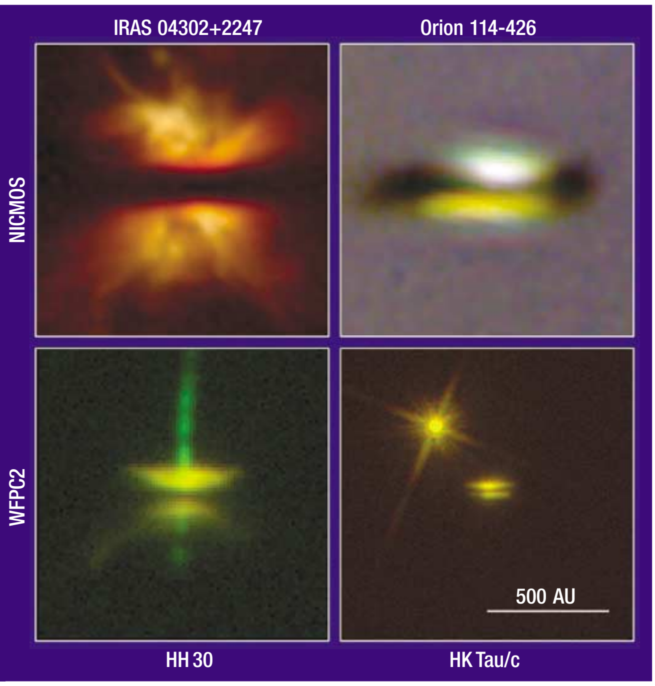
Theorists must yield to observations eventually. In the theoretical modelling of the solar system, for example, there are several convenient observational constraints on the imagination: most of the mass resides in a slowly rotating star; most of the angular momentum (or spin) resides in the planets; the planets orbit in the same direction about the Sun and in orbits that are largely coplanar; the age of the solar system is 4.6 Gyr or so, based on the radiometric dating of primitive meteorites. From these and other data, astrophysicists have constructed a standard model that explains the general characteristics of the solar system fairly well. In that model, the solar system formed about 5 Gyr ago from a placental cloud of gas and dust that was cold (on the order of 10–100 K), large (perhaps a tenth of a parsec across), and slowly rotating (but with large specific spin, i.e. large per unit mass). The cloud collapsed, perhaps triggered by the shock wave from a nearby supernova. Most of the mass, which was already concentrated towards the cloud's rotation axis, fell straight to the centre due to its low angular momentum. The remaining, higher angular momentum material rained down towards this central, growing protosun, but not directly; the large spin prevented direct accretion, and so instead the material fell into a growing circumstellar disk. Collapse probably lasted on the order of 100 000 years, and the disk, called the Solar Nebula, remained another few million years. It is from this disk that the planets somehow coalesced. Close to the forming Sun, where the temperatures were high enough to vaporize most volatiles, the terrestrial planets formed by the accumulation of silicon, iron, nickel and other refractory grains into progressively larger bodies. Far from the Sun, where it stayed cool enough for various ices to form, providing additional solid material for planet (core) building, the gas giants were born. Most of the remaining nebular material then dissipated, the thermonuclear fusion of hydrogen into helium started in the core of the Sun, and the remaining solid debris was incorporated into larger bodies, thrown into highly eccentric orbits, or incorporated, uncoalesced, in the asteroid and Kuiper belts. The result is the planetary system more or less as we know it today.

The above picture is the basic portrait painted for college students enrolled in introductory astronomy courses in the United States. Still, we are fortunate that we live in an age in which local observational constraints are not the only data available. Over the last two decades, for example, the astrophysical community has gone from debating the existence of protostellar disks – perhaps the solar nebulae for other stars – to imaging the disks themselves and, once again, speculating about the role they play in creating a planetary system (figure 1). Not only is it now widely accepted that many, perhaps most, young stars have disks around them, we now know of at least 110 extrasolar planets (e.g. Marcy *et al.* 2000). All of these planets are comparable in mass to Jupiter and so presumably are similar to the gas giants in our own solar system. The fact that most of these "exoplanets" lie much closer to their stars than Jupiter does to our Sun may be telling us something important about the dynamics of all solar systems. Indeed, theorists have shown that a growing gas giant planet can be rapidly dragged into its protosun (Lin and Papalouizou 1987, Bryden *et al.* 1999). Regardless of whether gas giant planets formed where they are currently found or migrated to their present locations, their most important features are that they exist, and that they exist in such numbers. Approximately 10% of surveyed stars have exoplanets, a number that is certain to increase as observations improve. Gas giant planets are more common than we could have guessed even 10 years ago.

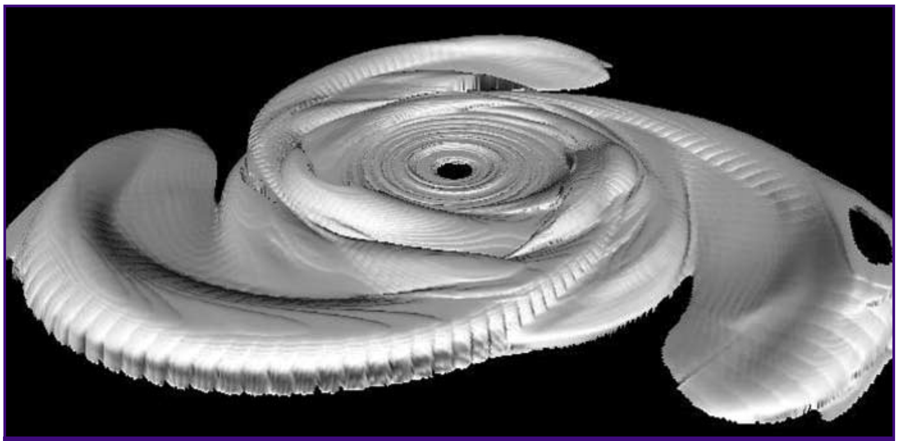
The tortoise and the hare

Nature, then, is pretty good at making gas giants. What is not exactly clear is how this happens. Theorists have examined two possibilities in detail, discussed here: the core-accretion model and the gravitational instability model.

The most widely accepted explanation for gas giant formation is the core-accretion model (Mizuno 1980, Pollack 1984, Pollack *et al.* 1996). In this scenario, solid material, including



1: A collection of Hubble Space Telescope images of protostellar disks seen in profile. In each case, the optically thick disk is the dark, horizontal lane; reflected light from the central star can be seen above and below the disk.



2: The surface of an evolved solar nebula model. The figure shows an isodensity surface for one of the author's simulations with strong (vertical) volumetric cooling and shock heating (Pickett *et al.* 2003). In this case, the initial model extends radially to 10 AU; the protosun sits in the centre of the grid and an inner gap separates the sun and the disk out to about 1 AU. The surface represents a density $\rho = 10^{-7}\rho_{max}$. Note the surface spirals and corrugations. Complex vertical structure will periodically intercept light from the star, with observational and dynamical consequences. The axial deformations are artifacts of the visualization software, but do indicate the approximate resolution of the numerical grid near the edge of the evolved model.

various ices, accumulates to form the future core of a gas giant planet. The same process is responsible for the formation of the terrestrial planets (e.g. Whetherill 1990). Once a trigger mass of about 10–15 Earth masses is achieved, the core rapidly gathers nebular gas; Jupiter, for example, contains at least 300 Earth masses of hydrogen and helium. The actual accretion of the core may take anywhere from about 10 to 100 million years, depending on model dependent parameters, particularly the local surface mass density of the disk (e.g. Pollack *et al.* 1996).

The core-accretion scenario has the great advantage of working, at least on paper. Nature may be another matter. Other authors have pointed to some of the difficulties with the model: gas giants like Jupiter may not even have appreciable cores (Guillot 1999); planetary migration, if it occurs, is a much faster phenomenon than planet building by accretion, and so the core of a proto-Jupiter would fall into the Sun before it could become massive enough to shut down migration, at least in a non-turbulent nebula (Nelson *et al.* 2000a); it is difficult to make objects more massive than Jupiter (Boss 2002). However, the single greatest defect, and one that is extremely difficult to fix, is that of timescale. Even as gas, dust and ice accumulate to form the protoplanetary disk around the young protostar, the race against time has started. We know, based on observations of young stars (e.g. Briceno *et al.* 2001), that stars older than about 10 million years do not have massive, optically thick circumstellar disks. Protoplanetary disks dissipate, and although the timescale for the disappearance of the disks is not entirely certain, it is on the order of or *smaller* than the timescale for core-accretion. Thus, by the time a core reaches the trigger mass, the nebular gas may have disappeared. There may be exposed cores of failed gas giants in the universe, but they are not among the extrasolar planets so far detected and, at any rate, their small masses make them invisible to detection by current spectroscopic methods. It is possible that Uranus and Neptune are examples of such objects, although they might owe their relatively small gaseous envelopes to photoevaporation from nearby, massive stars (Boss 2002).

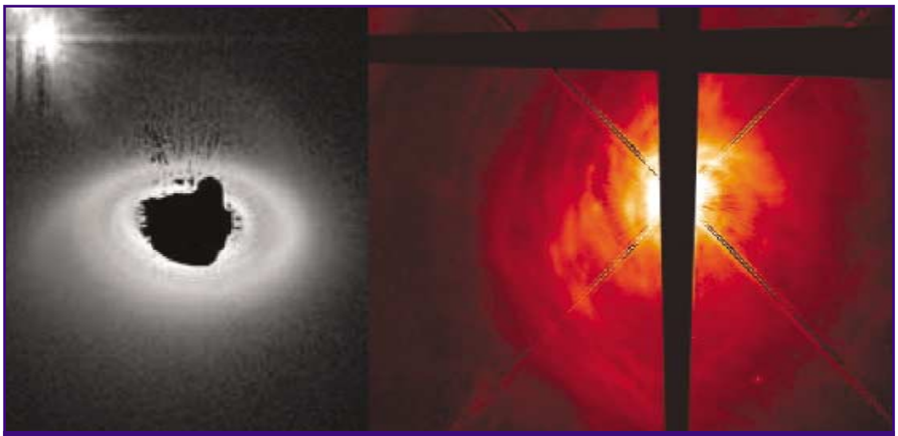
As standard models go, core-accretion is in serious trouble. However, until recently, there have been no serious alternatives. In a series of papers, Boss (1997, 1998, 2000, 2001, 2002) has rekindled interest in the idea that giants could form directly from disk gas via gravitational instabilities (GIs), a scenario first proposed more than 50 years ago (Kuiper 1951, Cameron 1978). According to this model, the protoplanetary disk becomes gravitationally unstable early in its development, when its mass is appreciable compared to that of the protosun. The manifestation of the GIs is non-axisymmetric structure, particularly trailing, multi-armed spirals. As spiral features intensify, and perhaps interact with each other, gaseous giant protoplanets (GGPPs) might congeal directly from nebular material. Since planetary core formation would then occur by the sedimentation of dust and ice into the growing gas spheres, the predicted core masses should be substantially lower than that needed in the core-accretion model (Boss 2002).

The conditions required for a disk to be unstable to the rapid growth of spiral structure depend on the disk's temperature, mass and rotation. Toomre (1964) first quantified this condition in his local stability parameter, Q:

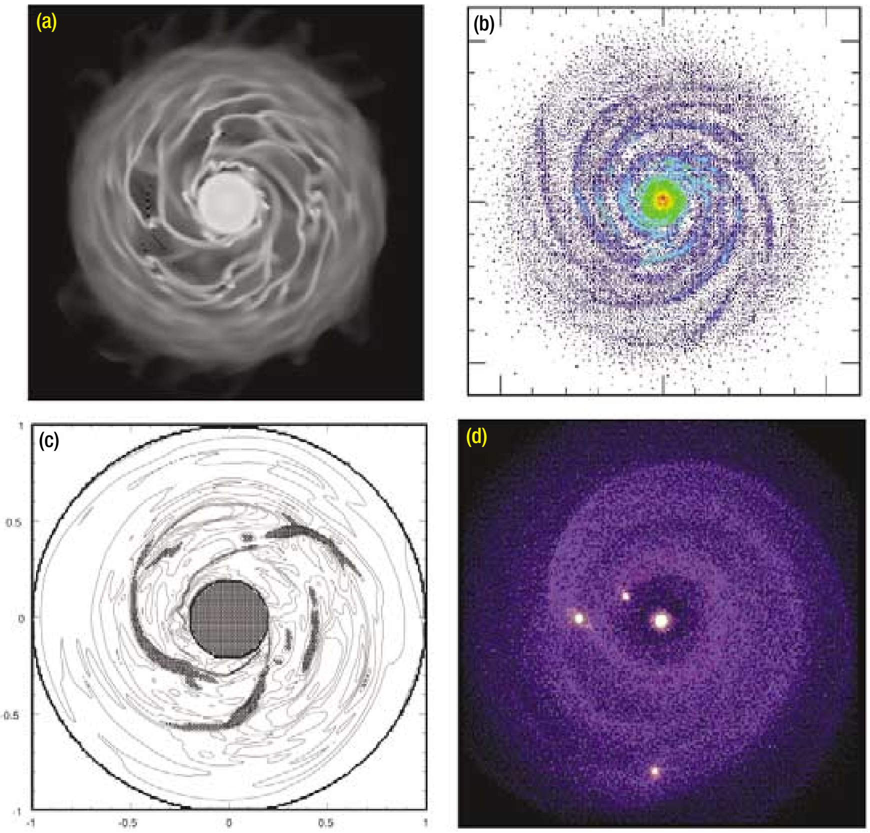
$$Q = \kappa c_s/(\pi G \Sigma).$$

Here κ is the epicyclic frequency, c_s is the adiabatic sound speed, G is the universal gravitation constant, and Σ is the surface mass density. The epicyclic frequency is the frequency of oscillation an orbiting particle exhibits if it is slightly perturbed, for example by interactions with other disk particles. In cold, nearly massless disks, where the disk pressure and self-gravity forces are negligible, the epicyclic frequency is essentially the orbital frequency. Toomre (1964) suggested that the disk should be gravitationally unstable to the growth of axisymmetric disturbances – rings – over narrow radial regions when $Q < 1$. In fact, numerical studies have shown that the Q parameter is also a good predictor of wide-scale, global instability. A disk can be expected to become gravitationally unstable to non-axisymmetric disturbances when the minimum value of the Toomre parameter $Q_{min} \sim 1.5$ or smaller (Pickett *et al.* 1998), i.e. when the denominator begins to dominate the numerator in the above equation. A disk can be stabilized, for example by high temperature (represented by large c_s). On the other hand, gravitational instabilities will grow rapidly if the disk is cold (low c_s) or massive (large Σ). An analogous process is thought to be responsible for the beautiful arcs of stars and gas seen in the grand-design spiral galaxies.

Dynamic, non-axisymmetric disturbances are versatile. Even if GGPPs are not formed in this way, these spiral waves are extremely efficient at transporting angular momentum and mass in the protostellar disks (Laughlin and Bodenheimer 1994, Pickett *et al.* 2000a, 2003). In our own simulations we have seen prodigious transport in both the positive and negative radial directions in the disk. Material spreading such as this could explain in part how disk gas is dissipated. In addition, inwardly moving gas that falls on to the central protostar may power FU Orionis outbursts, if the mass inflow rate is high enough (Bell *et al.* 2000). Spiral deformations are also an inherently three-dimensional phenomenon, causing significant vertical restructuring of the disk (figure 2). The resulting surface corrugations, which typically follow the underlying spiral features in the disk midplane, could have dramatic observational consequences, such as the periodic dimming of the central protostar (Durisen *et al.* 2003), orbital timescale variability in luminosity and spectral energy distribution (Nelson *et al.* 2000) or the production of linear chains of methanol masers observed near massive protostars (Durisen *et al.* 2001). The spirals might also be evident in images of the disks themselves, at least in principle. It is true that a few face-on protostellar disks exhibit wide-scale asymmetry (figure 3), though their nature and the origin of the non-axisymmetry is not well determined; it is not clear, for example, whether or not the structure is due to gravitational instabilities or embedded planets or shadowing because of outflows. Gravitational instabilities may occur in a variety of disks, and depending on the size scale of the collapsed spiral features, this mechanism may explain the formation of giant planets, brown dwarfs and perhaps some binary stars. It could even be that a first generation of planets formed around the first stars by gravitational instabilities; such planets, if they exist, would be difficult to explain using the standard core-accretion scenario, because few or no accretional building blocks would be available in the early universe.



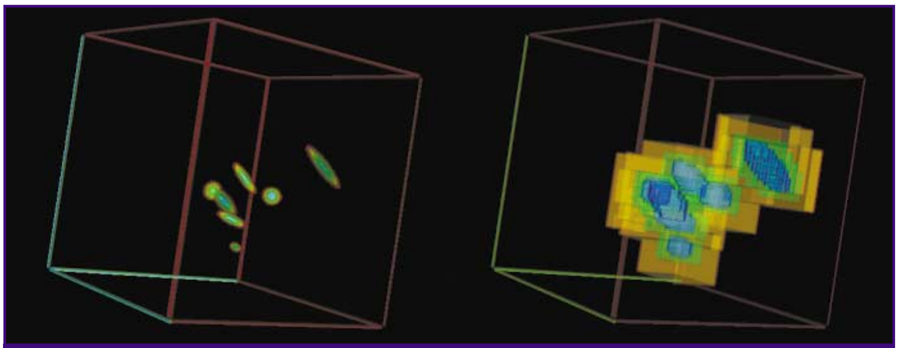
3: HST images of protostellar disks with non-axisymmetric structure. Left: The disk around HD 141569A (NASA, Clampin/Ford/Illingworth/Krist/Ardila/Golimowski, ACS Science Team, ESA). Right: The disk surrounding AB Aurigae. The light from the central stars has been removed artificially. Both stars are a few million years old (NASA, Grady/Woodgate/Bruhweiler/Boggess/Plait/Lindler).



4: Representations of midplane density for simulations of four different solar nebula models. (a) High-resolution locally isothermal simulation of the massive, cold star/disk system studied in Pickett *et al.* (2000a). (b) Surface mass density for the locally isothermal SPH simulation of a protostellar disk model from Nelson *et al.* (2000). (c) Equatorial mass density for the high-resolution solar nebula simulation with radiative physics in Boss (2002). The cross-hatched regions are areas of high overdensity (clumps). (d) Surface mass density of the locally isothermal SPH simulation in Mayer *et al.* (2002).

The most important feature of the GI scenario, however, is the counterpoint to the major failing of the core-accretion model: the time required to build a planet. Since the GIs are inherently dynamic phenomena, one would expect spirals to appear and grow on orbital timescales, i.e. 100s to 1000s of years, depending on their location in the disk. In fact, many simulations have shown just this (figure 4). It is one thing, however, for a disk to break into spiral arms, and another thing entirely for the spiral arms to produce Jupiters.

For this is the main detraction of the GI mechanism. Attractive as it is, both aesthetically and scientifically, this scenario has a problem that is hard to ignore: it doesn't seem to work. Simulations have shown that it is extraordinarily difficult for planets to congeal from the spirals in a disk model. While some theorists have shown that temporary condensations and knots of material can and do form, these blobs rarely complete more than, at most, a few orbits about



5: Adaptive mesh. **Left:** Density colourscale representing seven extended test masses. **Right:** The computational mesh used to evolve the test masses. Here, computational cell size decreases (resolution increases) with density. Blue cells are the smallest and correspond to the highest densities on the grid.

the central star. The exception seems to be a recent, smoothed particle hydrodynamics (SPH) simulation of a protoplanetary disk that produced long-lasting protoplanetary clumps, though under highly idealized conditions (Mayer *et al.* 2002). Often, tidal, thermal or rotational stresses in the disk are enough to rip apart potential protoplanets before they are fully formed (Pickett *et al.* 2000a,b). Gravitational instabilities are fast and furious, but it is not clear yet whether or not they make planets or just a mess.

Blanket in the wind

Assuming that core-accretion is seriously flawed and that no other alternatives exist, can the GI mechanism be made to work? What is needed to answer this question is a careful examination of all relevant numerical and physical issues that may affect the ability of spirals to make protoplanets that survive many orbits. This is the bread and butter of computational astrophysicists, and while such investigations often lead to greater understanding, they can be frustrating exercises. Often it can seem as if fixing one numerical problem produces others – like trying to spread a picnic blanket on a windy day: just when you get one corner down on the ground, the other three flap in the air.

In principle, numerical effects are straightforward to locate and fix. Perhaps the most significant is inadequate resolution. Interestingly, having poor grid resolution can lead to the artificial production of clumps in some cases (Truelove *et al.* 1998) and the artificial destruction of clumps in others (Boss 2001, Pickett *et al.* 2003). The main problem lies in the nature of the numerical game. A grid code solves the equations of hydrodynamics (the equations of motion, the mass continuity equation, the internal energy equation, if necessary) and Poisson's equation by approximating differentials as differences across zone boundaries. Different codes use different means of approximation, but the general approach is the same. How well a code performs boils down to how well the code approximates accelerations. If the resolution is too low, for example, the gravitational acceleration at the surface of a potential protoplanetary clump may be too low. As a result, the internal pressure of the clump overwhelms gravity, dispersing it before it gets a chance to pull together into a protoplanet. On the other hand, low resolution may also yield an approximation for the local gravitational acceleration that is too high, resulting in the artificial coalescence of a clump. Adequate resolution, therefore, is critical. Recent simulations (Boss 2001, Pickett *et al.* 2003) have shown that much higher resolution than is usually used may be necessary to characterize the ability of a disk to create and maintain small-scale density enhancements. The most straightforward way to achieve increased resolution is by decreasing the computational cell size everywhere in the numerical grid. Unfortunately this will also substantially increase the time required for a computation, perhaps beyond practical limits.

An alternative, more efficient, approach is that of adaptive mesh refinement (AMR). The resolution of an AMR hydrodynamics code varies across the simulation, the idea being to concentrate the computation in regions of the solution that are considered to be "interesting" by placing high-resolution (i.e. small) cells in these regions. Although in some cases it is possible to decide in advance where the high-resolution regions should be, in more complex situations such as that described here the adaptive algorithm must be able to analyse the solution during runtime and decide for itself where the resolution should be increased, decreased or remain the same. This results in a somewhat complicated piece of software, but the saving in computation can be orders of magnitude for large 3-D simulations. A typical example of the grid structure obtained is shown in figure 5. Of course, the effectiveness of an AMR scheme hinges on what the algorithm considers to be "interesting". Many approaches can be used, such as the time or space differentials of the gas variables, truncation errors between grid levels or multi-level analyses like Richardson Extrapolation. In solar nebula simulations, regridding may also be based on quantities such as the gradient of the gravitational potential, the local Jeans mass or the divergence of the gas velocity. Either way, an AMR code will succeed or fail based on the adaption criterion.

The identification and inclusion of all the relevant physical effects is an arduous task, but equally necessary. The fascinating thing about gravitational instabilities is what apparently controls them. It is not the disk's gravity, as you might expect, although that is largely responsible for the initial appearance of structure. Beginning in the early 1990s (Tomley *et al.* 1991, 1994), it became clear that the thermal balance of the disk is the key. If thermal energy is lost efficiently, spiral features appear and intensify, because the disk gas cannot readily resist further compression. Conversely, if disk gas can heat efficiently, dense structures can be dispersed by internal gas pressure. Thus, the effectiveness of the GI mechanism turns on the balance of heating and cooling in a disk, whatever the source. Despite the importance of this result, early simulations like the ones detailed in Tomley *et al.* (1991, 1994) used particle methods to evolve the gas disk, and consequently the thermal behaviour of the gas was only very crudely treated. Moreover, the simulations were of infinitesimally thin disks, and so ignored important vertical behaviour of gas, some of which could lead to local heating or cooling. This was also the case for earlier, related work on galactic structure (Hohl 1971, Sellwood and Carlberg 1984). More recent simulations, including our own, have begun to tackle the problem with 3-D hydrodynamic codes that have included a host of fluid behaviours.

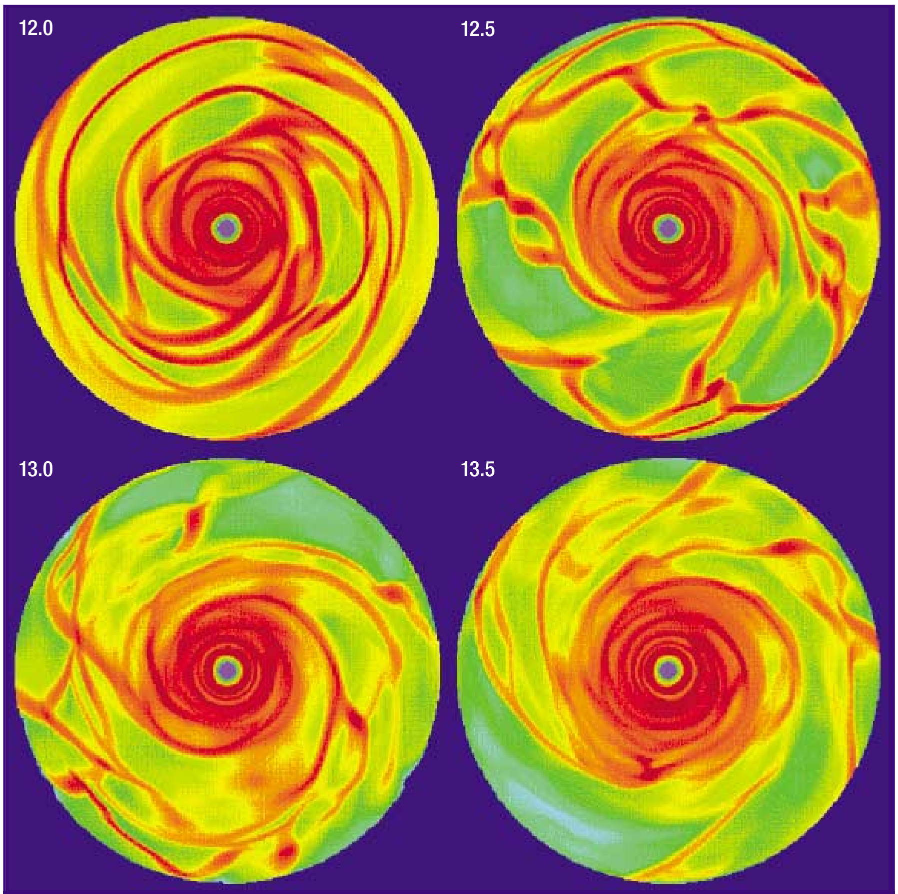
In principle, any process that heats or cools a disk will affect its stability. This is a somewhat surprising result and it means that the large-scale activity, i.e. planet building, is driven by local microphysics and chemistry. Such processes include shock heating from supersonically moving arms; the viscosity of disk gas; the association/disassociation and ionization/recombination of nebular gas, particularly hydrogen; grain and ice opacities; irradiation of the disk surface by the central star or neighbouring stars; the gravitational effects of neighbouring stars; and cooling by radiation. An accurate assessment of the viability of the GI mechanism will require the inclusion of these effects and other processes that affect the thermal energy balance of a protoplanetary disk at high resolution.

A disk full of Jupiters?

The research groups currently engaged in exploring the efficacy of the GI mechanism have generated an interesting and sometimes lively debate about the history of the early solar system, the growth and effects of gravitational instabilities, and the formation of Jupiter-like planets (most recently: Boss 2003, Nelson *et al.* 2000, Mayer *et al.* 2002, Pickett *et al.* 2003, Rice *et al.* 2003). The primary issue, that of the GI mechanism, is still in doubt, due in part to the seemingly contradictory results obtained by different groups using similar models. What most of the people working on the disk problem agree on is that a sufficiently cold, self-gravitating (i.e. low Q) disk will succumb rapidly to spiral deformations. If heating of any kind is inefficient compared to cooling, then the disk can be shattered into high-density spiral arms and spiral arm fragments in a few outer disk orbits; in fact, most of the material in such a disk will be located in these arms rather than the inter-arm gas (Pickett *et al.* 1998). What happens next is arguable, although again there is some common ground, namely the roles that heating and cooling play in the nonlinear development of the disk.

If the disks are sufficiently resolved and cooling overwhelms heating globally, or if there are no additional heating sources, such as shocks, stellar irradiation and so on, then several researchers have shown that the spirals and spiral fragments continue to collapse and eventually form energetically bound clumps of material – possibly future protoplanets (Boss 2002, Mayer *et al.* 2002). In some recent cases (Mayer *et al.* 2002), these clumps survive many orbits, and result in a system of gas planets that superficially resemble extrasolar planetary systems. Nevertheless it should be pointed out that: 1) an extremely idealized treatment of the gas thermal physics (local isothermality) was used, and 2) highly resolved simulations of similar models discussed in Nelson (2003) do not result in bound protoplanetary clumps. Furthermore, the permanence of a clump is not necessarily established by determining that its total energy is negative at one point in a simulation. A gravitationally unstable disk is a complex and violent environment, and interactions with remaining disk material and other clumps can throw a nascent "bound" planet into the central protostar or disrupt it completely (Pickett *et al.* 2000a).

On the other hand, additional heating sources can either prevent strongly nonlinear features from forming in the first place (Nelson 2000, Nelson *et al.* 2000, Pickett *et al.* 2000a,b) or diffuse spirals and clumps once they have formed (Pickett *et al.* 2000a, Pickett *et al.* 2003). Much of the current debate has now shifted to what exactly are the relevant heating sources and what are their appropriate strengths. For example, Boss (2003) has pointed out that when bulk viscosity, used to model supersonic shocks, is employed in his simulation, "clumps" still form – though the clumps are decidedly elongated (figure 4); only when the heating generated by shocks is artificially increased to 10 times the normal level do the clumps not form. This is somewhat at odds with previous simulations run with "normal" viscosity strengths (Nelson 2000, Nelson *et al.* 2000, Pickett *et al.* 2000a,b, 2003), and will require future comparative simulations between the groups, as has been done, to good effect, in the past (e.g. Boss 2000, Pickett *et al.* 2000b).



6: High-resolution volumetric cooling evolution from Mejia *et al.* (2003). Shown are snapshots of the equatorial plane density for a high-resolution (512 azimuthal zone) solar nebula simulation with volumetric cooling and shock heating. The colourscale spans 10 orders of magnitude in density, from red (highest) to blue (lowest). The cooling time here is only ¼ of an outer orbital period, or about 7.5 years. The time in outer rotation periods is shown in the upper right of each panel. The initially axisymmetric disk erupts into a complicated set of spirals, which eventually give rise to the formation of several high-density clumps (at times 12.5 and 13.0). By 13.5 outer rotation periods (400 years), the clumps have disappeared.

While it is true that shock heating has dramatic effects on the disk evolution, it is not the only thermal process that must be considered. Any process that converts one kind of energy into thermal energy, and vice versa, must be at least considered in dynamic evolutions of the solar nebula. A disk may experience local cooling, for example, if thermal energy is used to excite, ionize or disassociate disk species. The general state of the disk gas is captured by the equation of state, which may be a highly idealized approximation like the locally isothermal case (temperature is independent of time) to more complex equations of state that include several gas species in various states of excitation, ionization or association (Boss 2002, Durisen *et al.* 2003). Additionally, irradiation from the central star or radiation scattered from the placental envelope back on to the disk are potentially important – possibly the most important – contributors to heating the disk (Mejia *et al.* 2003). Boss (2002) has most recently argued that the most important cooling mechanism is vertical convection – something that is not seen in other simulations (Pickett *et al.* 2003). Of course, as numerical astrophysicists seek to include more and more of these physical behaviours in our disk simulations, the more computationally intensive they become, especially if they are done at the highest possible grid resolution, even more so if the grid is not adaptive.

Ring around the solar system?

Can gravitational instabilities make gas giants? Some of the latest simulations seem to suggest that the GIs are a promising route to exoplanets. Yet we are a long way from a complete, accurate accounting of all the relevant thermal processes. At the moment, the jury is still out.

A related question – in some ways a more important question – is: do protoplanetary disks even reach the stage of violent activity seen in

7: Equatorial density for the volumetric cooling solar nebula simulation in Mejia *et al.* (2003). The frame shows the midplane density near the end of a simulation. The colours represent temperature in degrees Kelvin, from 0 K (black) to 50 K (white). The central star is not in the image. Radiative cooling, irradiation from the central star and shock heating are included in the code physics. The box spans 80 AU on a side. Note the presence of two high-density rings near the inner edge of the disk. A third ring, exterior to the other two, is in the process of forming.

numerical simulations? In fact, a more quiescent evolution of the disk may be conducive to protoplanetary clump survival, if the clumps form and are somehow protected from violent disruption. Until recently, *all* numerical simulations used initial models with low Q – less than about 1.5, and for good reason. Marginally unstable models would need to be evolved over impractically long periods of time, due to the slower growth rates of any disturbances.

Presumably, a protoplanetary disk evolves from a stable state to a violently unstable state. For example, an initially hot, stable (high Q) disk should approach instability as it cools by radiation. Protoplanetary disks are probably self-gravitating at some point in their evolution; typical models of the solar nebula that are only somewhat more massive than the present planetary system are marginally unstable (Boss 2002). As the disk cools (decreasing c_s and therefore Q), it should first pass through a marginally unstable state, one that is not susceptible to violent instabilities, but one in which mass and angular momentum transport occur due to mild spiral activity. If this marginally unstable state is prolonged, the disk could evolve to a new quasi-stable condition, by-passing fragmentation altogether (Laughlin and Bodenheimer 1994). In this scenario, disk gas would be slowly dissipated by accretion on to the star, or ejection from the system, or, indeed, incorporation into already formed giant protoplanets.

We have recently conducted the first 3-D hydrodynamics simulations of a marginally stable disk that approaches instability by cooling (Pickett *et al.* 2003, Mejia *et al.* 2003). Our first simulations used a simple constant volumetric cooling function, i.e. one in which a specified amount of internal energy was extracted from the grid at every radius with a rate such that the cooling time was equal to two outer rotation periods everywhere (equal to about 60 years at 10 AU). Later, more sophisticated simulations have included radiative cooling and stellar irradiation. We see four general stages of disk evolution (figure 6): initial equilibrium, a burst of violent non-axisymmetric activity, notably a four-armed spiral, followed by the approach to a quasi-equilibrium state in which heating and cooling come into balance. The spirals and spiral fragments wrap increasingly and though clumps are produced, they are thermally or rotationally disrupted. We have followed this state for nearly 20 outer rotation periods in some cases. The final stage is ring development, which begins after saturation of the nonlinear structure. We typically see three dense rings appear and grow steadily in mass and density. In one simulation (Mejia *et al.* 2003), the rings formed at 4, 8, and 12 AU, and contained several Jupiter masses of gas (figure 7).

Could these rings represent yet another mechanism for the formation of giant planets? We are still investigating the nature of these rings, but they do appear in many calculations, and under different thermal assumptions. One possibility is that, even as the non-axisymmetric structure dies away in the main disk, these rings will continue to grow, until at some point they themselves become gravitationally unstable. The result, presumably, would be jovian-mass clumps in roughly circular orbits (Pickett *et al.* 2003). Interaction with disk material and each other may endanger these clumps, of course. Future simulations will be required to understand the dynamic nature of these regions. Another possibility is that the rings act as "dust collectors" – places where grains and ices can settle and accrete, safe from the violence of the disk (Durisen *et al.* 2003). This would represent a promising hybrid of the core-accretion and GI scenarios, a sort of GI-assisted core accretion. It may be, in the end, that the two competing mechanisms, flawed individually, will in combination be the answer to the question of Jupiter's origin. ●

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References

Bell K R *et al.* 2000 in *Protostars and Protoplanets IV* eds Mannings, Boss and Russell, University of Arizona Press, Tucson, pp897.
Boss A P 1997 *Science* **276** 1836.
Boss A P 1998 *Astrophys. J.* **503** 923.
Boss A P 2000 *Astrophys. J.* **545** L61.
Boss A P 2001 *Astrophys. J.* **563** 367.
Boss A P 2002 *Astrophys. J.* **576** 462.
Boss A P 2003 *34th Annual Lunar and Planetary Science Conference* abstract no.1075.
Bodenheimer P *et al.* 2000 *Icarus* **143** 2.
Briceño C *et al.* 2001 *Science* **291** 93.
Bryden G *et al.* 1999 *ApJ* **514** 344.
Cameron A G W 1978 *Moons and Planets* **18** 5.
Durisen R H *et al.* 2003 *Recent Research Developments in Astrophysics* **1** 173.
Guillot T 1999 *Planet. Space Sci.* **47** 1183.
Hohl F 1971 *Ap.J.* **168** 343.
Kley W and Lin D N C 1999 *Astrophys. J.* **518** 833.
Kuiper G P 1951 *Astrophysics: A Topical Symposium* ed. J A Hynek, McGraw-Hill, New York, pp357.
Lin D N C and Papaloizou 1987 *MNRAS* **191** 37.
Lissauer J J 1987 *Icarus* **69** 249.
Laughlin G and Bodenheimer P 1994 *Astrophys. J.* **436** 335.
Marcy G W *et al.* 2000 in *Protostars and Protoplanets IV* eds Mannings, Boss and Russell, University of Arizona Press, Tucson, pp897.
Mayer L *et al.* 2002 *Science* **298** 1756.
Mejía A C *et al.* 2002 *Scientific Frontiers in Research on Extrasolar Planets* ed D Deming, ASP Conference Series, in press.
Mejía A C *et al.* 2003 *Astrophys. J.* in preparation.
Mizuno H 1980 *Progr. Theor. Phys.* **64** 544.
Nelson A F *et al.* 1998 *Astrophys. J.* **502** 342.
Nelson A F *et al.* 2000 *Astrophys. J.* **529** 357.
Nelson A F 2000 *Astrophys. J.* **537** L65.
Nelson A F 2003 *Scientific Frontiers in Research on Extrasolar Planets* ed D Deming, ASP Conference Series, in press.
Nelson R P *et al.* 2000a *MNRAS* **318** 18.
Pickett B K *et al.* 1998 *Astrophys. J.* **504** 468.
Pickett B K *et al.* 2000a *Astrophys. J.* **529** 1034.
Pickett B K *et al.* 2000b *Astrophys. J.* **540** L95.
Pickett B K *et al.* 2003 *Astrophysical J.* **590** 1060.
Pollack J B 1984 *ARAA* **22** 389.
Pollack J B 1996 *ARAA* **22** 389.
Pollack J B *et al.* 1994 *Astrophys. J.* **421** 615.
Pollack J B *et al.* 1996 *Icarus* **124** 62.
Rice W K M *et al.* 2003 *MNRAS* **339** 1025.
Sellwood S L and Carlberg R G 1984 *Ap.J.* **282** 61.
Tomley L *et al.* 1991 *Astrophys. J.* **382** 530.
Tomley L *et al.* 1994 *ApJ* **422** 850.
Toomre A 1964 *ApJ* **139** 1217.
Truelove J K *et al.* 1997 *Astrophys. J.* **89** L179.
Weidenschilling S 1977 *MNRAS* **180** 57.
Whetherill G W 1990 *Ann. Rev. Earth Planet. Sci.* **18** 205.