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# STAR FORMATION FROM GRAVOTURBULENT FRAGMENTATION

Ralf S. Klessen[1]

RESUMEN

La turbulencia a gran escala proveé un apoyo a las nubes colapsantes, mientras que promueve el colapso localmente. El nacimiento de estrellas está intimamente ligado al comportamiento dinámico de la nube materna. Una formación estelar lenta, ineficiente y aislada se da en regiones soportadas por turbulencia mientras que una formación rápida, eficiente y en grupos se da en ausencia de ésta. El comportamiento dinámico de un cúmulo en formación tiene un impacto en el espectro de masas estelares y la ecuación de estado juega un papel principal en la fragmentación. Bajo condiciones típicas las estrellas masivas se forman en grupos, sin embargo en un gas con un índice politrópico efectivo $> 1$, la formación estelar se decanta por una formación de estrellas masivas aisladas. Ello puede ser de gran relevancia para estrellas de Población III.

ABSTRACT

Turbulence on global scales provides cloud support, while at the same time, it can promote local collapse. Stellar birth is thus intimately linked to the dynamical behaviour of the parental gas cloud. A slow, inneficient, isolated star formation is a hallmark of turbulent support, whereas fast, efficient and clustered star formation occurs in its absence. The dynamical evolution of a nascent cluster strongly influences the stellar mass spectrum and the equation of state plays a pivotal role on the fragmentation process. Under typical cloud conditions, massive stars form as part of dense clusters. However, for gas with an effective polytropic index $> 1$, star formation becomes bias towards isolated massive stars, which may be of relevance for Pop III stars.

*Key Words:* **ISM: CLOUDS — ISM: MOLECULES — ISM: TURBULENCE — STARS: FORMATION — STARS: LUMINOSITY, MASS FUNCTION**

## 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. In this proceedings paper we discuss the dynamical complexity arising from the interplay between supersonic turbulence and self-gravity and introduce the process of gravoturbulent fragmentation.

## 2. SPATIAL DISTRIBUTION AND TIMESCALE

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. For further references see the reviews by Larson (2003) and 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 et al. 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

[1]Astrophysikalisches Institut Potsdam, Germany.

sonic scale where turbulence turns from supersonic to subsonic (Vázquez-Semadeni et al. 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. The situation is similar to localized turbulent decay, and quickly a cluster of protostellar cores builds up. Prominent examples are the Trapezium Cluster in Orion with a few thousand young stars. However, this scenario also applies to 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. 1999). 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, and stars are dispersed throughout the cloud.

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 – *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. 1999). 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

$$\lambda_J = 1.5\, T_{10}\, A_V^{-1}\ \mathrm{pc}, \tag{1}$$

$$\tau \sim 3.7\, T_{10}^{1/2}\, A_V^{-1}\ \mathrm{Myr}. \tag{2}$$

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 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 smoothed particle hydrodynamics (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 $0.033\,\mathrm{g\,cm^{-2}}$, corresponding to a visual extinction of ∼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 collapsing objects, the protostars. However, the situation is quite complex. Just like in Taurus, the filament in Figure 1 is not a perfect cylinder, the collapsed objects are not perfectly equally spaced as

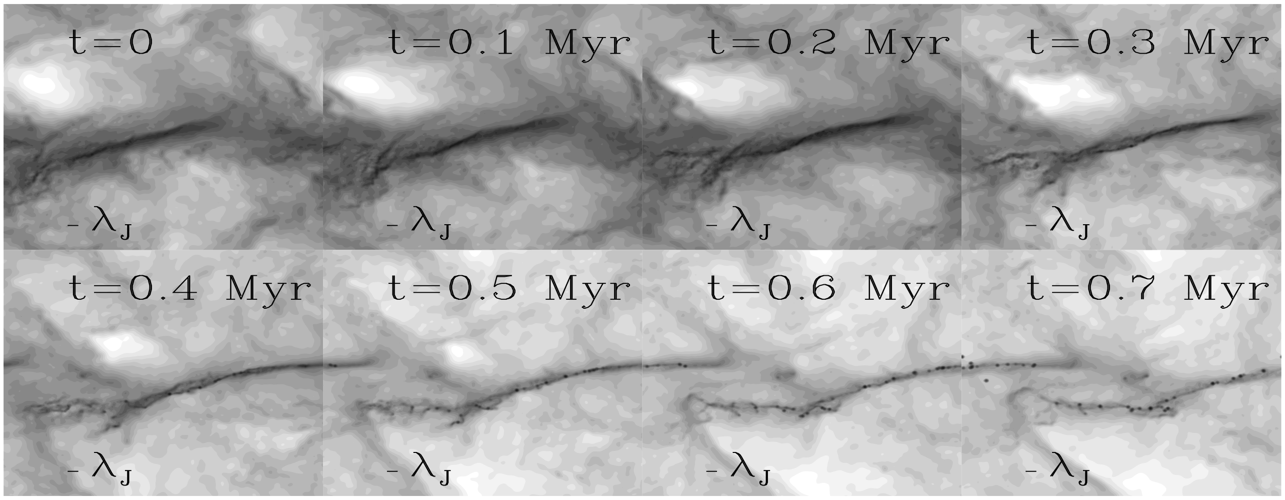


Fig. 1. Evolution of the column density of an SPH simulation. The filament in the first frame (before self-gravity is turned-on) shows that turbulence is responsible in forming this kind of structures. The small bar in the bottom-left of each frame denotes the Jeans length (equation 1) at this time. At later times, self-gravity is turned on and the filament suffers gravitational fragmentation on a free-fall timescale (equation 2).

predicted by idealized theory, and protostars do not form simultaneously but during a range of times (between $t \approx 0.3$ and $0.6\,\mathrm{Myr}$). Even though the theory of gravitational fragmentation of a cylinder appears roughly, it becomes clear that the properties of the star forming region not only depend on the conditions set initially but are influenced by the large-scale turbulent flow during the entire evolution. Gravoturbulent fragmentation is a continuous process that shapes the accretion history of each protostar in a stochastic manner (e.g. Klessen 2001a).

## 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 gravoturbulent 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 fragmentation has lead to the accumulation of $M_* \approx 5\%$, $M_* \approx 30\%$ and $M_* \approx 60\%$ 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 $M \approx 0.4\,\langle M_\mathrm{J}\rangle$ with slope $-1.5$. The spectrum strongly declines beyond the SPH resolution limit.

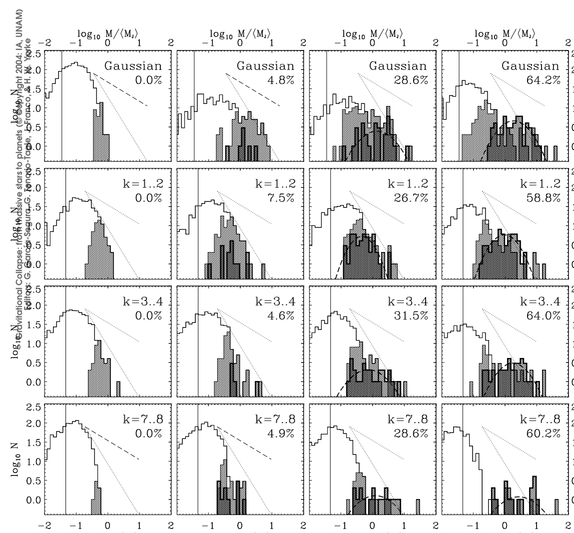


Fig. 2. Mass spectra of protostars (hatched thick-lined histograms), of gas clumps (thin lines), and of the subset of Jeans unstable clumps (thin lines, hatched distribution). Different evolutionary phases are defined by the fraction of mass converted into protostars and are indicated in the upper right corner of each plot. Masses are binned logarithmically and normalized to the average Jeans mass $\langle M_\mathrm{J}\rangle$. (From Klessen 2001b.)

Individual clumps are hardly more massive than a few $\langle M_\mathrm{J}\rangle$.

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 num-

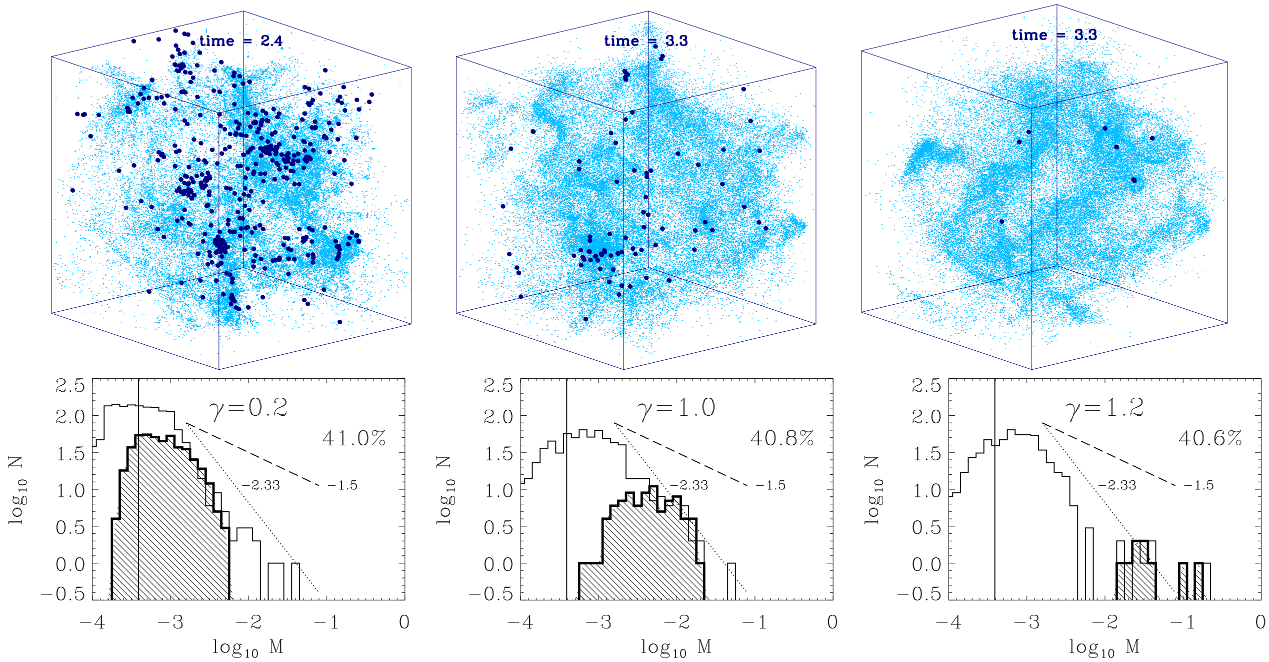


Fig. 3. Top: 3-D distribution of the gas and protostars for different $\gamma$. Bottom: Mass spectra of gas clumps (*thin lines*) and of protostars (collapsed cores: *hatched thick-lined histograms*) for the corresponding cube above. The percentage shows the fraction of total mass accreted onto protostars. The vertical line shows the SPH resolution limit. Shown also are two power-law spectra with $\nu = -1.5$ (dashed-line) and $\nu = -2.33$ (dotted line). (Figure adopted from Li et al. 2003.)



ber 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* $\langle M_{\rm J}\rangle$ 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 focused on isothermal models of molecular clouds only. 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 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 protostellare 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 in a low-$\gamma$ environment stars tend to form in clusters and with small masses. On the other hand, massive stars can form in small groups or in isolation in gas with $\gamma > 1.0$.

The formation of isolated massive stars is of great interest, as usually, massive stars are found in clusters. 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. This is consistent with our models assuming $\gamma > 1.0$.

High resolution simulations by Abel et al. (2002) of the formation of Population III stars suggest that in very metal-deficient gas only one massive object 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, supporting the hypothesis that the very first stars build up in isolation.

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