Molecular Cloud Support, Turbulence, and Star Formation in the Magnetic Field Paradigm

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Star Formation Rate is LOW

A key issue on the Large Scale

Total molecular (H$_2$) gas mass

\[ M_{tot} \approx 10^9 \, M_{\text{sun}} \]

Dynamical time (for gravity-driven fragmentation and collapse)
Avg. \( n = 100 \, \text{cm}^{-3} \)

\[ t_d \approx \frac{1}{2} \frac{1}{\sqrt{G \rho}} \approx 3 \times 10^6 \, \text{yr} \]

Implied star formation rate (SFR)

\[ \dot{M}_{SF} \approx \frac{M_{tot}}{t_d} \approx 300 \, M_{\text{sun}} / \text{yr} \]

BUT, observed Galactic SFR is

\[ \dot{M}_{SF,obs} \approx 1 - 5 \, M_{\text{sun}} / \text{yr} \]

e.g. Williams and McKee (1987), Misiriotis et al. (2006), Robitaille & Whitney (2010), and many others
Taurus - low SFR in a single cloud

Goldsmith et al. (2008): Stellar mass only \( \sim 1\% \) of total mass. Most of cloud is empty of “cores”. Mass is mostly in the low density “envelope”.

Heyer et al. (2008): Polarization of starlight plus velocity data → low density regions are magnetically dominated.

Goldsmith et al. (2008), \(^{12}\text{CO} \) emission

Striations of gas emission consistent with magnetically-dominated envelope.
Pipe Nebula – $B$ dominates?

Magnetically regulated cloud formation?

Pipe (and Taurus) → formed by flow or contraction along $B$?

Alves, Franco, & Girart (2008)
Stability Analysis with $B$

Critical magnetic field if

$$\frac{B^2}{8\pi} = \frac{\pi}{2} G\Sigma^2$$

$\Sigma = \text{surface density of sheet}$

Magnetic pressure, self-gravitational pressure

$\mu = \frac{\Sigma}{B} 2\pi G^{1/2} < 1$
Subcritical cloud
No fragmentation occurs

$\mu = \frac{\Sigma}{B} 2\pi G^{1/2} > 1$
Supercritical cloud
Fragmentation occurs

When magnetic flux-freezing applies:
MC Progenitors are H I Clouds

Flux freezing in HI gas ➔ Significant regions of molecular clouds may be subcritical.
Ambipolar Diffusion $\Rightarrow B$ diffuses relative to neutral gas

Gravitationally-driven inward neutral drift, championed by Mouschovias (1978, and onwards)

Surface density of neutral gas, $\Sigma$, can grow with lesser increase of magnetic field strength $B$.

The mass-to-flux ratio $\mu$ is then increased in some regions.

The process works fastest in regions of strong magnetic field gradient – it is a nonlinear diffusion process.

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Turbulence and AD in a fully 3D Model

Nonlinear initial velocity field

\[ v_k^2 \propto k^{-4} \]

allowed to decay

rms amplitude

\[ v_a = 3c_s \approx v_{\text{Alf}} \]

trans-Alfvénic

\[ \mu_0 = 0.5 \]

Gas density in midplane (z=0)

A vertical slice of gas density


Box width = 2.5 pc

Earlier 64 x 64 x 40 cells, now running 256 x 256 x 40.
How Does Turbulent Ambipolar Diffusion Work?

Runaway collapse of the first core occurs almost 10 times faster.

Early turbulent compression

$$\tau_{AD} \propto L^{5/2} \Rightarrow \beta \uparrow \text{ quickly as } L \downarrow$$

Later evolution at higher mean density than in initial state

$$\beta \uparrow \text{ continues more slowly}$$

Rapid contraction when/where $$\beta > 1$$.

$$\beta$$ is a proxy for $$\mu$$.

Kudoh & Basu (2008)
Large-Scale Subcritical B $\rightarrow$ low SFE

Nakamura & Li (2008): subcritical cloud fragment plus AD, sink cells, and feedback, and study long-term evolution

$t_s \approx 2t_{ff}$
Magnetic Model (Thin Disk Approx.)

Finite difference solution on (x,y) grid. Periodic BC’s in (x,y) directions. Vertical (z) structure assumed to be in hydrostatic equilibrium. External magnetic field effects included. Model is “global” vertically, and “local” horizontally.


Start evolution by superposing either linear or nonlinear perturbations on uniform background state.
Turbulent Decay — Usually Fast, but...

Basu, Ciolek, Dapp, & Wurster (2009)

Turbulent non-compressive IC’s with AD

Turbulent compressive IC’s and flux-freezing; fluctuations persist!

Turbulent compressive IC’s with AD
Dispersion relation for small-amplitude perturbations on a magnetized sheet (flux-freezing)

\[ \omega^2 = \left( V_A^2 + c_s^2 \right) k^2 + 2\pi G\sigma_{n,0} \left( \mu_0^{-2} - 1 \right) |k| \]

Leads to magnetosonic mode in sheet

Grav. Instability if \( \mu_0 > 1 \), magnetic tension driven waves if \( \mu_0 < 1 \) (subcritical)

\[ v_{ph} \equiv \frac{\omega}{k} = \sqrt{\left( \mu_0^{-2} - 1 \right) G\sigma_{n,0}} \lambda \]

Strong B and Flux freezing → Long-lived oscillations

Thin disk model with effect of external magnetic field

Magnetic tension driven waves

A possible model for UV photoionized molecular cloud envelopes.

\[ v_{ph} = \sqrt{(\mu^{-2} - 1)G\sigma_{n,0}\lambda}, \]
\[ \mu = 0.5, \lambda = 8c_s^2/G\sigma_{n,0} \]

(box size)

\[ \Rightarrow v_{ph} \approx 5c_s. \]

Residual rms material motions < 40% of \( v_{ph} \) can persist; residual \( v_{rms} \sim 1.6 \, c_s \) in this model.

Basu & Dapp (2010), also Basu, Ciolek, Dapp, & Wurster (2009)
Magnetic Fields and Origin of the CMF

\[ \mu_0 = 0.5 \]

\[ x' = x / (2\pi Z_0), \text{ etc.} \]

Periodic isothermal thin-sheet model.
Initial small amplitude perturbations. \( B \) is initially normal to sheet.

\[ \mu_0 = 2.0 \]

\[ \mu_0 = 1.1 \]

Column density and velocity vectors (unit 0.5 \( c_s \)).
Note variation in sizes, shapes, velocity fields.

Basu, Ciolek & Wurster (2009, NewA, 14, 221)
Magnetic Fields and Origin of the CMF

Add results from a range of models with $\mu_0 = 0.5$ to $\mu_0 = 2.0$.

Get a broad distribution of core masses if $\mu_0$ varies in a single cloud, i.e. in the core-forming region.

Cumulative histogram of 1524 cores from over 400 separate simulations

Basu, Ciolek & Wurster (2009)
Magnetic Field Geometry reveals Ambient Conditions

Extensive parameter study in two papers:
Basu, Ciolek & Wurster (2009, NewA, 14, 221)
Basu, Ciolek, Dapp, & Wurster (2009, NewA, 14, 483)

Above: strong $B$ model.
Right: moderate $B$ model

Below: moderate field with nonlinear flow IC’s

Velocity fields can also be used to decipher initial conditions. Also, core spacing and shapes differ in alternate scenarios.
• Strong magnetic fields in molecular cloud envelopes are interesting!
• Subcritical large-scale magnetic fields and turbulent IC’s can in principle explain observations of low star formation rate with an early onset
• Long-lived turbulent motions may be possible due to global effect of interaction with external magnetic field
  Works for subcritical magnetic field and effective flux-freezing, as may apply to molecular cloud envelopes
• A narrow range of initial mass-to-flux ratios (centered on the critical value) in dense core-forming regions can explain a broad range in the core mass function
• Magnetic field line curvature from polarimetry can be used as a new proxy for measuring magnetic field strength