Protostellar Outflow-Driven Turbulence

A Numerical Look

M. Gorelick C. Matzner

University of Toronto,
Dept Astronomy/Astrophysics

AST425 Presentations, 2009

Outline

Problem With Molecular Clouds

Star Formation Rates

- Using classical theory, $SFR_{ff} = 1.0$
  - We observe $SFR_{ff} \approx 10^{-1.7}$. [Krumholz and Tan, 2007]
  - Solar system needs a relatively sparse cloud for current stability.

Cloud Stability

- Should collapse within t_{ff}
- Clouds are very diffuse
  - Far more mass is lost than converted to stars

Problem With Molecular Clouds

Star Formation Rates

- Using classical theory, $SFR_{ff} = 1.0$
  - We observe $SFR_{ff} \approx 10^{-1.7}$. [Krumholz and Tan, 2007]
  - Solar system needs a relatively sparse cloud for current stability.

Cloud Stability

- Should collapse within t_{ff}
- Clouds are very diffuse
  - Far more mass is lost than converted to stars

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
    - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
    - Too infrequent.
    - Requires mature stars
- HII Regions?
    - Falls short for dense/compact clouds.
    - Requires O/B type stars.
- Protostellar Outflows?
    - Outflows seem to be wherever protostars are
    - Happen often, early, and more energy than HII
    - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Possible Solutions

- Intrinsic Turbulence?
  - Decays quickly [Stone et al., 1998, Low, 1999]
- Supernovae?
  - Too infrequent.
  - Requires mature stars
- HII Regions?
  - Falls short for dense/compact clouds.
  - Requires O/B type stars.
- Protostellar Outflows?
  - Outflows seem to be wherever protostars are
  - Happen often, early, and more energy than HII
  - Good agreement to observation & past work [Nakamura and Li, 2007, McKee and Ostriker, 2007]

Project Scope

- Implement model for supersonic protostellar-outflow driven turbulence by Matzner [2007]
- Verify some of the model's claims:
  - Collimation results in stronger turbulent line-widths
  - Characteristic lengths and times are increased in the collimated regime
  - Velocity dispersion displays features at the characteristic scales
  - Energy spectrum follows Burger turbulence [Kida, 1979]

Dimensional Analysis

[Matzner, 2007]

- Fundamental quantities: $\mathcal{I}\left[\frac{kg\cdot m}{s}\right]$, $\mathcal{S}\left[\frac{\#}{s\cdot m^3}\right]$, $\rho_0\left[\frac{kg}{m^3}\right]$.

$$m=\left(\frac{\rho_0^4\mathcal{I}^2}{\mathcal{S}^2}\right)^{1/7},\ \ell_{merge}=\left(\frac{\mathcal{I}}{\rho_0\mathcal{S}}\right)^{1/7},\ t_{merge}=\left(\frac{\rho_0^3}{\mathcal{I}^3\mathcal{S}^4}\right)^{1/7}$$

$$v_{merge}=\frac{\ell_{merge}}{t_{merge}}=\left(\frac{\mathcal{I}^4\mathcal{S}^3}{\rho_0^4}\right)^{1/7}$$

NGC1333

$$\mathcal{I}=10^{39.6}g\,cm\,s^{-1},\ \mathcal{S}=10^{-67.2}cm^{-3}\,s^{-1},\ \rho_0=10^{-19.6}g\,cm^{-3}$$

$$\Rightarrow \ell_{merge}=0.38pc,\ t=0.34Myr,\ m=19M_\odot,\ \ell/t=1.1km\,s^{-1}$$

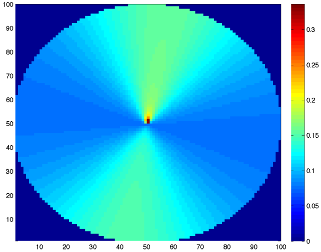
Collimation

- Physical outflows are not spherical.

$$\hat{\mathcal{I}}(\phi) = \mathcal{I}P(\phi)$$

$$P(\phi) = \mathcal{X}(\theta_0) \cdot \frac{1}{1+\theta_0^2 - cos(\phi)^2}$$

[Matzner and McKee, 1999]



Turbulence Analysis

- Velocity Dispersion: $\sigma(\ell_{merge})^2 = \lambda^2 \frac{\mathcal{SI}}{\rho_0} \ell_{merge}.$
  - $\lambda =$ Coupling Coefficient
- Enhancement Factor: $\varepsilon = \left. \frac{\sigma^2_{\theta_0 \neq \infty}(\ell_{merge})}{\sigma^2_{\theta = \infty}(\ell_{merge})} \right|_{t \gg t_{merge}}$
  - Ratio of effective pressures from collimated and un-collimated.
- Energy Spectrum: $E(k) = A \frac{\mathcal{SI}}{\rho_0} k^{-2}$

Note:

$$\frac{\mathcal{SI}}{\rho_0} \sim \frac{\# \cdot m^2}{s^2}$$

The Code

- 2^{nd} order rTVD (Relaxing Total Variation Diminishing) (based on Pen et al., 2003)
  - Solves evolution of conserved quantities
  - Pure Hydrodynamics
  - Strict Isothermal (No $\gamma = 1 + \epsilon$ tricks!)
  - Restrict motion to .95dx per dt
- The Grid
  - 400^3 cells (Thanks to MPI/openMP)
  - Simulation units
    - $dx = c_s = \rho_0 = 1$
  - Periodic Boundry

Fixing Instabilities

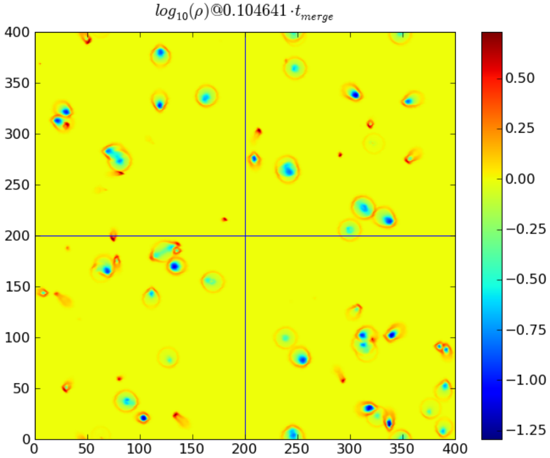
- Set the freezing speed to be constant throughout the grid
  - Limits the flux through cell boundaries [Jin and Xin, 1995]
- Injected mass along with momentum
  - $P(|\phi|) \cdot \frac{3\mathcal{I}}{4\pi r_{inj}^{3} v_{max}} \cdot dx$
  - Avoids unnaturally large velocities in low density regions
  - Scale momentum/density by $\frac{M_{tot}}{M_{tot}+dM}$ to keep density constant

Run Parameters

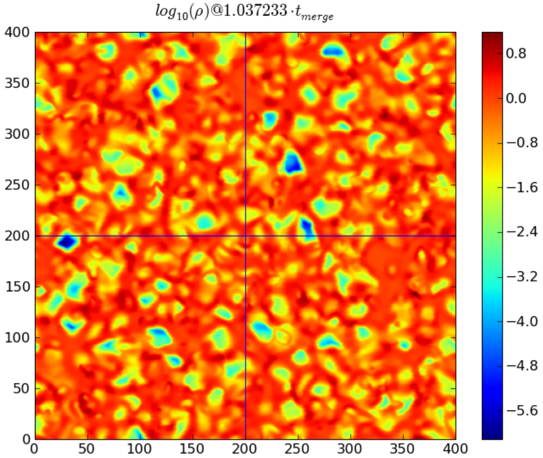
Run #	$\mathcal{I}$	$\mathcal{S}$	θ_0	l_{merge}	v_{char}	t_{merge}	L_{box}
I	20000	$1.5625 \cdot 10^{-5}$	∞	$8dx$	$2.5c_s$	$8\sqrt{\frac{c_s}{dx}}$	$400dx$
II	20000	$1.5625 \cdot 10^{-5}$	0.5	$8dx$	$2.5c_s$	$8\sqrt{\frac{c_s}{dx}}$	$400dx$
III	20000	$1.5625 \cdot 10^{-5}$	0.05	$8dx$	$2.5c_s$	$8\sqrt{\frac{c_s}{dx}}$	$400dx$
IV	16000	$1.25 \cdot 10^{-5}$	∞	$10dx$	$2.0c_s$	$10\sqrt{\frac{c_s}{dx}}$	$400dx$
V	16000	$1.25 \cdot 10^{-5}$	0.5	$10dx$	$2.0c_s$	$10\sqrt{\frac{c_s}{dx}}$	$400dx$
VI	20000	$1.5625 \cdot 10^{-5}$	∞	$8dx$	$2.5c_s$	$8\sqrt{\frac{c_s}{dx}}$	$200dx$

Chose parameters to vary: $\frac{\ell_{merge}}{L_{box}}, \frac{v_{char}}{\sigma_{turb}}, \frac{\ell_{merge}}{r_{inj}}$

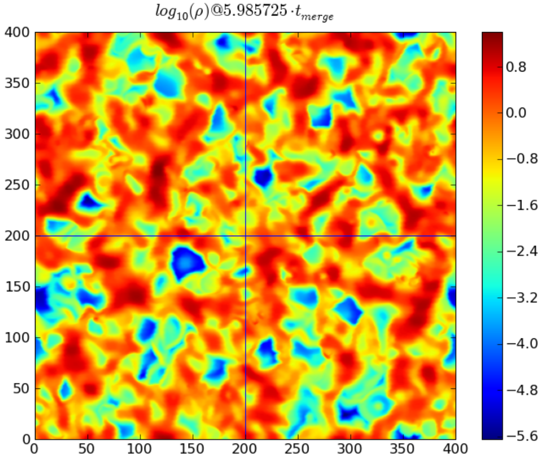
Collimated Density



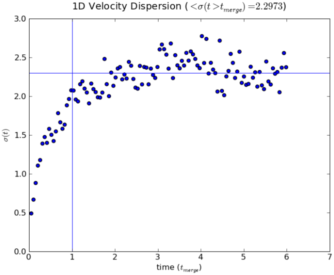
Collimated Density

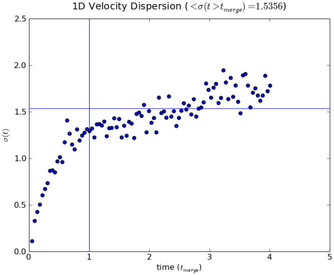


Collimated Density



Velocity Density





Coupling Coefficient

Run	θ_0	t_{merge}	λ^2
I	∞	$8\sqrt{\frac{c_s}{dx}}$	0.49
II	0.5	$8\sqrt{\frac{c_s}{dx}}$	0.64
III	0.05	$8\sqrt{\frac{c_s}{dx}}$	0.84
IV	∞	$10\sqrt{\frac{c_s}{dx}}$	0.54
V	0.5	$10\sqrt{\frac{c_s}{dx}}$	0.81
VI	∞	$8\sqrt{\frac{c_s}{dx}}$	0.48

- Collimated runs injects more momenta into the medium
  - Coupling coefficient seems to follow:
    - $\lambda^2_{col} \approx \mathcal{F}(\mathcal{I}, \mathcal{S}, \rho_0) \cdot \ln\left(\frac{1-\theta_0}{\theta_0}\right) + \lambda^2_{sph}$ with

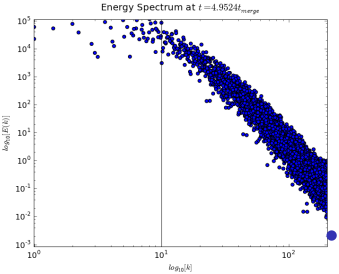
$$\mathcal{F}(\mathcal{I}, \mathcal{S}, \rho_0) = \begin{cases} 0.11; & Runs\ I/II/III \\ 0.25; & Runs\ IV/V \end{cases}$$

Enhancement Parameter

Run	θ_0	v_{merge}	ε
II	0.5	$2.5c_s$	1.71
III	0.05	$2.5c_s$	2.94
V	0.5	$2.0c_s$	2.25

- As expected, $\varepsilon > 1$
- Enhancement clearly dependent on merging velocity and collimation

Energy Spectrum



- $k > \ell_{merge}^{-1}$ shows the cascading of the momentum to lower scales
  - Follows $E \sim k^{-\beta}$ *with* $\beta \sim 4$ *instead of* $\beta = 2$ *for* $k > \ell_{merge}^{-1}$
    - Also seen by others [Carroll et al., 2009]
    - Explainable by shock waves sweeping up small-scale eddies
- $k \leq \ell_{merge}^{-1}$ shows turbulence effecting global dynamics
  - Expected since grid is saturated with outflows!

Conclusion

Current

- Most predictions from Matzner [2007] have been valid
- We have shown characteristics of supersonic outflow-driven turbulence
- Preliminary connection between spherical and collimated

Soon

Now that there are no more instabilities......

- More runs to determine $\mathcal{F}(\mathcal{I}, \mathcal{S}, \rho_0)$ more accurately
- Better characterize the $\beta \sim 4$ relation in energy spectrum
- Thorough analysis of possible numerical error

References

Jonathan J Carroll, Adam Frank, Eric G Blackman, Andrew J Cunningham, and Alice C Quillen. Outflow-driven turbulence in molecular clouds. *The Astrophysical Journal*, 695:1376, Apr 2009. doi: 10.1088/0004-637X/695/2/1376. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2009ApJ...695.1376C&link_type=ABSTRACT.

S Jin and Z Xin. The relaxation schemes for systems of conservation laws in arbitrary space dimensions. *Communications on Pure and Applied Mathematics*, Jan 1995. URL http://www3.interscience.wiley.com/journal/113401027/abstract.

S Kida. Asymptotic properties of burgers turbulence. *Journal of Fluid Mechanics*, 93:337, Jul 1979. doi: 10.1017/S0022112079001932. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=1979JFM....93..337K&link_type=ABSTRACT.

Mark R Krumholz and Jonathan C Tan. Slow star formation in dense gas: Evidence and implications. *The Astrophysical Journal*, 654:304, Jan 2007. doi: 10.1086/509101. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2007ApJ...654..304K&link_type=ABSTRACT. (c) 2007: The American Astronomical Society.

Mordecai-Mark Mac Low. The energy dissipation rate of supersonic, magnetohydrodynamic turbulence in molecular clouds. *The Astrophysical Journal*, 524:169, Oct 1999. doi: 10.1086/307784. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=1999ApJ...524..169M&link_type=ABSTRACT.

Christopher D Matzner. Protostellar outflow-driven turbulence. *arXiv*, astro-ph, Jan 2007. URL http://arxiv.org/abs/astro-ph/0701022v1. 15 pages, 3 figures, submitted to ApJ.

Christopher D Matzner and Christopher F McKee. Bipolar molecular outflows driven by hydromagnetic protostellar winds. *arXiv*, astro-ph, Sep 1999. URL http://arxiv.org/abs/astro-ph/9909479v1. 4 pages, 1 figure, submitted to ApJL.

Christopher F McKee and Eve C Ostriker. Theory of star formation. *Annual Review of Astronomy & Astrophysics*, 45:565, Sep 2007. doi: 10.1146/annurev.astro.45.051806.110602. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2007ARA%2526A..45..565M&link_type=ABSTRACT.

Fumitaka Nakamura and Zhi-Yun Li. Protostellar turbulence in cluster forming regions of molecular clouds. *Triggered Star Formation in a Turbulent ISM*, 237:306, Jan 2007. doi: 10.1017/S1743921307001640. URL http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2007IAUS..237..306N&link_type=ABSTRACT.

Ue-Li Pen, Phil Arras, and ShingKwong Wong. A free, fast, simple, and efficient total variation diminishing magnetohydrodynamic code. *The Astrophysical Journal Supplement Series*, 149: 447, Dec 2003. doi: 10.1086/378771. URL http://adsabs.harvard.edu/cgi-bin/nph-data