

# TURBULENCE AND MAGNETIC FIELDS IN CLOUDS

*Discussion*

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**Abstract** We discuss several categories of models which may explain the IMF, including the possible role of turbulence and magnetic fields.

## 1. Introduction

Given the pervasive presence of non-thermal motions in molecular clouds and evidence for energetically significant magnetic fields, it is tempting to suggest that turbulence and/or magnetic fields play a critical role in determining the stellar initial mass function (IMF). In this discussion, we review several categories of IMF models, and discuss how they are influenced by turbulence and magnetic fields.

On one hand, the IMF can be thought to be determined by a direct mapping from the core (or condensation) mass function (CMF), if the core truly represents a finite mass reservoir for star formation. Alternatively, the IMF may be determined from interactions that happen very close to a forming protostar, as it accretes matter from its parent core. In the latter case, the CMF may not be directly mapped onto the IMF. We review several possibilities in the next two sections.

## 2. The CMF leads to the IMF

The main difficulty to overcome here is the definition of a core itself. A core boundary is not nearly as well defined as a stellar surface, so the mapping of a CMF to IMF is problematic from the outset.

Cores have often been defined as a region within which emission from a certain molecule is detected. This is hardly a physical demarcation.

More recently, near-infrared absorption maps (Bacmann et al. 2000) have captured the merger of a density profile into the background. This may represent a physical boundary. A theoretical definition of a core boundary may rely on the presence of a magnetically subcritical envelope around a supercritical inner region (the core), or it may rely on the (usually larger) gravitational zone of influence of a density peak.

In any case, there are three main candidates for the determination of the CMF: (1) pure gravitational fragmentation; (2) turbulent fragmentation, and (3) magnetically regulated fragmentation. Furthermore, in an extension to these models, the CMF (if clearly definable) may develop a power-law tail due to accretion effects. We treat this as a fourth possibility which is not independent of the first three.

## 2.1 Gravitational fragmentation

Any non-isotropic medium that is dominated by gravity is expected to fragment into Jeans-mass type fragments, through an initial collapse into a sheet, followed by the break up of the sheet. This is the famous Zeldovich (1970) hypothesis in cosmology. In the interstellar medium, sheet-like initial configurations may be promoted by effectively one-dimensional compressions due to supernova shock waves and expanding HII regions, or by relaxation along magnetic field lines. The preferred fragmentation scale in an isothermal non-magnetic flattened sheet of column density  $\Sigma$  is  $\lambda_m = 4.4 c_s^2 / (G\Sigma)$  (Simon 1965), where  $c_s$  is the isothermal sound speed and  $G$  is the gravitational constant. The formation time for a cluster of stars is effectively the sound crossing time across this distance, typically less than a few Myr for most molecular clouds. Mass that does not accrete to one gravitating center is within the gravitational sphere of influence of a neighboring core. We note that the resulting CMF (by any definition) from this kind of fragmentation will likely be peaked around the Jeans mass  $M \sim \Sigma \lambda_m^2$ , but has not yet been calculated in detail.

The most likely candidates for gravitational fragmentation are the embedded clusters in which multiple stars are forming in close proximity, and which account for a majority of star formation (Lada & Lada 2003). However, the above authors also point out that the star formation efficiency (SFE, defined as the fraction of gas mass converted into stars) in these clusters is still quite low, in the 10% - 30% range. Perhaps the feedback effect of outflows can explain at least the upper values ( $\sim 30\%$ ) of SFE's (e.g., Matzner & McKee 2000). A full numerical simulation of the feedback on a cloud from outflows is still prohibitive. However, pure gravitational fragmentation does seem to be excluded as a possibility for

giant molecular clouds (GMC's) as a whole, since their overall SFE is only a few percent (Lada & Lada 2003). This point can be traced back to Zuckerman & Evans (1974).

## 2.2 Turbulent fragmentation

A way to explain the low SFE is to postulate that turbulent support prevents gravitational fragmentation on large scales, but that cores are also created by turbulent compressions. This is broadly consistent with the observation that turbulent motions dominate on large scales but become sub-thermal on dense core scales, in accordance with the well-known linewidth ( $\sigma$ )-size ( $R$ ) relation,  $\sigma \propto R^{0.5}$  (e.g., Solomon et al. 1987). Strong turbulent driving in clouds can explain the overall low SFE (see Vazquez-Semadeni, this volume), by keeping most material in a disturbed and non-self-gravitating state. It has also been shown that isothermal turbulence leads to a lognormal probability density function (pdf) for the gas density (e.g., Padoan, Nordlund, & Jones 1997; Pas-sot & Vazquez-Semadeni 1998; Scalo et al. 1998; Ostriker, Stone, & Gammie 2001; Klessen 2001). Elmegreen (2002) demonstrates that a lognormal density pdf will lead to power-law clump mass distribution when thresholded at various levels, with different indices for different threshold levels. Padoan & Nordlund (2002, see also Padoan in this volume) also demonstrate that a lognormal density pdf is consistent with a power-law CMF given that the power-spectrum is a power law, and assuming that the cores have sizes comparable to the thickness of post-shock gas layers.

In all models of turbulent fragmentation, an important question arises: is the CMF just a property of how cores are defined, or does it represent the finite reservoirs of mass that may be available for star formation? A further problem is that turbulence tends to decay away in a crossing time if not continually driven, so that turbulent fragmentation may quickly give way to gravitational fragmentation. If the latter leads to runaway peaks and star formation within a crossing time, we are again hard pressed to understand the overall low SFE of GMC's.

## 2.3 Magnetically regulated fragmentation

Real interstellar clouds are both turbulent and contain magnetic fields which are in approximate equipartition with gravity (e.g., Crutcher 1999). The turbulence itself likely consists of MHD disturbances. Therefore, a realistic scenario is that of turbulent dissipation followed by magnetically regulated fragmentation in dense regions. The unique features of fragmentation of clouds with near-critical mass-to-flux ratio are: (1)

a longer timescale for collapse than simply the hydrodynamic crossing time, and (2) the outer envelopes may remain supported against global collapse. Basu & Mouschovias (1995) have demonstrated that a magnetically supercritical fragment within a subcritical envelope evolves very rapidly once it is large enough to also be thermally unstable. The resulting collapse scale is smaller than the original fragmentation scale of a subcritical cloud. Hence, an inter-core medium exists which is subcritical and remains in a state of slow evolution. Furthermore, Basu & Ciolek (2004) have demonstrated that even if the background cloud has an exactly critical mass-to-flux ratio, the mass and flux redistribution effected by ambipolar diffusion naturally leads to both supercritical cores and a subcritical envelope.

Magnetic fields may also prevent unstable fragments from becoming extremely elongated, as occurs in models of pure gravitational fragmentation (Miyama, Narita, & Hayashi 1987). Two-dimensional magnetic fragmentation models of Basu & Ciolek (2004) show much milder elongations when magnetic fields are significant, and are in principle more consistent with the inference from observations that cores are overall triaxial but more nearly oblate than prolate (Jones, Basu, & Dubinski 2001). Their results also show that the magnitude of infall motions and the preferred fragmentation scale are dependent on the initial mass-to-flux ratio. Li & Nakamura (2004, also Nakamura this volume) have developed a model of turbulent fragmentation in a subcritical cloud with ambipolar diffusion, also using a two-dimensional simulation. They show that supercritical fragments can be formed in a few Myr, but that the magnetic field helps maintain a relatively low SFE.

A key challenge to this theory is to find the putative subcritical envelopes through highly sensitive Zeeman observations of molecular cloud envelopes. If subcritical envelopes are observed, this will go a long way toward explaining the low inferred SFE. Current magnetic field data is consistent with a near-uniform (and near-critical) mass-to-flux ratio in the column density range  $10^{21} \text{ cm}^{-2} - 10^{23} \text{ cm}^{-2}$ . However, there is an apparent mild bias toward subcritical mass-to-flux ratios at low column densities (Crutcher 2004).

## 2.4 Accretion modification of the CMF

If any of the above scenarios lead to a lognormal initial distribution of core masses, it is possible that the gravitational influence of the core on the surrounding cloud will lead to accretion that alters the distribution of masses  $M$ . An original model of this type is due to Zinnecker (1982), in which Bondi accretion ( $dM/dt \propto M^2$ ) leads to a power-law tail in

the number ( $N$ ) of stars per unit mass interval, i.e.,  $dN/dM \propto M^{-2}$ . This is due to larger initial masses growing at a relatively faster rate. A different model in this category is due to Basu & Jones (2004, see also this volume); they show that an exponential distribution of accretion lifetimes and accretion rate  $dM/dt \propto M$  can lead to a power-law tail in  $dN/dM$ . This can produce an IMF with a lognormal body and a power-law tail. A similar explanation was offered by Myers (2000).

### 3. The IMF from star-core interactions

There are two main ideas for how the IMF may be determined by interactions occurring very close to a forming protostar: (1) outflow limited accretion, and (2) termination of accretion by an ejection process. In an extreme form of this approach, the IMF is irrelevant because infall is terminated before any finiteness of the available mass comes into play.

#### 3.1 Outflow interactions

Strong outflows are present in the earliest observed stages of protostellar accretion (see André, this volume). It has been proposed that winds and/or swept-up outflows can reverse infall (e.g., Shu, Adams, & Lizano 1987). Some IMF models have been developed based on this concept. Adams & Fatuzzo (1996, see also Adams in this volume) have argued that mass accretion will be halted when its rate drops below the mass outflow rate. The presence of a variety of multiplicative input parameters leads them to infer a near-lognormal distribution for the IMF. A similar model has been presented by Silk (1995, see also this volume), which results in a power-law IMF. However, it is still not clear that outflows are sufficiently wide-angled to reverse infall in all directions, so a finite mass reservoir may still be necessary.

The best scenario may be a combination of a nearly finite mass reservoir and the action of outflows to clear residual material. Shu, Li, & Allen (2004) have carried forward the type of model presented by e.g., Basu & Mouschovias (1995) to its logical limit, by studying the accretion onto a protostar from a subcritical envelope. They find that a final equilibrium is possible only if the gravity of the point mass (the protostar) at the core can be offset by unrealistically large amounts of magnetic flux within the protostar. The breakdown of ideal MHD near the protostar will ultimately prevent magnetic levitation of the subcritical envelope, but outflows are invoked as a last line of defense against the low-level infall from the subcritical envelope.

The above scenario may be appropriate to explain isolated star formation as well as cluster formation in which the SFE is quite low. For

regions that give rise to bound open clusters (a distinctively rare occurrence according to Lada & Lada 2003) the SFE must be rather high for the cluster to remain bound. In such cases, a simple gravitational (or highly supercritical) fragmentation model may be adequate.

### 3.2 Competitive accretion

Another process that occurs deep within a core is the interaction between protostars that may have formed in the same core. Multiple protostars come from direct fragmentation during collapse, or from the fragmentation of a circumstellar disk after the first protostar has formed. Bate, Bonnell, & Bromm (2003, see also Bate in this volume) have argued that the IMF can be explained by the evolution of multiple protostars which start out with a mass approximately equal to the Jeans mass for the density  $n \sim 10^{10} \text{ cm}^{-3}$  at which the gas becomes opaque. Dynamical interactions between the protostars then cause them to be ejected from the parent core at various stages of mass accretion from that core. Their simulations show this effect and the calculated protostar mass distributions resemble a lognormal, but may be interpreted as having a weak power-law tail. In this picture, star formation is very efficient, and the problem of low SFE is pushed back to the unmodeled regions outside the cluster-forming cores. Turbulence and magnetic fields are also not required except to understand the outer unmodeled regions.

## 4. Conclusions

Both turbulence and magnetic field effects are important physical processes in molecular cloud evolution, and are a great challenge to theorists due to the complexity of the nonlinear equations that describe them. However, for the purpose of this discussion, it is also worth asking the hard question: do these effects fundamentally affect the IMF? Heyer (this volume) has questioned the existence of any linkage between turbulent properties of a cloud and the rate of star formation within them. Large-scale magnetic fields are also invoked as a formidable opponent to gravity, but if most stars form in local cluster-forming regions which are supercritical, then the magnetic field may not be a dominant effect. On the other hand, magnetic fields are necessary for the generation of outflows, which are in turn invoked to explain why observed dense embedded clusters have an SFE no greater than about 30%. A key outstanding question is whether outflows can really limit the SFE to 30% (or less!) in a highly supercritical cloud region. An ultimate model of star formation will likely have to account for the low SFE of GMC en-

velopes (using turbulent and/or magnetic effects) as well as include the self-consistent feedback effect of outflows upon gravitational collapse.

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