Linking numerical simulations of molecular cloud structure with observations

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Ophiuchus

The Pipe Nebula
More dense gas

Less dense gas

Kainulainen et al. (2009)
Federrath (2013)

solenoidal driving

compressive driving

Federrath (2013)
Why do we need to understand molecular cloud structure?

I: **Star formation** is linked to the internal cloud structure.

II: Cloud structure **carries imprints** of fundamental physical processes.
Log Probability Distribution Function (PDF)

Log (density, $\rho$), or
Log (projected density, $N$)

$$\sigma_s^2 = \ln \left( 1 + b^2 M^2 \frac{\beta}{\beta + 1} \right)$$

Molina et al. (2012)

$M \sim$ turbulence energy, $b \sim$ compression, $\beta \sim$ magnetic field energy

see also, e.g., Vazquez-Semadeni et al. (1994); Padoan et al. (1997); Ostriker et al. (2001); Federrath et al. (2008); Federrath & Klessen (2013a, b)
Understanding (column) **density statistics** of molecular clouds
Understanding (column) **density statistics** of molecular clouds

Now — building a comprehensive observational view:

1 pc —— 10 pc —— 100 pc —— 1 kpc —— 10 kpc
Dust extinction mapping in near-infrared
(e.g., Lombardi et al. 2006; Kainulainen et al. 2009; Rowles & Froebrich 2011; Schneider et al. 2011)

Dust emission measurements with Herschel
(e.g., Andre et al. 2011; Hill et al. 2011; Schneider et al. 2013; Alves de Oliveira 2014; Sadavoy et al. 2014; Lombardi et al. 2015)
Key observational studies

See also, e.g., Lombardi et al. (2006, 2008, 2015); Schneider et al. (2013); Alves de Oliveira (2015)

A star-forming cloud

A non-star-forming cloud

Study of 20 Solar neighborhood clouds

Kainulainen et al. (2009)

power-law slope ~ -1

1 pc — 10 pc — 100 pc — 1 kpc — 10 kpc
1 pc — 10 pc — 100 pc — 1 kpc — 10 kpc

Herschel-derived column density
Stutz & Kainulainen (2015)

$N$-PDFs (shifted)

$\alpha_{\text{all}} = -1.90$
$\alpha_1 = -0.93$
$\alpha_2 = -1.03$
$\alpha_3 = -1.95$
$\alpha_4 = -2.26$
$\alpha_5 = -2.04$
$\alpha_6 = -2.30$
$\alpha_7 = -1.91$
$\alpha_8 = -2.95$
**Key observational studies**

- *Intro*
  - 1 pc
  - 10 pc
  - 100 pc
  - 1 kpc
  - 10 kpc

**Star formation rate decreases**

**N-PDFs (shifted)**

- $\alpha_{\text{all}} = -1.90$
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**N (class 0) / region**

- Stutz & Kainulainen (2015)

**Bottom-heavy**

**Top-heavy**

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IAU Divisional Meeting  
10th Aug 2015
Abreu Vicente et al. (2015)

Key observational studies

Link to ISM physics

1 pc — 10 pc — 100 pc — 1 kpc — 10 kpc

See also Russeil et al. (2013); Schneider et al. (2015a, b)
**Key observational studies**

Top-heaviness of $N$-PDFs correlates with $\Sigma$(star clusters)

Credit: PAWS team/IRAM/NASA HST/T.A. Rector (University of Alaska Anchorage)
Link to ISM physics with the help of numerical simulations
Gravo-turbulent (M)HD simulations (continuously driven/decaying)

(e.g., Klessen 2000; Collins et al. 2010; Cho & Wang 2010; Kritsuk et al. 2011; Federrath & Klessen 2013, 2014)

Turbulence-induced initial condition

Gravity switched on

Gravity-dominated state
Star-formation (with sink particles)

Evolution as a function of star formation efficiency (SFE)

Federrath & Klessen (2013)
Highly idealised setup
(first turbulence, then gravity, no environment)

Simulations where clouds form \textit{in situ}.
Colliding warm gas flows

Gomez & Vazquez-Semadeni et al. (2014)

Ballesteros-Paredes et al. (2011)
Resolution $\sim 0.5$ pc at GMC densities

Smith et al. (2014); AREPO code
Resolution $\sim 0.5$ pc at GMC densities

Smith et al. (2014); AREPO code
Ibanez-Mejia et al. (in prep.)
evolution with self-gravity \( t_{SG} = 0.0 \) Myr
Emerging picture:

N-PDFs of most molecular clouds are heavily affected by gravity

… i.e., turbulence plays a less significant role.

N-PDFs quite possibly evolve in time-scales relevant for star formation

… but simulations of where clouds form in situ are needed.

Galactic-scale understanding of the PDFs is crucially missing

… but on its way as we speak.
Feedback?

Gatto et al. (2015)
Relative density structure affects analytic SF laws

\[ SFR_{ff} \propto \int_{s_{\text{crit}}}^{\infty} \frac{t_{ff}(\rho_0)}{t_{ff}(\rho)} \frac{\rho}{\rho_0} p(s) \, ds. \]

\[ s = \ln \left( \frac{\rho}{\rho_0} \right) \]

Probability density function of gas density (\( \rho \)-PDF)

Krumholz & McKee (2005)
Padoan & Nordlund (2011)
Hennebelle & Chabrier (2011, 2013)
Zamora-Avile et al. (2012)
Krumholz et al. (2012)
Federrath & Klessen (2013),
...

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