Clustered vs. Isolated Star Formation

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Abstract. I argue that star formation is controlled by supersonic turbulence, drawing for support on a number of 3D hydrodynamical and MHD simulations as well as theoretical arguments. Clustered star formation appears to be a natural result of a lack of turbulent support, while isolated star formation is a signpost of global turbulent support.

1. Introduction

The big question in star formation is not how to form stars, but how to prevent stars from forming. In the Milky Way, slow, continuous star formation is seen, despite the presence of a great deal of gas. The free-fall time for gas is

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} = (1.2 \times 10^7 \text{ yr})(n/10 \text{ cm}^{-3})^{-1/2}, \]

where \( n \) is the number density of the cloud, and I assume the mean molecular mass \( \mu = \rho/n = 3.32 \times 10^{-24} \text{ g} \). Yet, much of this gas must have been around for times of order the Galaxy lifetime of \( 10^{10} \text{ yr} \). How can we explain this? Galaxies show a wide variety of star formation rates, ranging from low surface brightness galaxies with plenty of gas and virtually no star formation, to starbursts with star formation rates sufficient to consume their gas in a small fraction of a Hubble time if sustained. How can we explain the variation between galaxies?

One way out of this problem is for molecular clouds to last far longer than a free-fall time, as was suggested by Blitz & Shu (1980), who argued on the grounds of star formation rate, ages of stars associated with clouds, and positions of clouds behind spiral shocks, for cloud lifetimes of order 30 Myr. Recently, though, much shorter lifetimes for molecular clouds of only 5–10 Myr have been suggested by Ballesteros-Paredes, Hartmann, & Vázquez-Semadeni (1999), based on the lack of observed post-T Tauri stars associated with molecular clouds, and the observation that density enhancements in interstellar medium (ISM) simulations are created and destroyed quickly.

Molecular clouds are observed to have linewidths much broader than thermal, created by hypersonic random motions in the clouds. Such random motions produce strong shocks, which ought to dissipate the energy in roughly a crossing time. The question of how the observed motions can be maintained appears intimately intertwined with the question of how the clouds avoid collapse on a free-fall time.

In what might be called the standard theory of star formation, magnetic fields are invoked to answer both of these questions. If fields are strong enough, they can magnetostatically support clouds against collapse. The star formation
rate would then be determined by the rate of ambipolar drift of neutral gas past ions tied to the magnetic field towards the centers of self-gravitating cores (Mouschovias 1977, Shu 1977). Furthermore, if the fields are strong enough that the Alfvén speed \( v_A \) reaches the rms velocity \( v \), then strong shocks will be converted to MHD waves. As linear Alfvén waves are lossless, it was thought that motions remaining from the initial formation of the clouds might be enough to explain the observation (Arons & Max 1975).

In this review I will explain why both of these ideas now appear questionable. I will call on computations performed with two different methods: Eulerian hydrodynamics and MHD on a grid, using the code ZEUS-3D (Stone & Norman 1992a, b; Clarke 1994; Hawley & Stone 1995; available from the Laboratory for Computational Astrophysics at [http://zeus.ncsa.uiuc.edu/lea_home_page.html](http://zeus.ncsa.uiuc.edu/lea_home_page.html)), and Lagrangian hydrodynamics using a smoothed particle hydrodynamics (SPH) code derived from that described by Benz (1990) and Monaghan (1992), running on special purpose GRAPE processors (Ebisuzaki et al. 1993; Steinmetz 1996), and incorporating sink particles (Bate, Bonnell, & Price 1995).

### 2. Energy Dissipation

Does trans-Alfvénic turbulence decay at a rate substantially slower than hypersonic turbulence? Mac Low et al. (1998) tested this idea by directly computing the decay of 3D hypersonic turbulence with and without an initially uniform magnetic field in a domain with periodic boundary conditions. They found that the kinetic energy of unmagnetized turbulence decayed following a law \( \dot{E}_{\text{kin}} \propto t^{-\eta} \), with \( \eta = 1 \). This result was supported by comparison between ZEUS and SPH results using resolution studies over models ranging from \( 32^3 \) to \( 256^3 \) zones and \( 19^3 \) to \( 70^3 \) particles, respectively. Adding weak magnetic fields, with initial sound speed \( c_s = v_A \), reduced the decay rate only slightly, to \( \eta = 0.91 \). Even a strong magnetic field, with initial \( v_A = v \), decayed with \( \eta = 0.87 \). While the difference in decay rates is of interest to theorists seeking to understand the detailed behavior of MHD turbulence, it is clearly insufficient to explain the observed motions in molecular clouds as coming from their initial conditions. It appears that the interaction of a full set of MHD waves in 3D transfers sufficient power to waves with wavelengths of order the dissipation scale, whatever it may be, to dissipate energy quickly.

To quantify the decay rate of hypersonic and compressible MHD turbulence, Mac Low (1999) used a uniform, fixed pattern of Gaussian perturbations to the velocity field with typical wavenumber \( k \) to drive the turbulence with a fixed energy input rate. The squares in Fig. 1 show that the measured energy dissipation rates for hypersonic unmagnetized turbulence follow the pattern expected from dimensional analysis, with the actual rate given by

\[
\dot{E}_{\text{kin}} = (0.21/\pi)mv^3 \text{,} \tag{1}
\]

where \( m \) is the mass in the cube. The triangles show results from magnetized models with varying field strengths. Weak field models appear to diverge more from the hydrodynamical result as the fields are tangled than strong-field models, where the flow is organized by the field into a roughly 1D flow along the field lines.
Knowing the decay rate allows calculation of the formal decay time $t_d = E_{\text{kin}}/\dot{E}_{\text{kin}}$ in terms of the free-fall time $t_{\text{ff}} = \lambda_J/c_s$, where $\lambda_J = c_s(\pi/G)^{1/2}$ is the Jeans wavelength. Taking their ratio, Mac Low (1999) finds that
\begin{equation}
\frac{t_d}{t_{\text{ff}}} = 1.2 \frac{\lambda_d}{\lambda_J} \frac{\pi}{M_{\text{rms}}} \ll 1,
\end{equation}
where $\lambda_d = 2\pi/k$ is the driving wavelength, and $M_{\text{rms}} = v/c_s$ is the rms Mach number. The driving wavelength needs to be shorter than the Jeans wavelength to provide turbulent support against collapse, as suggested by Bonazzola et al. (1987, 1992), while the typical observed Mach number is substantially higher than $\pi$, so turbulence capable of supporting molecular clouds decays in substantially less than a free-fall time. Thus, the observed motions cannot come from initial conditions unless the clouds are very young, or the motions are very long wavelength.

3. Turbulent Support

Magnetohydrostatic support of molecular cloud cores balanced by ambipolar diffusion allowing collapse appears attractive because it can extend the star formation timescale by more than an order of magnitude. Strong magnetic fields are indeed observed in very dense regions in molecular clouds with $n > 10^6 \, \text{cm}^{-3}$, as can be deduced from water maser measurements (e.g. Elitzur, Hollenbach, & McKee 1992).

However, recent measurements of magnetic field strengths in lower density regions using OH Zeeman measurements have gradually been leading to the conclusion that the field is roughly a factor of two lower than required for magnetostatic support (Crutcher 1999), although the error bars are still of the same size as the measurement. Another piece of evidence against magnetostatic support is the column density contrast of observed cores, which is far higher than...
would be expected for subcritical, magnetically supported cores (Nakano 1998). Finally, the ambipolar diffusion picture would predict that roughly one core in seven had a condensed protostar in its center, while ISO observations reveal as many as one in two (Ward-Thompson, Motte, & Andre 1999).

Supersonic turbulence offers an alternative support mechanism against collapse, as reviewed by Scalo (1985). Analytic work by Léorat et al. (1990) and Bonazzola et al. (1988, 1992) suggested that it would indeed be effective in preventing collapse, but only if the driving wavelength $\lambda_d < \lambda_J$. Numerical models including self-gravity were used to directly test how effective supersonic turbulence is at supporting a region against collapse.

Quantification of star formation rates from our simulations is difficult, as sufficient resolution to follow the collapse and fragmentation of protostellar cores, as specified by Truelove et al. (1997) for grid codes and Bate & Burkert (1997) for SPH, will require adaptive mesh refinement techniques. Instead, we bracket the true behavior with ZEUS and sink particles in the SPH code. Collapsed regions in ZEUS cannot collapse past the grid scale, so remain far too large, and too easily destroyed by passing shocks. On the other hand, mass swallowed by sink particles is never given up, so they give an upper limit to the amount of mass going into the cores, and ultimately into stars.

A region of gas at rest, or one initialized with turbulent motions that are allowed to decay both collapse efficiently (Klessen, Burkert, & Bate 1998; Klessen & Burkert 2000). If we add driving, we get the results shown in the right panel of Figure 1, which shows the fraction of mass going into condensed objects for a number of SPH runs with different driving parameters. All of these runs are formally supported against collapse by the turbulent Jeans criterion, $< M_J >_{turb} = \rho^3 (3\pi/32G)^{1/2} > m$, where $m$ is the mass of the region. Nevertheless, as much as 80% of the mass ends up in collapsed cores, depending on the driving parameters. Stronger driving (larger turbulent Jeans mass) and shorter wavelength driving both inhibit collapse.

The collapse rate can be decreased to values consistent with those observed of a few percent over tens of free-fall times with strong enough driving. To completely prevent collapse, however, requires driving not just strong enough and at short enough wavelengths to support the average density, but rather values a factor of the Mach number $M$ stronger and shorter. Not only must the whole region be supported, but the density enhancements caused by isothermal shocks must also be supported. Isothermal shocks cause compressions proportional to $M^2$, so $< M_J >_{turb} \propto \rho^{-1/2}$ must be increased by $M$ to support them, and correspondingly for the driving wavelength. Magnetic fields do not qualitatively change this conclusion (Heitsch, Mac Low, & Klessen 2001), although they do reduce the rate of collapse for any particular level of driving. Isolated regions of collapse are thus an observational sign of overall turbulent support.

Furthermore, the distribution of resulting condensed objects depends on the properties of the driving as shown in Figure 3. Strong, short-wavelength driving results in condensed cores distributed evenly across the region, reminiscent of low-rate star formation as is seen, for example, in Taurus. Long-wavelength driving, or the absence of driving, on the other hand, leads to clustered core formation, with most of the mass ending up in a rather small region of the total volume. This reproduces the clustering seen not only in regions of massive star
formation like Orion, but also in starburst regions in nearby and distant galaxies.

4. Driving Mechanisms

Both support against gravity and maintenance of observed motions appear to depend on continued driving of the turbulence, as I have described. What then is the energy source for this driving?

Motions coming from gravitational collapse have often been suggested but fail due to the quick decay of the turbulence as described above. If the turbulence decays in less than a free-fall time, then it cannot delay collapse for substantially longer than a free-fall time (Klessen & Burkert 2000).

Protostellar jets and outflows are another popular suspect for the energy source of the observed turbulence. They are indeed quite energetic, but they deposit most of their energy into low density gas, as is shown by the observation of multi-parsec long jets extending completely out of molecular clouds (Bally & Devine 1994). Furthermore, the observed motions show increasing power on scales all the way up to and perhaps beyond the largest scale of molecular cloud complexes (Ossenkopf & Mac Low 2001). It is hard to see how such large scales could be driven by protostars embedded in the clouds.

Another energy source that has long been considered is shear from galactic rotation. Recent work by Sellwood & Balbus (1999) has shown that magnetorotational instabilities (Balbus & Hawley 1991, 1998) could couple the large-scale motions to small scales efficiently. For parameters appropriate to the far outer H I disk of the Milky Way, they derive a resulting velocity dispersion of $6 \text{ km s}^{-1}$, close to that observed. This instability may provide a base value for the velocity dispersion below which no galaxy will fall. If that is sufficient to prevent collapse, little or no star formation will occur, producing something like a low surface brightness galaxy with large amounts of H I and few stars.

In active star-forming galaxies, however, clustered and field supernova explosions, predominantly from B stars no longer associated with their parent gas, appear likely to dominate the driving, raising the velocity dispersion to the 10–
Figure 3. Simulated observations of a supernova-dominated ISM from the model described by Avillez (2000). These are images of column density in three velocity intervals separated by 5 km s\(^{-1}\), viewed from above, in a 1 \times 1 \times 10 \text{kpc} simulation domain. The densest regions are likely to form molecular gas. These slices may be directly compared to the observations of the LMC by Kim, Dopita, & Staveley-Smith (1999).

15 km s\(^{-1}\) observed in star-forming portions of galaxies (see work cited in Mac Low 2000 for example). This provides a large-scale self-regulation mechanism for star formation in disks with sufficient gas density to collapse despite the velocity dispersion produced by the magnetorotational instability. As star formation increases in such galaxies, the number of OB stars increases, ultimately increasing the supernova rate and thus the velocity dispersion, which will restrain further star formation.

Supernova driving not only determines the velocity dispersion, but may actually form molecular clouds by sweeping gas up in a turbulent flow. A snapshot of such a flow is shown in Figure 4. The densest regions are formed by shock-wave interactions (cooling is included, but not self-gravity) on a dynamical timescale, and disperse on the same short timescale. The domain shown is 1 kpc\(^2\), giving dynamical timescales of a few million years, as estimated by Ballesteros-Paredes et al. (1999) for the lifetime of molecular clouds.

5. Final Thoughts

Support by driven supersonic turbulence balanced against self-gravity appears able to explain a number of things, including the timescales for star formation, the observed supersonic motions in molecular clouds, their filamentary, clumpy morphology, the different modes of star formation observed, and ultimately the difference between steady, low-efficiency star formation and starburst behavior. It is consistent with observed magnetic fields, although they do not play a central role. Open questions in this picture are then: 1) Can we derive a quantitative star formation rate given the velocity dispersion and local density of the gas? 2) What determines global behavior such as the Schmidt law for star formation? 3) Are supernovae the primary mechanism driving the turbulence?

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