Gravitoturbulent Star Cluster Formation

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Abstract.
Stars form by gravoturbulent fragmentation of interstellar gas clouds. The supersonic turbulence ubiquitously observed in Galactic molecular gas generates strong density fluctuations with gravity taking over in the densest and most massive regions. Collapse sets in to build up stars and star clusters.

Turbulence plays a dual role. On global scales it provides support, while at the same time it can promote local collapse. Stellar birth is thus intimately linked to the dynamical behavior of parental gas cloud, which determines when and where protostellar cores form, and how they contract and grow in mass via accretion from the surrounding cloud material to build up stars. Slow, inefficient, isolated star formation is a hallmark of turbulent support, whereas fast, efficient, clustered star formation occurs in its absence.

The fact that Galactic molecular clouds are highly filamentary can be explained by a combination of compressional flows and shear. The dynamical evolution of nascent star clusters is very complex. This strongly influences the stellar mass spectrum. The equation of state (EOS) plays a pivotal role in the fragmentation process. Under typical cloud conditions, massive stars form as part of dense clusters. However, for gas with effective polytropic index greater than unity star formation becomes biased towards isolated massive stars, which may be of relevance for understanding Pop III stars.

1. Introduction

Star clusters form by gravoturbulent fragmentation in interstellar clouds. The supersonic turbulence ubiquitously observed in Galactic gas clouds generates strong density fluctuations with gravity taking over in the densest and most massive regions. Once such cloud regions become gravitationally unstable, collapse sets in and leads to the formation of stars and star clusters. Yet the conditions for fragmentation and the physical processes that govern the early evolution of nascent star clusters are poorly understood.
Following up on analytical studies (starting with Jeans 1902; and later Larson 1969; Shu 1977; Elmegreen 1993; Padoan 1995; Padoan & Nordlund 2002), most current investigations concentrate on a numerical approach to star cluster formation. For example, the effects of interstellar turbulence have been studied extensively in a series of 3D simulations by Klessen, Burkert, & Bate (1998), Klessen, Heitsch, & Mac Low (2000), Klessen & Burkert (2000, 2001), Heitsch, Mac Low, & Klessen (2001a,b), Klessen (2001). See also Ballesteros-Paredes et al. (1999ab, 2003), Padoan & Nordlund (1999), Padoan et al. (2001), Bate, Bonnell, & Bromm (2003) or Bonnell, Bate, & Vine (2003). A complete overview is given in the reviews by Larson (2003) and Mac Low & Klessen (2004).

In this proceedings paper we call your attention to the dynamical complexity arising from the interplay between supersonic turbulence and self-gravity, and introduce the concept of gravoturbulent fragmentation. We argue that in typical star forming clouds turbulence generates the density structure in the first place and then gravity takes over in the densest and most massive regions to build up the star cluster. In Section 2 we focus on spatial distribution and timescale of star formation, then in Section 3, we discuss a specific example of a star forming filament similar to those observed in Taurus, and in Section 4 we speculate about the mass spectra of clumps and stars in the context of the gravoturbulent fragmentation model. Finally, in Section 5 we demonstrate that the equation of state (EOS) of the interstellar gas plays a pivotal role in gravoturbulent fragmentation. The EOS determines whether molecular cloud regions build up clusters of low to intermediate-mass stars, or form isolated high-mass objects.

2. Spatial Distribution and Timescale of Star Formation

Supersonic turbulence plays a dual role in star formation. While it usually is strong enough to counterbalance gravity on global scales it will usually provoke collapse locally (Mac Low & Klessen 2004). Turbulence establishes a complex network of interacting shocks, where regions of high-density build up at the stagnation points of convergent flows. These gas clumps can be dense and massive enough to become gravitationally unstable and collapse when the local Jeans length becomes smaller than the size of the fluctuation. However, the fluctuations in turbulent velocity fields are highly transient. They can disperse again once the converging flow fades away (Vázquez-Semadeni, Shadmehri, & Ballesteros-Paredes 2002). Even clumps that are strongly dominated by gravity may get disrupted by the passage of a new shock front (Mac Low et al. 1994).

For local collapse to result in the formation of stars, Jeans unstable, shock-generated, density fluctuations therefore must collapse to sufficiently high densities on time scales shorter than the typical time interval between two successive shock passages. Only then do they ‘decouple’ from the ambient flow pattern and survive subsequent shock interactions. The shorter the time between shock passages, the less likely these fluctuations are to survive. The overall efficiency of star formation depends strongly on the wavelength and strength of the driving source (Klessen et al. 2000, Heitsch et al. 2001). Both regulate the amount of gas available for collapse on the sonic scale where turbulence turns from supersonic to subsonic (Vázquez-Semadeni, Ballesteros-Paredes, & Klessen 2003).
The velocity field of long-wavelength turbulence is dominated by large-scale shocks which are very efficient in sweeping up molecular cloud material, thus creating massive coherent structures. These exceed the critical mass for gravitational collapse by far, because the velocity dispersion within the shock compressed region is much smaller than in the ambient turbulent flow. The situation is similar to localized turbulent decay, and quickly a cluster of protostellar cores builds up. Both decaying and large-scale turbulence lead to a \textit{clustered} mode of star formation. Prominent examples are the Trapezium Cluster in Orion with a few thousand young stars, but also the Taurus star forming region which is historically considered as a case of isolated stellar birth. Its stars have formed almost simultaneously within several coherent filaments which apparently are created by external compression (see Ballesteros-Paredes et al. 1999a). This renders it a clustered star forming region in the sense of the above definition.

The efficiency of turbulent fragmentation is reduced if the driving wavelength decreases. There is less mass at the sonic scale and the network of interacting shocks is very tightly knit. Protostellar cores form independently of each other at random locations throughout the cloud and at random times. There are no coherent structures with multiple Jeans masses. Individual shock generated clumps are of low mass and the time interval between two shock passages through the same point in space is small. Hence, collapsing cores are easily destroyed again. Altogether star formation is inefficient. This scenario then corresponds to an \textit{isolated} mode of star formation. Stars that truly form in isolation are, however, very rarely observed – most young stars are observed in clusters or at most loose aggregates. From a theoretical point of view, there is no fundamental dichotomy between these two modes of star formation, they rather define the extreme ends in the continuous spectrum of the properties of turbulent molecular cloud fragmentation.

Altogether, we call this intricate interaction between turbulence on the one side and gravity on the other – which eventually leads to the transformation of some fraction of molecular cloud material into stars as described above – \textit{gravoturbulent fragmentation}. To give an example, we discuss in detail the gravitational fragmentation in a shock-produced filaments that closely resembles structures observed in the Taurus star forming region.

3. Gravitational Fragmentation of a Filament in a Turbulent Flow

In Taurus, large-scale turbulence is thought to be responsible for the formation of a strongly filamentary structure (e.g. Ballesteros-Paredes et al. 1999a). Gravity within the filaments should then be considered as the main mechanism for forming cores and stars. Following earlier ideas by Larson (1985), Hartmann (2002) has shown that the Jeans length within a filament, and the timescale for it to fragment are given by

\begin{align}
\lambda_J &= 1.5 T_{10} A_V^{-1} \text{ pc,} \\
\tau &\sim 3.7 T_{10}^{1/2} A_V^{-1} \text{ Myr.}
\end{align}

where $T_{10}$ is the temperature in units of 10 K, and $A_V$ is the visual extinction through the center of the filament. By using a mean visual extinction for starless
Figure 1. Evolution of the column density of an SPH simulation. The filament in the first frame (before self-gravity is turned-on) shows that turbulence is responsible in forming this kind of structures. The small bar in the bottom-left of each frame denotes the Jeans length (equation 1) at this time. At later times, self-gravity is turned on and the filament suffers gravitational fragmentation on a free-fall timescale (equation 2).

cores of $A_V \sim 5$, equation 1 gives a characteristic Jeans length of $\lambda_J \sim 0.3$ pc, and collapse should occur in about 0.74 Myr. Indeed, Hartmann (2002) finds 3 – 4 young stellar objects per parsec with agrees well with the above numbers from linear theory of gravitational fragmentation of filaments.

In order to test these ideas, we resort to numerical simulations. We analyze a SPH calculation (Benz 1990, Monaghan 1992) of a star forming region that was specifically geared to the Taurus cloud. Details on the numerical implementation, on performance and convergence properties of the method, and tests against analytic models and other numerical schemes in the context of turbulent supersonic astrophysical flows can be found in Mac Low et al. (1998), Klessen & Burkert (2000, 2001) and Klessen et al. (2000).

This simulation has been performed without gravity until a particular, well defined elongated structure is formed. We then turn-on self-gravity. This leads to localized collapse and a sparse cluster of protostellar cores builds up. Timescale and spatial distribution are in good agreement with the Hartmann (2002) findings in Taurus. For illustration, we show eight column density frames of the simulation in Figure 1. The first frame shows the structure just before self-gravity is turned-on, and we note that the filament forms cores in a fraction of Myr. The timestep between frames is 0.1 Myr. The mean surface density for the filament is $0.033 \text{ g cm}^{-2}$, corresponding to a visual extinction of $\sim 7.5$. Using equations 1 and 2 this value gives a Jeans length of $\lambda_J \sim 0.2$ pc, and a collapsing timescale of $\tau \sim 0.5$ Myr. Note from Figure 1 that the first cores appear roughly at $\tau \sim 0.3$ Myr, although the final structure of collapsed objects is clearly defined at $t = 0.5$ Myr. The typical separation between protostellar cores (black dots in Figure 1) is about the Jeans length $\lambda_J$.

This example demonstrates that indeed turbulence is able to produce a strongly filamentary structure and that at some point gravity takes over to form collaps-
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4. Mass Spectra of Clumps and Protostellar Cores

The dominant parameter determining stellar evolution is the mass. We discuss now how the final stellar masses may depend on the gravitoturbulent fragmentation process, and analyze four numerical models which span the full parameter range from strongly clustered to very isolated star formation (for full detail see Klessen 2001b).

Figure 2 plots the mass distribution of all gas clumps, of the subset of Jeans critical clumps, and of collapsed cores. We show four different evolutionary phases, initially just when gravity is ‘switched on’, and after turbulent fragmen-
tation has lead to the accumulation of $M_\star \approx 5\%$, $M_\star \approx 30\%$ and $M_\star \approx 60\%$ of the total mass in protostars. In the completely pre-stellar phase the clump mass spectrum is very steep (about Salpeter slope or less) at the high-mass end. It has a break and gets shallower below $M \approx 0.4 \langle M_1 \rangle$ with slope $-1.5$. The spectrum strongly declines beyond the SPH resolution limit. Individual clumps are hardly more massive than a few $\langle M_1 \rangle$. Gravitational evolution modifies the distribution of clump masses considerably. As clumps merge and grow bigger, the spectrum becomes flatter and extends towards larger masses. Consequently the number of cores that exceed the Jeans limit increases. This is most evident in the Gaussian model of decayed turbulence, the clump mass spectrum exhibits a slope $-1.5$.

The mass spectrum depends on the wavelength of the dominant velocity modes. Small-scale turbulence does not allow for massive, coherent and strongly selfgravitating structures. Together with the short interval between shock passages, this prohibits efficient merging and the build up of a large number of massive clumps. Only few clumps become Jeans unstable and collapse to form stars. This occurs at random locations and times. The clump mass spectrum remains steep. Increasing the driving wavelength leads to more coherent and rapid core formation, resulting in a larger number of protostars.

Long-wavelength turbulence or turbulent decay produces a core mass spectrum that is well approximated by a log-normal. It roughly peaks at the average thermal Jeans mass $\langle M_1 \rangle$ of the system (see Klessen & Burkert 2000, 2001) and is comparable in width with the observed IMF (Kroupa 2002). The log-normal shape of the mass distribution may be explained by invoking the central limit theorem (e.g. Zinnecker 1984), as protostellar cores form and evolve through a sequence of highly stochastic events (resulting from supersonic turbulence and/or competitive accretion).

5. Effects of the Equation of State

So far, we concentrated on isothermal models of Galactic molecular clouds. More generally, however, the balance of heating and cooling in a molecular cloud can be described by a polytropic EOS, $P = K \rho^\gamma$, where $K$ is a constant, and $P, \rho$ and $\gamma$ are thermal pressure, gas density and polytropic index, respectively. A detailed analysis by Spaans & Silk (2000) suggests that $0.2 < \gamma < 1.4$ in the interstellar medium.

Li, Klessen & Mac Low (2003) carried out detailed smoothed particle hydrodynamics (SPH) simulations to determine the effects of different EOS on gravoturbulent fragmentation by varying $\gamma$ in steps of 0.1 in otherwise identical simulations. Figure 3 illustrates how low $\gamma$ leads to the build-up of a dense cluster of stars, while high values of $\gamma$ result in isolated star formation. It also shows that the spectra of both the gas clumps and protostars change with $\gamma$. In low-$\gamma$ models, the mass distribution of the collapsed protostellar cores at the high-mass end is roughly log-normal. As $\gamma$ increases, fewer but more massive cores emerge. When $\gamma > 1.0$, the distribution is dominated by high mass protostars only, and the spectrum tends to flatten out. It is no longer described by either a log-normal or a power-law. The clump mass spectra, on the other hand, do show power-law behavior at the high mass side, even for $\gamma > 1.0$. 
This suggest that stars tend to form in clusters in a low-$\gamma$ environment. Protostellar cores are of low mass in this case. The apparent lack of power-law behavior for the cores in the protostellar cluster might imply that simple accretion is unable to generate as many high-mass stars as predicted by the observations, hinting that other mechanisms such as collisions (Bonnell, Bate & Zinnecker 1998) may be at work to produce the massive stars in a cluster. Higher resolution models will be necessary to confirm this, however.

On the other hand, our results also imply that massive stars can form in small groups or alone in gas with $\gamma > 1.0$. Spaans & Silk (2000) suggest that a stiffer EOS ($\gamma > 1.0$) leads to a peaked IMF, biased toward massive stars, while an EOS with $\gamma < 1.0$ results in a power-law IMF, in general agreement with our simulations.

The formation of isolated massive stars is of great interest, as usually, massive stars are found in clusters. But recently, Lamers et al. (2002) reported observations of isolated massive stars or very small groups of massive stars in the bulge of M51. Also Massey (2002) finds massive, apparently isolated field stars in both the Large and Small Magellanic Clouds. From our simulations, we see that when $\gamma > 1$, only very few or possibly only one fragment occurs. These then are massive, and would result in the formation of high-mass stars.

High resolution simulations by Abel, Bryan & Norman (2002) of the formation of the first star suggest that initially only one massive metal-free star forms per pregalactic halo. In the early Universe, inefficient cooling due to the lack of metals may result in high $\gamma$. Our models then suggest weak fragmentation, resulting in the formation of only one massive star per cloud.
Acknowledgments. We thank for support from various sources: RSK from the Emmy Noether Program of the Deutsche Forschungsgemeinschaft (grant no. KL1358/1); JBP from Conacyt’s grant I39318-E; MMML from a NASA ATP grant NAG5-10103, and a NSF CAREER grant AST99-85392.

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Discussion

Lamers: 1) You showed that the SFR decreases exponentially. What is the predicted time scale? 2) You showed that clouds with a hard equation of state, $P \sim \rho^p$ with $p > 1$ will preferentially form single massive stars. We have found evidence that this indeed occurred near the core of M51, where the radiation from the huge central starburst destroyed the CO-molecules which prevents efficient cooling. This is somewhat similar to what may have happened in the early Universe (Lamers et al. 2002, ApJ).

Klessen: 1) The decay time scales can vary considerably between different protostars. For low-mass stars the accretion rates decrease quickly, while high-mass stars end up with high masses because they grow in an environment that allows them to keep high mass-accretion rates for a considerable time. In general the time scale for the exponential decline of $\dot{M}$ is of order of $10^5$ years. 2) Thank you for that comment. These are indeed applications we have in mind. (see Li, Klessen, MacLow, 2003, ApJ).

Clark: Given that GMCs are thought to survive for only $\sim 10^6$ yrs and that turbulence decays on $\sim 10^6$ yrs within these structures, is it really necessary to drive turbulence at the GMC scale?

Klessen: I think GMCs live for several crossing or dynamical times. That means some degree of driving is necessary. It is probably provided by the very processes that created the cloud in the first place. Molecular clouds form in the high-density stagnation points of large-scale flows, as part of the large-scale turbulence in the Galactic disk. GMCs are highly structured, exhibiting extremely complex morphology and velocity distribution. Some parts of the GMC will have decaying internal turbulence, in other parts, turbulence is still strongly driven. The driving source for internal turbulence, in essence, is the large-scale compression, with energy transferred to smaller scales (into the cloud) probably by Vishniac-type instabilities, accompanied by Rayleigh-Taylor or Kelvin-Helmholtz instabilities.

Tan: 1) What do you think are the most important physical processes, apart from feedback, that are not in your simulations, and how would they affect your results? 2) Are your initial conditions consistent with the observed mass spectra of pre-stellar cores seen in various clouds, some of which have very narrow line widths?

Klessen: 1) I think, the most important physical effects missing in the current numerical schemes ARE indeed feedback processes (winds, outflows, radiation). Their influence on the local star formation efficiency is in essence not known. Other physical processes that are of relevance (but not of dominance) are magnetic fields and chemistry. Feedback is likely to retard and eventually terminate SF locally (this is clearly the case for ionizing UV radiation). The same retarding effects are expected from magnetic fields (see Heitsch, MacLow, Klessen, 2001). 2) Yes, we can reproduce the observed clump-mass spectrum. Also, even for highly-supersonic turbulent flows, you get a large fraction of quiescent (coherent) cores (see Klessen et al. ApJL, submitted). The reason is that cores form at the stagnation points of convergent turbulent flows. Their internal velocity differences (r.m.s. velocity dispersion) are thus much smaller than in the
ambient flow. In about one-third of all cases they have properties very similar
to observed quiescent cores.