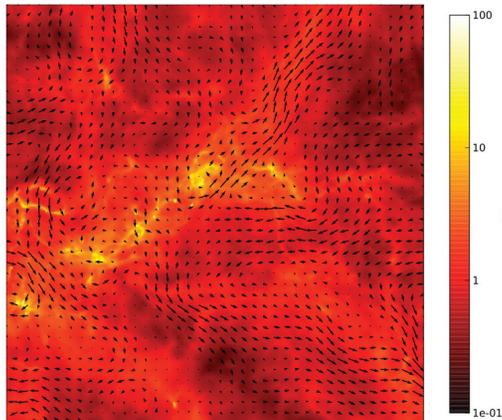


The Two States of Star Forming Clouds: AMR MHD Simulations of Self-Gravitating Turbulence

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Star formation is one of the most fundamental unanswered problems in astrophysics. In order to build a more complete picture of star-forming clouds in the galaxy, we performed a suite of high-resolution adaptive mesh refinement (AMR) magnetohydrodynamics (MHD) simulations of self-gravitating supersonic turbulence. The simulations used large (512^3) root grids and four levels of refinement for an effective resolution of 8192^3 . Mach 10 turbulence with a variety of magnetic field strengths was used. We find that the effects of self-gravity bifurcate the cloud into two distinct states: a low-density turbulent state, and a high-density self-gravitating state that can be described by an ensemble of self-similar spheres. This improved description of the statistical properties of star-forming clouds will impact star formation models, which to date have dealt with turbulence alone. Magnetic fields decrease compressibility of the gas and prevent sub-Alfvénic gas from collapsing. This can be used to explain the somewhat conflicting observations of the role of magnetic fields in the galaxy.

Fig. 1. Projected density in a subset of the domain in the mid-field strength simulation. Prestellar cores are seen in yellow in the center, collected along a filament formed from the intersection of shocks. Vectors show strength and direction of the magnetic field, showing that the prestellar objects are formed in regions where the field is weak and not aligned perpendicular to the shock.



Star formation rates are observed to be significantly lower than expected from free fall alone. The two primary physical mechanisms for delaying the collapse are turbulence and magnetic fields, though the relative importance of these two effects has been hotly debated over the past fifty years [1,2]. Molecular clouds, the birthplace of nearly all stars, are observed to be both supersonically turbulent and magnetized. Unfortunately, numerical simulation of these clouds is computationally challenging because the proper resolution of turbulence requires high-resolution simulations, and the collapse involves enormous dynamic range. The advent of adaptive-resolution magnetohydrodynamics (MHD) methods [3] and the increase in computing power have allowed us to overcome these numerical restrictions and examine these systems in better detail.

We began three simulations with uniform density and magnetic fields, with a resolution of 512^3 . The three field strengths were chosen so that they had initial thermal-to-magnetic pressure ratios, $\beta_0 = 0.2, 2,$ and 20 . The boxes were stirred at fixed resolution by a large-scale driving pattern until a statistically steady state was achieved, with a mean Mach number of 9. Then gravity and adaptive mesh refinement (AMR)

were introduced, and the simulation was evolved for 0.6 times the free-fall time at the mean density. In this time, the low-density gas was relatively unaffected by gravity, while the gas that was compressed by shocks during the driving phase was further collapsed into material that approximates self-similar collapse solutions developed earlier. Figure 1 shows a projection through one of the simulations at the end of the collapse phase. This illustrates the filamentary structure that accompanies many observed star-forming regions. The vectors show the direction and magnitude of the magnetic field. The collapsing region coincides with reduced magnetic-field strength, while the region where the field aligns with the filament is supported against collapse by magnetic pressure.

The probability density function (PDF) of supersonic isothermal turbulence has been shown to follow a lognormal distribution [4]. This lognormal has been used to predict a number of properties of star-forming clouds, such as the initial mass function of stars and the star formation rate [2,5]. While magnetized gas is not strictly lognormal, we find that the approximation is reasonable. We also find that the addition of self-gravity introduces an excess of high-density gas, which forms a powerlaw tail. The slope of this powerlaw can be understood to be the product of self-similar collapse of the gas. Figure 2 shows the density PDF, $V(\rho)$, for each simulation ($\beta_0 = 0.2$ in red, $\beta_0 = 2$ in

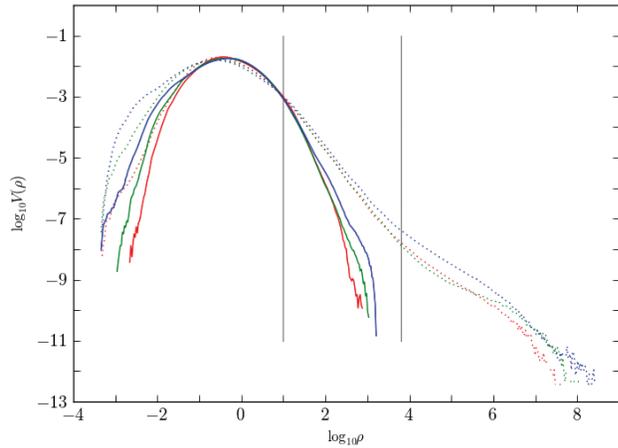


Fig. 2. Density probability distribution function for the early turbulent gas (solid lines) and the late time collapse gas (dotted lines), with red, green and blue lines showing the $\beta_0=0.2, 2, \text{ and } 20$ respectively. Grey lines separate the low-density turbulent state (left) from high-density collapsing state (middle) and very-high-density gas that is numerically unresolved. Turbulence generates a lognormal density PDF, while gravity generates a powerlaw.

green, and $\beta_0 = 20$ in blue) at the beginning (solid lines) and the end (dotted lines) of the self-gravitating phase. The figure additionally shows two grey lines that divide the gas into three sections: low-density turbulent gas (left section), high-density self-gravitating gas (center section), and very-high-density gas that is numerically unresolved (right section). This gas is qualitatively interesting, but due to numerical inaccuracies is not quantitatively reliable. For the early snapshot, a lognormal is seen in all three simulations. The late snapshot shows the development of the powerlaw tail at high density, while retaining the lognormal shape at low

density. Self-similar collapse solutions have the form of a powerlaw density distribution, $\rho \propto r^m$. This in turn gives a volume PDF $V(\rho) \propto \rho^m$, where $m = \frac{3}{n}$.

We find that the slope m increases with decreasing field strength, with $m=-1.8$ for the strongest mean field strength, and $m=-1.64$ for the weakest.

Magnetic fields are extremely difficult to observe in space, and we often must rely on circumstantial evidence to infer the strength of the magnetic field. Recent observations have shown that velocity scaling is anisotropic in some molecular clouds [6]. This is expected in strongly magnetized turbulence, as eddies are elongated in the direction of the mean magnetic field, which indicates that molecular clouds are magnetically dominated. However, this anisotropy decreases as the density increases. At stellar densities, the direction of outflows from young stellar objects is uncorrelated with the local magnetic field [7]. These observations indicate that, at some point, collapsing objects must decouple from the mean magnetic field. This behavior is also seen in, and can be explained by, our simulations. We find that the high-density state is super-Alfvénic for all values of the mean field. Figure 3 shows the ratio of dynamic pressure to magnetic pressure, β_{dyn} versus density

for the strong field case. While the low-density gas is evenly distributed around $\beta_{\text{dyn}}=1$, the high-density gas is dynamically dominated by a factor of 100. This is due to the fact that the magnetic field reduces the compressibility of the gas, thus the density in shocked material, and the dynamic pressure must overcome magnetic pressure in order to increase the density of gas to a point at which it begins to collapse.

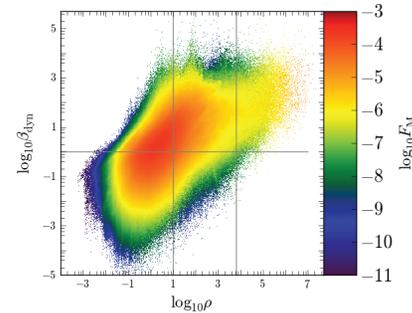


Fig. 3. Dynamic-to-magnetic pressure ratio, β_{dyn} , versus density for the strong field simulation after gravity has acted. Vertical grey lines separate turbulent (left), collapsing (middle) and unresolved (right) gas. Color shows mass fraction. Nearly all high-density gas is dominated by kinetic energy, even though the mean field is strong, similar to what is observed in nature.

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