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Impulsively triggered star formation

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Abstract. I contend that impulsively triggered star formation is at least as important as spontaneous quasistatic star formation regulated by ambipolar diffusion, and probably more so. To support this contention, I describe and discuss SPH simulations of (i) star formation triggered by colliding clouds and expanding nebulae (HII regions, stellar-wind bubbles, and supernova remnants); (ii) violent interactions between protostellar discs and the resulting genesis of binary systems and low-mass companions; and (iii) protostellar collapse induced by a sudden increase in external pressure.

1. Introduction

There are two well studied models for star formation which are essentially spontaneous, and in which the approach to instability is relatively quasistatic.

In the first model, due to Shu and co-workers (Shu 1977; Shu, Adams & Lizano 1987) a singular isothermal sphere collapses from the inside-out, giving rise to a constant accretion rate onto the central point-mass protostar. There are four critical problems with this model. (i) It has never been explained in detail - or demonstrated numerically - how nature might contrive to create a singular isothermal sphere in the first place (Whitworth & Summers 1985), let alone large ensembles of singular isothermal spheres ready to collapse more or less simultaneously to produce whole clusters of stars. (ii) The velocity fields generated by inside-out collapse are very different from the velocity fields inferred for candidate star-forming cores like L1544, from observed molecular-line profiles. (iii) Inside-out collapse from a singular isothermal sphere delivers a constant accretion rate, whereas the statistics of protostars seem to imply that the mean accretion rate onto a protostar starts high (in the Class 0 phase) and then decreases by about an order of magnitude into the Class I phase (André, Ward-Thompson & Barsony, 2000). In fact, the accretion rate may be episodic, with rapid accretion bursts interspersed with longer slower accretion periods. (iv) Inside-out collapse from a singular isothermal sphere leads to the formation of single stars, whereas most young stars are born in binary (and higher multiple) systems.

In the second model (e.g. Ciolek & Basu 2000) a magnetically supported (i.e. magnetically subcritical) core leaches flux by ambipolar diffusion until its central regions become magnetically supercritical and collapse to form a protostar. This model appears to reproduce the velocity fields observed in cores

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like L1544, viz. a subsonic inward velocity field in the outer regions and apparently static inner regions. It also delivers an accretion rate which starts high and then declines. However, the resulting time-scales for the various phases are then difficult to reconcile with the statistics of prestellar and protostellar cores. Additionally, no obviously subcritical cores have yet been found. And finally, this model, like the first has difficulty producing either binaries or clusters; basically the quasistatic approach to instability focuses the ensuing collapse too symmetrically on a single point.

It is therefore sensible to consider whether impulsively triggered star formation modes might reproduce the observed features of star formation more readily. This contribution explores that possibility. Not surprisingly, we find that impulsive triggers can co-ordinate the almost simultaneous collapse of many neighbouring clumps and cores, and can launch material directly into the non-linear regime of gravitational fragmentation. This greatly facilitates the formation of clusters, sub-clusters, binaries and higher multiples (cf. Pringle 1989). It also delivers velocity fields and time-varying accretion rates like those inferred from observation. The inevitable draw-back is that the parameter space of initial conditions proliferates. Therefore initially it is sensible simply to investigate the phenomenology of triggered star formation – rather than aiming for a completely predictive model. Indeed, such a model is not possible until (a) the initial conditions for star formation are much better constrained, and in particular the pre-existing density structure in the interstellar medium can be accurately modelled, and (b) the effective viscosity of interstellar gas is better understood and quantified. We note that these two uncertainties are related. If the interstellar medium is as lumpy as it appears to be, its effective viscosity is determined by the mean-free paths of its constituent lumps and may be very large. It is then not even desirable to obtain truly inviscid shocks between colliding clouds – let alone practical with SPH.

2. Cloud/cloud collisions

It has long been speculated that colliding clouds, or more generally colliding streams of interstellar gas, might trigger gravitational fragmentation and collapse – and hence star formation. We have explored this possibility by simulating low-Mach Number collisions between interstellar clouds, using Smoothed Particle Hydrodynamics (Turner et al. 1995, Whitworth et al. 1995, Bhattal et al. 1998). For simplicity, the clouds are modelled as truncated isothermal spheres, contained by the pressure of a hot rarefied intercloud medium. The structure of a cloud is then determined by its mass, its effective sound speed (i.e. its internal velocity dispersion, which is assumed to subscribe to Larson's relations (Larson 1981)), and the external pressure. The clouds which we model are stable individually, but if they collide supersonically they produce a shock-compressed layer; the collision is characterized by an impact parameter b and a velocity v. Significant fragmentation requires that the post-shock gas be cooler than the pre-shock gas, i.e. the shock must be strongly radiative. We impose this requirement by using a piecewise polytropic equation of state for the effective isothermal sound speed

$$a^2 = a_0^2 \left\{ 1 + (\rho/\rho_0)^{-1/3} \right\}, \qquad (1)$$

with $a_0 = 0.2\,\mathrm{km\,s^{-1}}$ and $\rho_0 = 3. \times 10^{-19}\,\mathrm{g\,cm^{-3}}$. This approximately mimics the expected thermal behaviour of protostellar gas at the densities with which we are concerned. The resulting shock compressed layer fragments whilst it is still contained by the ram pressure of the inflowing gas. As a result of this containment by ram pressure, the fragmentation wavelength λ is much larger than the thickness of the layer Δz, and the fragments are therefore well separated. Specifically

$$\lambda \simeq \left(\frac{v\, a_{\mathrm{layer}}}{G\, \rho_{\mathrm{cloud}}} \right)^{1/2} \simeq \left(\frac{v}{a_{\mathrm{layer}}} \right) \Delta Z\,. \qquad (2)$$

where a_{layer} is the effective post-shock sound speed in the layer, and ρ_{cloud} is the pre-shock density in the cloud (Whitworth et al. 1994a,b). The layer at first fragments into a network of filaments, and then into cores along these filaments. This is actually a generic feature of gravitational collapse and fragmentation, well known in cosmology: if collapse experiences less resistance in one dimension, or for some other reason gets ahead in that dimension, it tends to get further ahead. Here the main consequence is that cores grow by accreting material along the filaments (and not isotropically). Because of the sytematic angular momentum intrinsic to a collision at finite impact parameter, the layer and the filaments within it are tumbling and so the accretion along a filament has the effect of spinning up the core until it becomes rotationally unstable. Rotational instability is further promoted because the accreting material tends to be lumpy. The result is the formation of small-N subclusters of protostellar discs within the individual cores. Each sub-cluster contains, typically, 3-8 jostling protostellar discs. The whole ensemble of subclusters resembles an embryonic OB Association. Because of Eqn. (2), the individual cores, and hence also the subclusters which condense out of them, are well separated. Consequently the subclusters evolve in isolation to begin with. Later they disperse and merge with other subclusters, due to the overall lateral contraction of the layer.

It is rather hard to observe star formation triggered by cloud/cloud collisions. The typical velocities involved are quite modest, and not much greater than the internal velocity dispersion of an individual cloud. Indeed the colliding clouds may simply be clumps within a larger molecular cloud complex, in which case the relative velocity *is* the velocity dispersion of the molecular cloud complex. Moreover these velocities can only be measured if the collision is mainly along the line of sight, but in this case the star-forming layer is strongly obscured. Most importantly, by the time the new stars switch on, the collision is likely to be over and most of the relative kinetic energy of the two clouds has been dissipated. A possible case in point is W49N, where there is kinematic evidence for an ongoing cloud/cloud collision, and a compact cluster of HII regions with improbably short dynamical ages (implying very recent and close birth times).

There are however two indirect lines of evidence which strongly suggest that collisions are an important trigger of star formation. The first is that galaxies which are strongly disturbed by tidal interaction or merger appear to have higher than average rates of star formation; the inference is that the disturbance has

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perturbed cloud orbits and increased the rate of collisions between clouds. The second is that, in a disc galaxy the development of an exponential stellar disc appears to require approximate equality between the viscous time-scale and the time-scale for star formation. This equality is virtually guaranteed if a major part of the star formation is triggered by cloud/cloud collisions.

3. Expanding nebulae

An alternative – but phenomenologically rather similar – way of triggering extensive star formation is by means of expanding nebulae, i.e. HII regions (HIIRs), stellar-wing bubbles (SWBs), and supernova remnants (SNRs). Such nebulae can sweep up the surrounding gas into a dense shell, and if the column-density through the shell becomes sufficiently large – whilst it is still expanding supersonically – the shell fragments gravitationally. This is the basic mechanism invoked to explain sequentially self-propagating star formation, in which the massive stars of one generation excite expanding nebulae which sweep up the surrounding matter until it becomes unstable and collapses to form the next generation of stars (Elmegreen & Lada 1977). This is presumed to be occuring in, for example, Orion, M17SW, and on a grander scale in 30 Doradus.

The mechanism is similar to a cloud/cloud collision in that the shell is contained on its outer edge by the ram-pressure of the swept-up material, and consequently the fragmentation wavelength is much greater than the shell thickness and the fragments are well separated. Also fragmentation develops with the formation of filaments and then the formation of cores along the filaments. Nonetheless, there are two fundamental differences. First, the mechanism needs an initial generation of massive stars to get going; it cannot just grow from a small seed. Presumably this initial generation is likely to be formed following a cloud/cloud collision. Second, at least for the simple case of a nebula expanding into a homogeneous background medium there is no source of systematic angular momentum in the fragmenting gas – and hence no reason for the fragments to be spun up by accreting material with high specific angular momentum. However, this may be a rather artificial distinction to make, because in reality the medium into which a nebula expands is likely to be very clumpy, and so the effect of the expanding nebula will be to drive one clump into another. Hence on a small scale there will be lots of clump/clump collisions at finite impact parameter, similar to those described in the previous section.

4. Impulsive disc/disc and star/disc interations

The evolution of small-N subclusters of protostellar discs (like those which form from the rotational break-up of cores spun up by accretion in our simulations of cloud/cloud collisions) is likely to influence strongly the properties of binary systems (mass ratios, separations and orbital eccentricities). This evolution is essentially a competition between the internal evolution of an isolated protostellar disc, continuing infall onto the disc, and impulsive interactions between discs. The internal evolution of an isolated protostellar disc is driven by the redistribution of angular momentum, which results in the growth by accretion of the central young stellar object (YSO) and the spreading of the residual disc.

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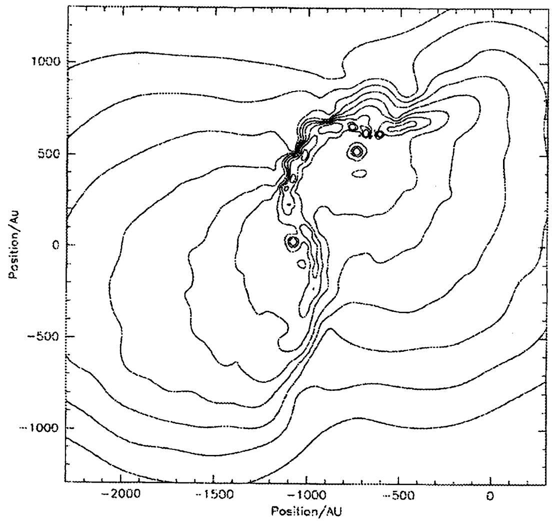

Figure 1. A coplanar collision between two discs with antiparallel spins. The filament swept up between the two discs fragments into numerous condensations, many of which survive as companions to the original protostars; one is ejected. The contours represent constant column-density at 5×10^{23} H_2 cm^{-2}, 10^{24} H_2 cm^{-2}, 2×10^{24} H_2 cm^{-2}, etc. (Boffin et al. 1998)

The protostellar disc may be replenished by continuing infall. Impulsive interactions between two protostellar discs, or between a single disc and a naked star, have the effect of accelerating accretion onto the central YSO. However, if the disc is sufficiently massive and the interaction is sufficiently violent, it can also create additional low-mass companions (Boffin et al. 1998, Watkins et al. 1998a,b). This happens when the discs collide and matter is swept up into a dense filament, which then fragments, producing low-mass companions. Violent interactions between protostellar discs are likely to be common in dense subclusters, and the process can repeat itself if the disc is replenished by continuing infall. Additionally the low-mass companions can grow in mass by accretion; in fact, if the infalling material has high specific angular momentum, it will be accreted predominantly by the low-mass secondaries, because they can accommodate high specific angular momentum more readily than the primaries. Moreover the mechanism can repeat itself hierarchically, thereby generating binary systems over a wide range of separations, in a more-or-less scale-free manner, and with a wide range of eccentricities – as observed in nature.

Figure 1 illustrates a simulation in which two counter-rotating discs have undergone a co-planar collision (a so-called spin-orbit mixed collision). Each disc comprises a $0.5M_{\odot}$ star surrounded by a $0.5M_{\odot}$ disc, which is just Toomre stable. The orbit is parabolic. The up-shot is that a dense filament is swept up between the discs, and we see it just as it has fragmented to produce several low-mass

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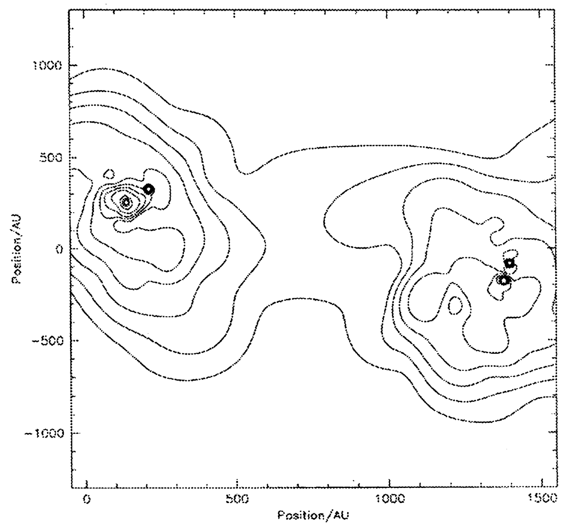

Figure 2. An hierarchical quadruple system formed by the collision of two massive protostellar discs. The collision was colpanar, and the spins were aligned, but this is not critical. The contours represent constant column-density at 5×10^{23} H_2 cm^{-2}, 10^{24} H_2 cm^{-2}, 2×10^{24} H_2 cm^{-2}, etc. (Boffin et al. 1998)

condensations. In interactions like this, some of the low-mass condensations end up being swallowed by the original protostars, some are tidally disrupted, but several survive, and many of these pair up to produce binary systems, either with one another or with the original protostars. In the case illustrated here, one of the primaries acquires a secondary, one remains single, two of the other low-mass fragments pair up to form a close binary, and one discless fragment is ejected. This ejectum should be identified with the diaspora of weak-line T Tauri stars seen around T Associations like Taurus-Auriga.

Figure 2 shows an hierarchical quadruple system formed as the result of a coplanar collision between two discs both having their spin axes aligned with the orbit (a so-called spin-orbit parallel collision).

We have displayed co-planar interactions because they are easier to vizualize. However, non-colpanar encounters have also been simulated (Boffin et al. 1998, Watkins et al. 1998a,b). From an ensemble of calculations spanning the parameter-space of collision parameters, we find that a coplanar spin-orbit parallel collision generates on average 2.4 new protostars, whereas a randomly orientated collision generates on average 1.2 new protostars. We might expect some correlation between the spins and orbits of interacting discs, so the mean proliferation factor is probably between 1.2 and 2.4. In other words, this is an efficient way of generating binaries. The ensemble of calculations suggests that immediately after an interaction, binaries having all eccentricities e in the range $0 \leq e \leq 0.9$ are well represented; mass-ratios q are in the range $0.05 \leq q \leq 0.3$;

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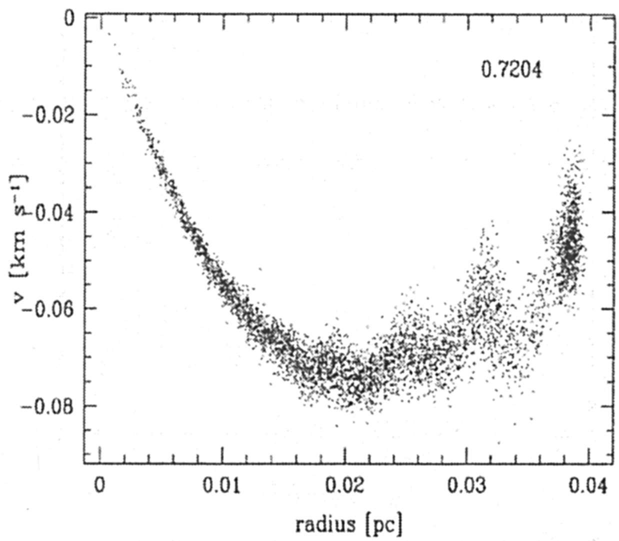

Figure 3. SPH simulation of a stable isothermal sphere subjected to steadily increasing pressure (the pressure doubles in one sound-crossing time). The velocity profile is shown just before the central protostar forms. (Hennebelle, Whitworth & Gladwin, 2001)

and separations are typically a small fractions (0.03 to 0.3) of the periastron of the interacting primaries. The mass-function of the fragments in the mass range $(0.02,0.3)M_{\odot}$ approximates to $-d\ell n\,[\mathcal{N}]\,/d\ell n[M] \simeq 1$, similar to the values that have recently been inferred from near IR surveys. (For comparison, Salpeter found $-d\ell n\,[\mathcal{N}]\,/d\ell n[M] \simeq 2.35$ in the higher-mass range $(0.4,10)M_{\odot}$.) However, our results depend on the effective viscosity of the disc-gas, and we have not yet made a comprehensive study of this dependence.

5. Molecular cores subjected to a sudden increase in external pressure

The nearest star-formation regions, for example Taurus-Auriga, exhibit more sparsely distributed star formation, and do not appear to have been very violently disturbed; certainly there is no evidence of massive stars or their attendant expanding nebulae. Nonetheless even here the spontaneous models of star formation, in which collapse is induced quasistatically, may not be applicable. In particular, Taurus appears to have an exceptionally high binary fraction, which may point to impulsively triggered collapse. Also, many of the candidate prestellar cores in the more distributed star formation regions have molecular-line profiles suggesting inward motions which are incompatible with the predictions of the singular isothermal sphere model. The candidate prestellar cores, of which the archetype is L1544, show molecular-line profiles which imply that the outer layers are flowing inwards at a sizeable fraction of the sound speed, whilst the

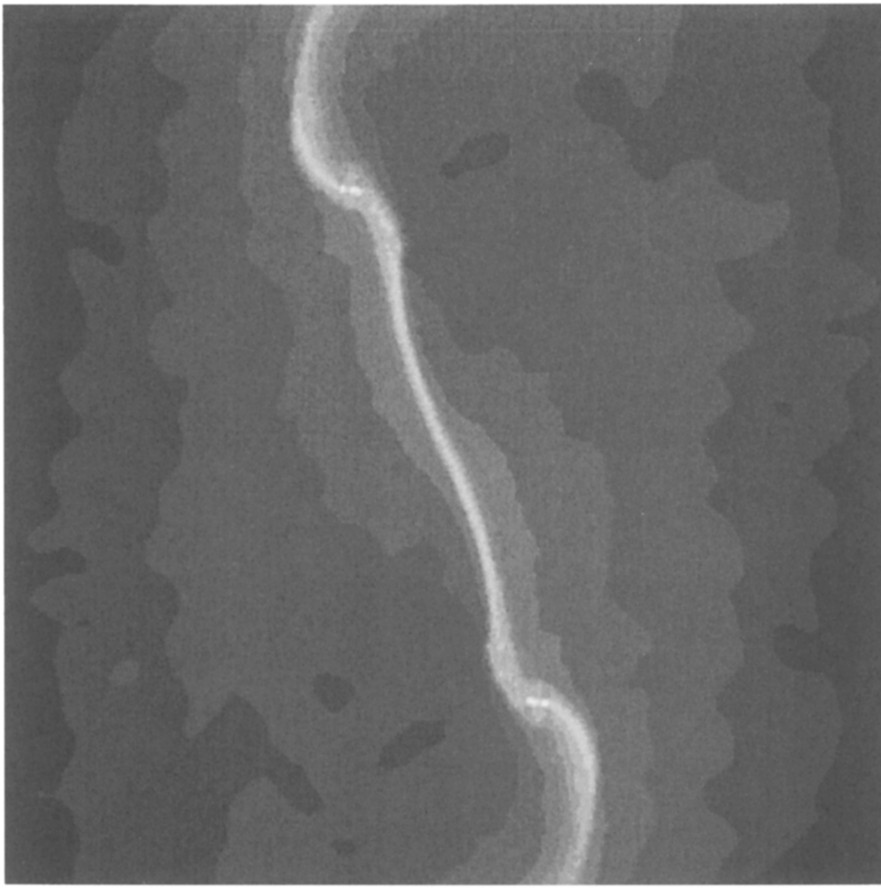

Figure 4. The BB79 test performed using only 45,000 particles initially and then On-The-Fly Splitting triggered above $\rho = \rho_{\rm critical} = 3 \times 10^{-14}$ g cm^{-3}. A column-density image of the central 0.004×0.004 pc^2 of the computational domain, looking down the (anticlockwise) rotation axis, at time $t = 1.270 t_{\rm freefall}$ when $\rho_{\rm max} \simeq 3 \times 10^{-9}$ g cm^{-3}. The column-density grey-scale is logarithmic, with sixteen equal intervals from $3.72 \times 10^{23}\,{\rm H_2\,cm^{-2}}$ to $1.55 \times 10^{27}\,{\rm H_2\,cm^{-2}}$ (or equivalently $1.49\,{\rm g\,cm^{-2}}$ to $6.19 \times 10^3\,{\rm g\,cm^{-2}}$) (Kitsionas & Whitworth, in preparation).

inner parts are still approximately static (Tafalla et al. 1998, Williams et al. 1999). This inflow pattern is typical of what happens when a core is subjected to a sudden increase in external pressure, which then drives a compression wave into the core, leaving in its wake an approximately uniform inward radial velocity field. The YSO is then formed when the compression wave converges on the centre. For instance, the two-dimensional family of similarity solutions for the collapse of an isothermal sphere all involve a compression wave propagating inwards and setting up a uniform inward velocity field in its wake. We have therefore simulated what happens when an isothermal gas cloud in stable equilibrium (i.e. a Bonnor Ebert sphere having "ξ_b" < 6.45, and contained by a finite external pressure P) is subjected to a sudden increase in external pressure (Hennebelle, Whitworth & Gladwin).

Figure 3 shows the velocity field which develops when the pressure acting on an isothermal cloud at 10 K increases at a rate $\dot{P} = 3P_{\rm initial}/t_{\rm SC}$, where $P_{\rm initial}$ is the initial equilibrium value of the external pressure and $t_{\rm SC}$ is the sound-crossing time. The inward radial flow at $\sim 0.07\,{\rm m\,s^{-1}}$ is very similar to that inferred for L1544. In addition, the accretion rate onto the central YSO is initially very high, but then falls to much smaller values. This is precisely the behaviour which has been deduced from the apparent paucity of Class 0 sources relative to Class I sources, and also from the stronger outflows generated by Class 0 sources relative to Calass I sources.

6. Particle splitting

Since this volume is concerned both with astrophysics and with numerical techniques, it is appropriate for me to conclude by presenting briefly some results obtained recently by Kitsionas and myself, using the technique of particle splitting. This affords a very efficient way to ensure that an SPH simulation always satisfies the Jeans condition. The Jeans condition simply requires that the Jeans mass should be resolved, at all times and in all parts of the computational domain. In an SPH simulation using ~ 50 neighbours, this means that the SPH particles must always have mass less than about one percent of the local Jeans mass. If this constraint is not met, then spurious fragmentation may occur, and real fragmentation may be suppressed (Bate & Burkert 1997, Truelove et al. 1997, Whitworth 1998).

Particles which are about to violate the Jeans condition are replaced by a close-packed (approximately spherical) cluster of 13 particles having one thirteenth the mass, and with their properties interpolated from the parent and her neighbours. Neighbour lists are constructed on the basis of requiring the total *mass* of neighbours to be about 50 times the mass of the home particle. The splitting can be implemented either in a pre-ordained sub-region of the computational domain (Nested Splitting), thereby initiating a fine-grained local simulation in which the boundary and initial conditions are furnished by a coarse-grained background simulation. Alternatively particles can be split as their density approaches the value at which they would otherwise violate the Jeans condition (On-The-Fly Splitting).

Figure 4 shows the result of performing the Boss & Bodenheimer (1979) test, starting with 40,000 particles and applying On-The-Fly Splitting. At the end the simulation has $\sim 150,000$ particles and has reached a density of $3 \times 10^{-9}\,\mathrm{g\,cm^{-3}}$. The filamentary singularity is still intact. As compared with a standard SPH simulation satisfying the Jeans condition, the memory requirements are reduced by ~ 4 and the CPU time by ~ 8.

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