Magnetic Fields and the Formation of Cores and Disks

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New Trends in Radio Astronomy in ALMA Era
Hakone, Japan
Tuesday, December 4, 2012
Star Formation and nonthermal motions in Taurus

sound speed
$c_s \approx 0.2 \text{ km/s}$

velocity dispersion
$\sigma \approx 0.6 \text{ km/s}$

$\sigma \approx 0.25 \text{ km/s}$

Onishi et al. (2002)
Magnetic Fields: Are Molecular Clouds Subcritical or Supercritical?

\[
\mu = \frac{\Sigma}{B} 2\pi G^{1/2}
\]

\[
\ll 1, \approx 1, \text{ or } \gg 1 ?
\]
Striations of gas emission consistent with magnetically-dominated envelope.

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

Palmierim et al. (2012).
Scenario

Supercritical high-density regions assembled by large scale flows/turbulence
\[ \mu \approx 1 \text{ is interesting!} \]

For partially ionized sheet, with half thickness \( Z_0 \).

\[ x_i = 10^{-7} \left( n_n / 10^4 \text{ cm}^{-3} \right)^{-1/2} \]

Cosmic ray ionization

\[ \tau_{g,m} \approx 10 \frac{Z_0}{c_s} \]

Ambipolar diffusion time

\[ \tau_{AD} \]

Fragmentation time scale

\[ \tau_{g,m} = \frac{Z_0}{c_s} \]

dynamical time

Magnetic Fields and Origin of the CMF

\[ \frac{\tau_{ni,0}}{t_0} = 0.2 \text{ (dotted line)} \]

\[ \Lambdabar_{g,m} = \frac{\pi^2}{4} \sum \lambda_{g,m}^2 \]

Can vary dramatically even with a narrow range of \( \mu_0 \).

\[ \lambda_{g,m} = 2\pi Z_0 \]

Standard value for CR ionized region

\[ x_i = 10^{-7} \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/2} \]

Ciolek & Basu (2006), see also Bailey & Basu (2012)
Magnetic Fields and Origin of the CMF

Initial small amplitude perturbations. $B$ is initially normal to sheet.

Periodic isothermal thin-sheet model.

Column density and velocity vectors (unit $0.5 \, c_s$)

Note irregular shapes with NO strong turbulence.

$\mu_0 = 0.5$

$x' = x / (2\pi Z_0)$, etc.

$\mu_0 = 2.0$

$\mu_0 = 1.1$

$\mu_0 = 10$
Two stage fragmentation

Ionization versus column density depth in a cloud – based on calculations of Ruffle et al. (1998)

Taurus Molecular Cloud (Onishi et al. 1998)
A transcritical cloud can start to fragment on long (~ Myr) time and (~pc) length scales, then undergo a subfragmentation on much smaller time and length scales once $x_i$ drops to cosmic ray ionization level.

Clump fragmentation and core subfragmentation may occur in shaded regions.

See poster #49 by Nicole Bailey that also includes some simulation results.
Core Mass Function

Hydrodynamic case

Lognormal column density pdf

Lognormal core mass function

\[ \lambda_{g,m} = \frac{2c_s^2}{G\Sigma} \]
Core Mass Function (MHD)

with magnetic field, flux freezing

also add ambipolar diffusion

Bailey & Basu (2013)
Core Mass Function (MHD)

Hydrodynamic

Ideal MHD

Non-ideal MHD

lognormal

broad tail

high mass truncation

Bailey & Basu (2013)
Hourglass Magnetic Fields

Recipe: large-scale background field + gravitational contraction + self-inductance.

Observation: NGC 1333 IRAS 4A, Girart et al. (2006)

Theory, e.g., Kudoh & Basu (2011)

Dashed lines are for flux-frozen model (extreme flaring of FL’s leads to braking catastrophe). Solid lines are for non-ideal MHD model (note relaxation of FL shapes within 10 AU).
Disk can form on small scales

At this time, Central mass $< 10^{-2} M_\odot$
Disk size $\approx 10R_\odot$

Dapp, Basu, and Kunz (2012)

The MB catastrophe!

Disk formation evidenced by:

- Toomre Instability
- Infall speed drops to zero
- Centrifugal balance

The MB catastrophe!
How to build large (low-mass) class II disks?

Potential problem: magnetic field dissipation zone only several AU in radius.

Solutions:

1. Disk formation may end with a small high-mass disk that grows at later times into a large low-mass disk due to angular momentum redistribution. For example

\[ R_{disk,\,init} = 5 \text{ AU} \quad \text{and} \quad \frac{M_{disk,\,init}}{M_{star}} = 0.1 \]

leads to

\[ R_{disk,\,final} \approx 500 \text{ AU} \quad \text{if} \quad \frac{M_{disk,\,final}}{M_{star}} = 0.01 \]

i.e., \( R_{d,\,final} \approx R_{d,\,init} \left( \frac{m_{disk,\,init}}{m_{disk,\,final}} \right)^2 \)

2. Late time disk formation epoch may occur with large centrifugal radius for outermost mass shells, since magnetic braking may be cut off by lack of envelope matter (Machida, Inutsuka, & Matsumoto 2011).

ALMA objective: characterize sizes of class 0 disks.
• Subcritical common envelope may explain lack of star formation in much of molecular cloud area
• Fragmentation may begin in transcritical regime, leading to clumps, then proceed to a second-stage cluster fragmentation event when UV shielding sets in
• Core Mass Function can be quite broad due to (transcritical) magnetic field strength distribution and ambipolar diffusion
• Core collapse initially accompanied by field-line dragging (hourglass pattern). But microphysics $\rightarrow$ significant flux loss within several AU scale near center
• Theory predicts small centrifugal disk ($\sim 10$ AU) in class 0 phase (ALMA target) and disk expansion or magnetic braking shut-off at late times to yield larger disk by class II phase