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Brown dwarfs from turbulent fragmentation

Paolo Padoan[1], Alexei Kritsuk[1], Michael, L. Norman[1] and Åke Nordlund[2]

[1] Department of Physics and Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0424; ppadoan@ucsd.edu, akritsuk@cosmos.ucsd.edu, mnorman@cosmos.ucsd.edu

[2] Astronomical Observatory / NBIfAFG, Juliane Maries Vej 30, DK-2100, Copenhagen, Denmark; aake@astro.ku.dk

Abstract. The origin of brown dwarfs (BDs) is an important component of the theory of star formation, because BDs are approximately as numerous as solar mass stars. It has been suggested that BDs originate from the gravitational fragmentation of protostellar disks, a very different mechanism from the formation of hydrogen burning stars. We propose that BDs are instead formed by the process of turbulent fragmentation, like more massive stars. In numerical simulations of turbulence and star formation we find that gravitationally unstable density peaks of BD mass are commonly formed by the turbulent flow. These density peaks collapse into BD mass objects with circumstellar disks, like more massive protostars. We rely on numerical experiments with very large resolution, achieved with adaptive mesh refinement (AMR). The turbulence simulation presented here is the first AMR turbulence experiment ever attempted and achieves an effective resolution of 1024^3 computational zones. The star formation simulation achieves an effective resolution of $(10^6)^3$ computational zones, from a cloud size of 5 pc to protostellar disks resolved down to 1 AU.

1. Introduction

Brown Dwarfs (BDs) are approximately as abundant as solar mass stars (e.g. Béjar et al. 2001; Chabrier 2002). The typical Jeans' mass in star–forming clouds is of order a solar mass, approximately two orders of magnitude more massive than a BD. This is usually considered the fundamental reason why solar mass stars are so common, but the existence of BDs is a challenge to this simple explanation. The origin of BDs is apparently an important test for the theory of star formation.

From a different perspective, we could instead assume that the origin of BDs is quite different from that of more massive stars, in which case their existence would not necessarily provide any constraints to the theory of star formation. This approach is exemplified in the recent suggestion by Reipurth & Clarke (2001) that BDs are the result of the gravitational fragmentation of protostellar disks, but that work does not draw a definite line separating BDs from more massive stars. At what mass does star formation switch from the standard mechanism to the disk fragmentation mode? Most likely not exactly at the hydrogen burning limit of 0.075 $m_\odot$, as this limit is defined by nuclear physics and can hardly affect the fragmentation process.

There is also no indication of a discontinuity in the stellar initial mass function (IMF) at approximately 0.075 $m_\odot$, and no evidence of special properties of young BDs relative to more massive stars, suggesting that perhaps a unique process can explain the formation of both hydrogen burning stars and BDs (e.g. Jayawardhana et al. 2003a,b).

The possibility that BDs and more massive stars have a common origin due to the process of turbulent fragmentation has been recently proposed by Padoan & Nordlund (2004). In that work, we show that BDs are predicted by our model for the origin of the stellar IMF from turbulent fragmentation (Padoan & Nordlund 2002), roughly as frequently as inferred from observations. Here we briefly summarize our theoretical predictions and present new numerical experiments.

2. Stellar and BD Masses from Turbulent Fragmentation

The gas density and velocity fields in star–forming clouds are highly non–linear due to the presence of supersonic turbulence. The kinetic energy of the turbulence is typically 100 times larger than the gas thermal energy on the scale of a few pc (the typical rms Mach number is of order 10) and the gas is roughly isothermal, so that very large compressions due to a complex network of interacting shocks cannot be avoided. Under such conditions the concept of gravitational instability, based on a comparison between gravitational and thermal energies alone in a system with mild perturbations, does not apply. Turbulent density peaks of any size can be formed in the turbulent flow, independent of the Jeans' mass. Peaks that are massive and dense enough (more massive their own Jeans' mass) collapse into protostars, while smaller subcritical ones re-expand into the turbulent flow. This is a process that we call *turbulent fragmentation*[1], to stress the point that stars and BDs, formed in supersonically turbulent clouds, are not primarily the result of gravitational fragmentation.

Because density peaks formed by the turbulent flow need to be larger than their critical mass to collapse, a necessary condition for the formation of BDs by supersonic turbulence is the existence of a finite mass fraction, in the turbulent flow, with density at least as high as the critical one for the collapse of a BD mass density peak. As the PDF of gas density in supersonic turbulence is fully determined by the mean density and the rms Mach number of the turbulent flow (Nordlund & Padoan 1999; Ostriker et al. 1999), we can compute this necessary condition for BD formation as an integral over the PDF of gas density. The result, discussed in Padoan & Nordlund (2004), is that in typical molecular clouds approximately 1% of the total mass is available for the formation of BDs. This fraction is approximately 10% for conditions found in regions of cluster formation. Based on this result, the observed frequency of BDs is consistent with the distribution of turbulent pressure, suggesting turbulence may play an important role in the the origin of BDs.

In Padoan & Nordlund (2002) the stellar IMF is interpreted as the result of the turbulent fragmentation of star–forming clouds. It is shown that: i) The power law slope, s, of the stellar IMF is directly related to the turbulent power spectrum slope, β, $s = 3/(4-\beta)$; ii) the abundance of stars of mass smaller than the IMF peak depends on the probability density function (PDF) of the gas density in the turbulent flow. As a result, the IMF is a power law with slope close to Salpeter's value (Salpeter 1955) at large masses, and the abundance of low mass stars and BDs is a function of the turbulent rms velocity, the mean gas density and the mean temperature. The IMF is fully determined once these physical parameters of the star–forming region are known. As shown in Figure 1, the predicted BD abundance increases with increasing Mach number and density (left panel) and is consistent with the abundance inferred in stellar clusters (right panel).

3. AMR Experiments

We employ a 3-D parallel structured adaptive mesh refinement (AMR) code, *Enzo*,[2] developed at the Laboratory for Computational Astrophysics by Bryan, Norman and collaborators (Bryan & Norman 1999; O'Shea et al.

[1] This term was probably first introduced by Kolesnik & Ogul'Chanskii (1990)

[2] See `http://cosmos.ucsd.edu/enzo/`

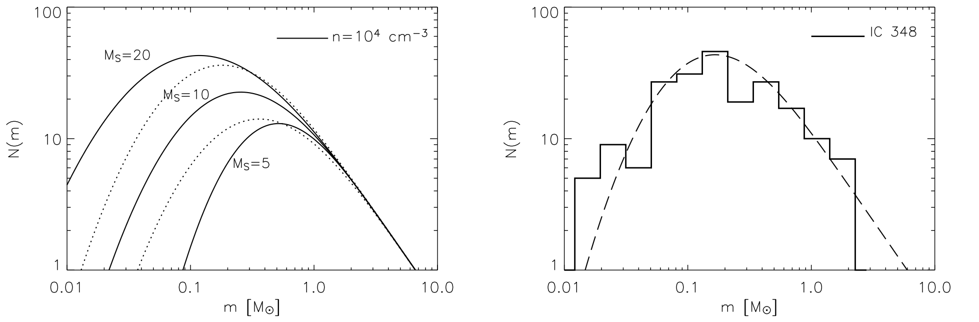

Fig. 1. Left panel: Analytical mass distributions computed for $\langle n \rangle = 10^4$ cm^{-3}, $T = 10$ K and for three values of the sonic rms Mach number, $M_S = 5$, 10 and 20 (solid lines). The dotted lines show the mass distribution for $T = 10$ K, $M_S = 10$ and $\langle n \rangle = 5 \times 10^3$ cm^{-3} (lower plot) and $\langle n \rangle = 2 \times 10^4$ cm^{-3} (upper plot). Right panel: IMF of the cluster IC 348 in Perseus obtained by Luhman et al. (2003) (solid line histogram) and theoretical IMF computed for $\langle n \rangle = 5\times10^4$ cm^{-3}, $T = 10$ K and $M_S = 7$ (dashed line).

2004). *Enzo* is a public domain Eulerian grid-based hybrid code which includes hydrodynamic and N-body solvers and uses the AMR algorithm of Berger & Colella (Berger & Colella 1989) to improve spatial resolution in regions where that is required. The central idea behind AMR is to solve the conservation laws on a grid, adding finer meshes in regions that require enhanced resolution. AMR is spatially– and time–adaptive, can be used with accurate methods for solving the (magneto)hydrodynamic equations. Mesh refinement can be automatically advanced to an arbitrary level, based on any combination of problem–specific local refinement criteria (e.g., density threshold, strong shocks, high vorticity, large gradients, Jeans length (Truelove et al. 1997), cooling time, etc.).

With this code, we have run the first AMR turbulence experiment ever attempted, achieving an effective resolution of 1024^3 computational zones (Kritsuk et al. in preparation). The rms Mach number of the turbulent flow is $M_s \approx 6$, and we have adopted an isothermal equation of state, periodic boundary conditions, large scale random forcing and mesh refinement based on the local shock or shear amplitude. The logarithm of the projected density field from a snapshot of this simulation is shown in Figure 2. The density field of this simulation shows an incredibly rich structure, with sharp filaments on all scales, broken into even denser peaks. Some of these density peaks are gravitationally unstable and would collapse if gravity were included in the experiment. We refer to these density peaks as *turbulent seeds*, as they are the turbulent progenitors of protostars. Turbulent seeds of BD mass are commonly found in the turbulent flow.

In order to verify the outcome of the gravitational collapse of the turbulent seeds, we run a second experiment with the same code, where self–gravity is included. In this experiment we use the AMR method to resolve the gravitational collapse. The computational box represents a star–forming cloud of size 5 pc and average number density 500 cm^{-3}. In the collapsing regions we are able to fully resolve protostellar disks down to a scale of approximately 1 AU. This simulation shows that the densest turbulent seeds, found primarily within dense filaments, collapse into protostars surrounded by protostellar disks. Figure 3 shows a typical filament containing many collapsing "seeds" (left panel). The seeds appear as small dense cores, because of the limited dynamical rage of the image. In fact, visualized with higher levels of refinement, they are seen to be collapsing into protostars with circumstellar disks (right panel of Figure 3). Many of these

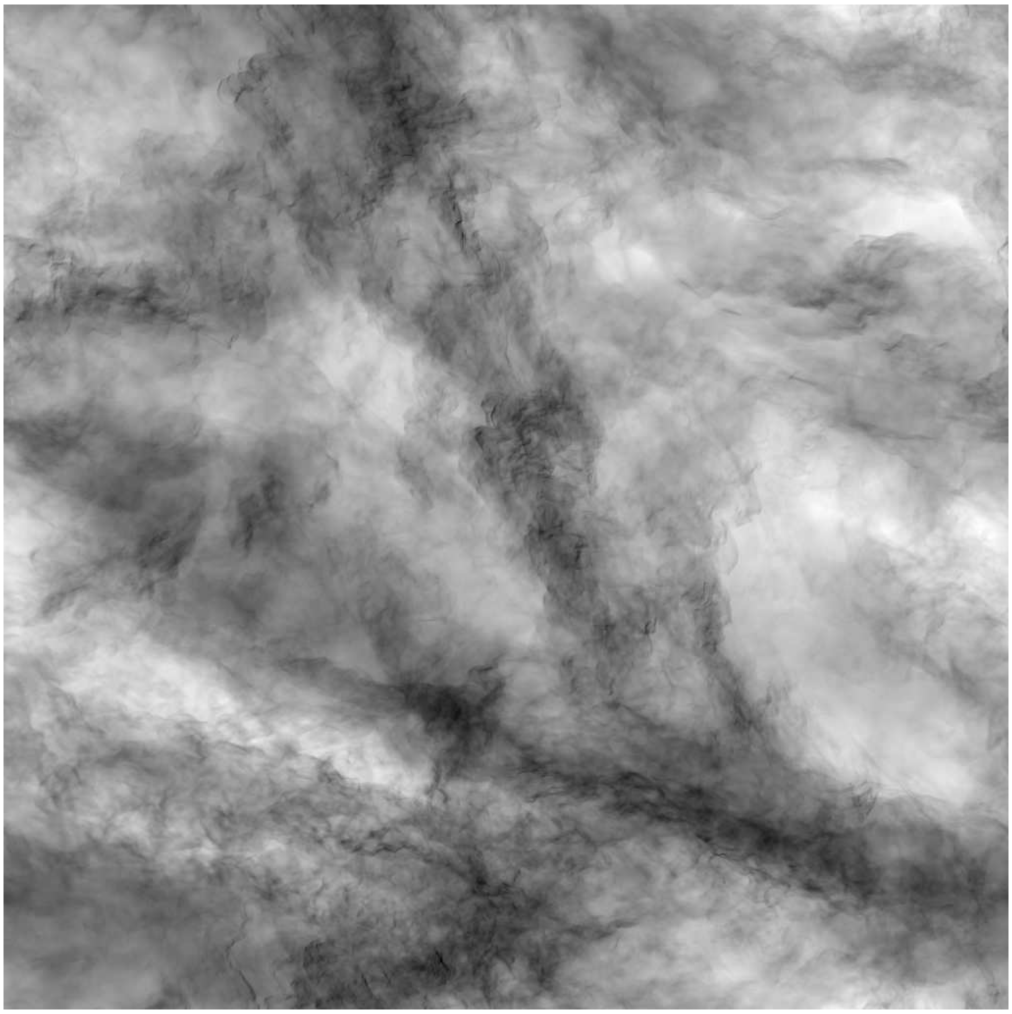

Fig. 2. Logarithm of the projected density field from an AMR simulation of isothermal, supersonic hydrodynamic turbulence with an effective resolution of 1024^3 computational zones (Kritsuk, Padoan & Norman, in preparation).

protostars contain a fraction of a solar mass, some only a BD mass.

Further analysis and runs with longer integration time will allow to establish the protostellar mass distribution. However, these simulations already teach us an important lesson: Turbulent seeds of BD mass are common and may collapse into BDs, with no need to form BDs from the fragmentation of protostellar disks. Simulations that do not resolve well the turbulent flow (like perhaps every smooth particle hydrodynamic (SPH) simulation to date) are bound to artificially suppress this important mechanism of BD formation. Furthermore, insufficient numerical resolution may also cause artificial fragmentation of protostellar disks (Fisher et al., in preparation). Recent attempts to support the disk fragmentation origin of BDs, and even deny the importance of turbulent fragmentation, based on SPH simulations (Bate et al. 2002) are affected by both problems. We also warn against a direct applica-

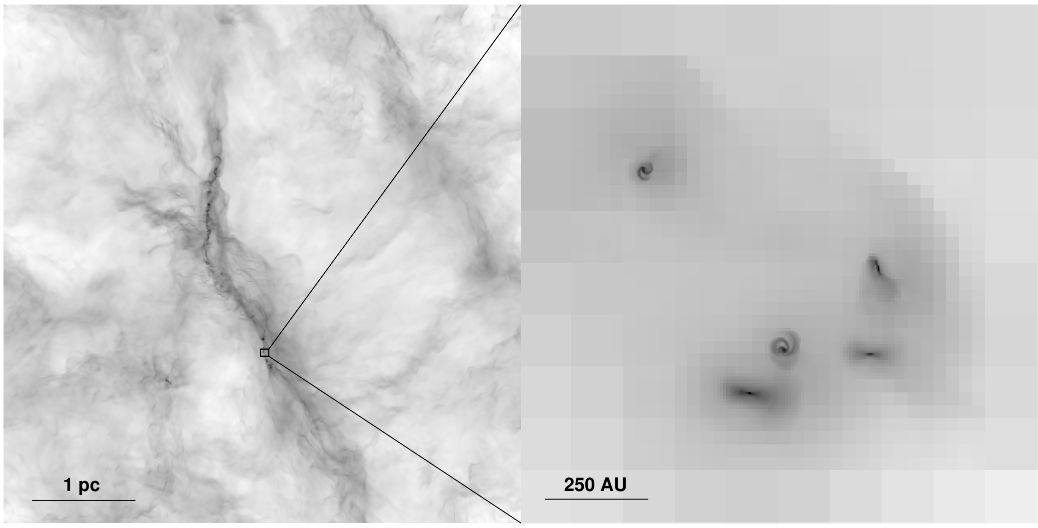

Fig. 3. Left panel: Logarithm of the projected gas density in our AMR simulation of star formation in a turbulent cloud (see text). Right panel: Higher resolution view of a small region inside the dense filament marked by the small square in the left panel. The small square is drawn larger than its actual size, as the magnification factor between the right and the left panels is 840.

tion of results from simulations without magnetic fields to present day star formation, because magnetic fields affect the fragmentation mechanism (Padoan & Nordlund 1999) and the angular momentum transport.

4. Conclusions

High resolution numerical experiments of supersonic turbulence and of star formation in turbulent clouds support the suggestion that BDs are formed primarily from the process of turbulent fragmentation, as *turbulent seeds*, like hydrogen burning stars. As frequently pointed out at this workshop, all the observational evidence points to a common origin of stars and BDs. Furthermore, observations have shown that the mass distribution of prestellar condensations is indistinguishable from the stellar IMF (Motte et al. 1998; Testi & Sargent 1998; Onishi et al. 1999; Johnstone et al. 2000a,b; Motte et al. 2001; Johnstone et al. 2001; Onishi et al. 2002), both in the functional shape and in the range of masses, including BD mass cores (Walsh et al. 2004). This direct evidence of the turbulent seeds provides strong support to the turbulent fragmentation origin of BDs.

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