Forming giant planets via fragmentation of protoplanetary disks

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ABSTRACT

The evolution of gravitationally unstable protoplanetary gaseous disks has been studied using three dimensional smoothed particle hydrodynamics (SPH) simulations with unprecedented resolution. We have considered disks with initial masses and temperature profiles consistent with those inferred for the protosolar nebula and for other protoplanetary disks. We show that long-lasting, self-gravitating protoplanets arise after a few disk orbital times if cooling is efficient enough to maintain the temperature close to 50 K. The resulting bodies have masses and orbital eccentricities remarkably similar to those of observed extrasolar planets.
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About 100 extrasolar planets have been detected by the wobble they induce on their star\(^1\),\(^2\). Their masses range from about one Jupiter mass (\(M_J\)) to more than 10 \(M_J\) and have orbits ranging from nearly circular to very eccentric. In the standard core-accretion model giant planets might require longer than 10\(^6\) years to form\(^3\),\(^4\), which could exceed observed disk lifetimes (5 – 7). In particular, more than 80% of the stars in the Galaxy probably formed in dense clusters like those in the Orion nebula\(^8\) where the ultraviolet radiation of bright stars can ablate the gaseous disk in far less than a million years\(^5\),\(^6\). Hence giant planet formation must occur quickly or such planets would be rare. Even in the case where a large solid core is assembled rapidly enough, torques acting between the disk and the protoplanets are believed to induce its complete inward migration in a few thousand years\(^9\),\(^10\) — planets could sink towards the star before being able to accrete the large gaseous masses observed\(^11\),\(^12\). Alternatively, giant planets could coagulate directly in the gas component as a result of gravitational instabilities in a cold disk with a mass comparable to that adopted in the core-accretion model\(^13\),\(^14\). Simulations done with codes that solve the hydrodynamical equations on a fixed grid show that slightly perturbed disks form strong spiral arms and overdensities at \(R > 10\) AU\(^15\),\(^16\) where the temperature can be lower than 60 K\(^17\),\(^18\). The trigger of the instability might come from material of the protostellar cloud infalling onto the disk\(^13\). If these condensations are long-lasting and can contract to planetary densities, gravitational instability would be the prevailing formation mechanism for giant planets because it takes less than a thousand years\(^13\),\(^15\). Solid cores with masses as low as currently estimated for Jupiter (between 0 and 10 Earth masses\(^19\)) could then form inside the gaseous protoplanets due to dust and planetesimals driven there by local pressure gradients in a few thousand years\(^20\).

However, due to the limitations of the techniques, simulations have not yet been able to show convincingly that the overdensities are not sheared apart by the tidal field of the star, nor that they can collapse into protoplanets\(^16\). One needs to achieve a high spatial resolution for such a purpose. Smoothed particle hydrodynamics (SPH) simulations\(^21\) describe the gaseous medium as a collection of particles and can follow arbitrarily high densities. Disks have been simulated with this technique in the past but with less than 10\(^5\) particles\(^22\) – \(^24\); with such a low mass resolution the evolution of the density distribution is considerably noisy and artificial fragmentation can take place\(^23\).

Here we report on the results of new 3D SPH simulations of marginally unstable disks of molecular hydrogen using as many as 1 million particles. The disks extend from 4 to 20 AU initially and are in nearly
keplerian rotation around a solar mass star represented by a point mass. They have a minimum Toomre Q parameter of either 1.4 or 1.75, and masses of, respectively, 0.1 and 0.08$M_\odot$ (see caption of Fig.1 for details). In the initial stage the disks are evolved using a locally isothermal equation of state; the initial temperature decreases with radius following a power law profile predicted by detailed calculations of thermal balance between the central star, the disk and the protostellar cloud(17) and is then held fixed locally. This approximation is based on the assumption that the cooling time is so short that the disk radiates away any thermal energy injection on a time-scale shorter than the orbital time. This seems to be supported by recent grid-based simulations that include radiative transfer in the diffusion approximation(16) but neglect the irreversible heating that can be generated by shock waves in a strongly unstable disk(25, 26). While further investigation on the balance between heating and cooling in realistic disks will be needed in the future (26), here we concentrate on showing that actual protoplanets can form if the disk remains cold long enough(27).

After $\sim$ 150 years, corresponding to about 5 orbital times at a radius of 10 AU, the disks develop trailing spiral arms and local overdensities at $R > 10$ AU. In the lighter disk the spiral arms grow in amplitude up to about 300 years, and then they settle down to a nearly stationary pattern (Fig.1). In the most massive disk ($Q = 1.4$) a two-armed mode grows in amplitude up to the point where, after about 200 years, fragmentation occurs along the arms, and more than one distinct clump appears (Fig.1); then additional strong arms appear even at $R \gtrsim 7 - 8$ AU, and more clumps are formed. Inside this radius the disk is too hot for condensations to form. Clumps quickly contract, reaching central densities of more than $10^5$ times the local density in a matter of a few orbital times (tens of years). These condensations are self-gravitating, their masses being larger than the local Jeans mass (28), and easily resist stellar tides.

Such dense objects would be optically thick and would be unable to cool radiatively as efficiently as assumed by the locally isothermal approximation(16, 25). Therefore, we run again the same initial conditions changing the equation of state to adiabatic(29) as soon as the spiral modes approach fragmentation, namely when they reach a density around ten times higher than the initial local density(16, 26). The equation of state is changed throughout the disk. After 350 years non-axisymmetric features in the disk are weaker compared to the isothermal simulation, yet clump formation has proceeded. Nearly as many clumps as in the locally isothermal run are still present at $R > 10$ AU and have central densities still $10^5$ times higher than the local density. The clumps are rapidly rotating spheroids; assuming conservation of angular momentum, bodies of about a Jupiter mass would have a rotation period of a few hours if they were allowed to contract further and reach the density of Jupiter.
The masses of the clumps shortly after all of them are in place (after ~ 350 years) range from 1 to 5 $M_J$ (all gas at densities at least ten times higher than the initial local density is identified as a clump), comparable to the masses of extrasolar planets(1). Clumps formed along the same spiral arm collide and merge into a more massive object sooner or later. In addition, all clumps accrete gas from the disk and begin to clear gaps.

Time-steps can be as small as a few hours inside the clumps, and this slows down the simulation considerably. To keep following the clumps on a longer timescale we resort to simulations with a resolution 5 times lower. By 350 years 7 clumps with masses comparable to the largest among the 13 clumps present in the higher resolution simulation have formed and are then followed for about 1000 years. We run both a locally isothermal and an adiabatic simulation to determine the role of the thermal structure of the disk in shaping the dynamics of clumps.

Clumps are born on orbits with a wide range of eccentricities driven by the underlying strongly non-axisymmetric disk potential. These orbits then evolve in a variety of ways (Fig.2). The smoother disk in the adiabatic run leads to less eccentric orbits; also, the higher pressure of the gas reduces considerably gas accretion by clumps. Slightly more circular orbits reduce the rate of close encounters and mergers between clumps relative to the isothermal run. After nearly a thousand years three clumps are left in the adiabatic run (Fig.2) as opposed to two clumps in the isothermal run. These numbers are comparable to those of extrasolar giant planets in multiple systems(1). The masses of the surviving clumps, located between 3 and 20 AU, are in the range 2-6 Jupiter masses in the adiabatic case and twice as big in the isothermal case. Most of the clumps have orbits with final eccentricities between 0.1 and 0.3 (Fig.2) as many of the observed extrasolar planets (Fig.2). The simulated protoplanets enter a rather quiescent evolutionary phase (no more mergers occur) several orbital times before the end of the simulations. However, inward migration might continue on time-scales longer than those explored here(10 – 12), and orbits can also change due to interactions between the planets(30).

This work shows that gravitational instability can actually form self-gravitating protoplanets and that long-lived systems with masses and orbits consistent with those of extrasolar planets arise. All this requires is to start with a marginally unstable disk ($Q_{\text{min}} = 1.4 – 1.5$) in which radiative cooling is efficient during the initial growth of the overdensities. We tested that hotter disks starting from a considerably higher $Q_{\text{min}}$ ($\sim 2$) can also become strongly unstable and form clumps if they are slowly cooled to temperatures comparable to those used in the disks that start with $Q_{\text{min}} \sim 1.4 (31)$. Therefore, clump formation does
not depend on how the disk reaches the state used in our initial conditions. Ice giant planets, like Uranus and Neptune, might also be formed by the same mechanism after a strong ultraviolet flux from nearby bright stars has photoionized the envelopes of protoplanets more massive than Jupiter, leaving a mostly metallic core\(^{(20)}\). Because instabilities occur quickly, future observations of planets around very young stars will be a test for this model. In addition, direct imaging of giant planets at large distances \((R > 50 \text{ AU})\) from the stars\(^{(32)}\) could also provide support to this model; as the outermost regions of the disk would be even cooler (and surface density and angular velocity fall equally with radius, i.e. as \(r^{-3/2}\)) \(Q\) will be still decreasing at \(R > 20 \text{ AU}\), and thus fragmentation should occur out to these large distances.

On the contrary, Jupiter-like planets would not form at such large distances in the core-accretion model because coagulation of planetesimals into a solid core would take too long with the small surface densities involved\(^{(33)}\). Future observations of the gaseous medium in disks at different evolutionary stages, for example with the Space Infrared Telescope Facility (SIRTF), will help constrain the evolution of disk structure and will show whether it is consistent with the gravitational instability picture.
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27. Artificial viscosity is used in both the momentum and energy equation but its contribution is minimized when the local flow is purely shearing by means of a correction term originally introduced by D.S. Balsara (*Comp. Phys.*, **121**, 357 (1995)); the latter term is necessary to prevent SPH from generating a large artificial viscosity in a purely shearing flow. In addition, when the disk evolves following a locally isothermal equation of state any entropy generated by the viscosity term is assumed to be instantly radiated away.

28. The Jeans mass is always resolved by more than several thousand particles at the locations of the clumps; this resolution is more than an order of magnitude higher than required to avoid artificial fragmentation based on the criteria developed by M. Bate, A. Burkert (*Mon. Not. R. Astron. Soc.* **288**, 1060 (1997)) for three-dimensional SPH simulations.

29. In this regime reversible heating arising from compressions is not radiated away and the artificial viscosity creates irreversible heating in regions where shock waves occur.

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31. For this test we increased the temperature of the most massive disk model (resolved by 200,000 particles) by a factor of 2, reaching 100 K in the outer region; 350 years after the start of the simulations the disk was still fairly axisymmetric and we started cooling it at the constant rate of about 0.2 Kelvin/year. The disk underwent increasingly strong spiral instabilities as it was cooled down; these produced an inward flux of mass and outward flux of angular momentum but overall the outer surface density did not change significantly. Therefore, reaching a temperature only slightly smaller than that used in the standard initial conditions (42 K as opposed to 50 K) was enough to compensate for the decrease of surface density and give rise to clump formation after about 650 years (cooling was stopped when fragmentation was approached).

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Fig. 1.— Snapshots of the simulations showing the protoplanetary disks seen face-on at different times. The colour-coded density on a logarithmic scale is shown out to 20 AU. Brighter colors trace higher densities; the density ranges between $10^{-14}$ and $10^{-6}$ g/cm$^3$ is shown using a logarithmic
scale. The evolution of two disks having a different initial minimum Toomre $Q$ parameter, $Q_{\text{min}}$, are shown. The Toomre parameter at a given disk location is defined as $Q = \frac{\Omega v_s}{\pi G \Sigma}$, where $\Sigma$ is the gas surface density, $\Omega$ is the angular velocity, $G$ is the gravitational constant, and $v_s$ is the sound speed, $v_s = \sqrt{\frac{P}{\rho}}$, where $P$ is the pressure and $\rho$ is the density of the gas. Disks have a surface density profile $\Sigma \sim r^{-3/2}(12)$ and temperature profiles as in Boss$(9 - 11)$. $Q$ reaches its minimum at $R > 10$ AU, where the temperature is as low as 50 K, while $Q > 4$ close to the inner disk boundary, where the temperature is around 650 K. The two upper panels show the disk with initial $Q_{\text{min}} \sim 1.75$ ($M_{\text{disk}} = 0.08 M_\odot$) at $T = 160$ yr (left) and $T = 350$ yr (right), while the two lower panels show the disk with $Q_{\text{min}} \sim 1.4$ ($M_{\text{disk}} = 0.1 M_\odot$) at $T = 160$ yr and $T = 350$ yr. Gravity is softened on scales of 0.06 AU for disk particles. The central stellar potential is exactly keplerian at 2.5 AU and it is softened on smaller scales to speed up the computation. Both the central star and the inner disk boundary are free to move. The simulations were performed with GASOLINE, a parallel N-body/SPH code in which gravity is computed using a binary tree$(34)$. 
Fig. 2.— Late stage of disk evolution. On top a face-on view of the disk after 800 years is shown for the 200,000 particles simulation in which the equation of state is switched to adiabatic after about 200 yr. The colour-coded logarithmic density (see Fig.1) is shown out to 25 AU. Three giant
protoplanets are left and their orbital evolution is shown in the plot at the bottom (thick lines) together with that of a clump from the simulation where the equation of state is kept isothermal (thin line). Each of the remaining clumps is the end result of a series of mergers; the orbital evolution of the most massive progenitor is shown. The complex combination of torquing by the non-axisymmetric disk and interactions with other clumps changes the orbital eccentricity and mean radius of the orbits. Overall the orbital evolution is considerably more complex than the nearly-steady inward migration expected in light, axisymmetric disks, eventually halting once the planet has cleared a gap(9 – 12).