Energy Budget of Forming Clumps in Numerical Simulations of Collapsing Clouds

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Observational surveys of molecular clouds and their substructure

Giant molecular clouds, molecular clouds, clumps, cores and dense cores observed in our galaxy and other galaxies. Both diagrams show a collection of clouds in a wide range of column density ($\Sigma$)...

$\alpha_k = \sigma_v^2/R$, $\alpha_G = \pi G \Sigma / 5$

$\Sigma$ (pc$^{-2}$) vs $\sigma_v / R^{1/2}$ as shown in Heyer et al. 2009.

This trend was also observed in Keto & Myers (1986)
Observational surveys of molecular clouds and their substructure

$$\frac{\sigma_v}{R^{1/2}} \sim (a \Sigma)^{1/2}$$

If $\Sigma$ is $\sim$constant, then Larson's scaling relations of density-size relation, $n \sim R^{-1}$, and velocity dispersion-size relation, $\sigma_v \sim R^{1/2}$ are obtained.

$$a=1 \text{ virial equilibrium}$$

$$2E_K = |E_g|$$

We refer to either condition as "near-energy equipartition" and, to diagrams showing this relation as Keto-Heyer, or KH, diagram. Keto & Myers (1986)

$$a = 2 \text{ free-fall } E_k = |E_g|$$

(Ballesteros-Paredes et al. 2011).

Why do some MCs show a kinetic energy excess?
Studying clumps’ energy balance through numerical simulations

“RUN20”
Gómez & Vázquez-Semadeni (2014)

Two cylindrical streams of warm neutral atomic gas collide at the central plane including small scale turbulent perturbations.

Initial uniform density $n_0 = 1 \text{ cm}^{-3}$
Initial temperature $T_0 = 5206 \text{ K}$
Mass per SPH particle $m_{\text{SPH}} = 0.02 \text{ M}_\odot$

“RUN03”
Heiner et al. (2015)

RUN03 was started by applying a Fourier turbulence driver over the first 0.65 Myr.

Initial uniform density $n_0 = 3 \text{ cm}^{-3}$
Initial temperature $T_0 = 730 \text{ K}$
Mass per SPH particle $m_{\text{SPH}} = 0.06 \text{ M}_\odot$
In both simulations, clouds, clumps and cores were defined as connected regions above various density thresholds \( (n_{th}, \text{shown in colors}) \) at different evolutionary states (shown by different symbols).
The most common velocity gradient, which is $\sim -0.125 \text{ km s}^{-1} \text{ pc}^{-1}$ in both simulations, indicates that the clumps are contracting on average, and therefore are in the process of assembly.

Low-\( \Sigma \) clumps in different mass ranges in the KH diagram. The scatter in \( \sigma_v / \sqrt{R} \) is interpreted as an excess of kinetic energy, or equivalently, a large velocity dispersion.

We attribute this \( \sigma_v \) to the turbulent velocity that causes the early assembly stages of the clouds.
Intermediate-\(\Sigma\) (and intermediate \(n\))

Given the analysis in the low-\(\Sigma\) range:
clumps are first assembled by large-scale turbulent compressions and,
as they grow, they transition from turbulent assembly to gravitational contraction.
Some dense cores have stellar particles that contribute to their gravitational potential. Clumps that are above equipartition may have their net gravitational masses underestimated. We propose two mechanisms for providing additional mass:

- Stellar mass effect
- Filament effect

\[ \text{Mass in stars} \quad \rightarrow \quad \text{Stellar mass effect} \]
\[ \text{Mass of external accreting material} \quad \rightarrow \quad \text{Filament effect} \]

\( \Sigma \) and high \( n \)
High-$\Sigma$ (and high n)

Some of these high density cores show embedded stellar particles (red diamonds in the figure).

$$\Sigma = (M_g + M_{\text{sink}}) / \pi R^2$$

Some dense cores appear unobund because they really are being disrupted.

Accounting for this mass brings the energetics of the cores closer to equipartition (as shown by the blue arrows).
To remember:

- The full ensemble of clouds, clumps and cores approximates the generalized Larson relation $\sigma / R^{1/2} \sim (\pi \Sigma)^{1/2}$

- The energy budget changes as column density increases. This is a consequence of an increasing relative importance of self-gravity at increasing $\Sigma$. This suggests an evolutionary process in which a turbulent compression initially dominates the kinetic energy and exceeds the gravitational energy of the forming cloud until it gains mass to gravity become dominant.

- Low column density clumps exhibit a large scatter of the $\sigma / R^{1/2}$ ratio. More than 50% of these clumps exhibit a convergent velocity field, meaning they are being assembled by an external compression. The other half is really dispersing.

- Some of the high-column density cores that exhibit kinetic energy excesses contain stellar particles that increase the total gravitational potential in the volume of the clump. The apparent excess disappears when this extra mass is accounted for in the energy budget of the cores.

![Graph showing energy equipartition with $\Sigma$ and $\sigma / R^{1/2}$]
Density-size relation $n \propto L^{-1}$

No Larson-like relation is observed for the entire sample.

According to BP11, a ~constant volume density is observed for clumps selected by $n_{th}$.

Clouds, clumps and cores for both simulations. Different colors represent different $\Sigma$. 
Density-size relation \( n \propto L^{-1} \)

Clumps show Larson-like relation when they are selected by column density.

Clouds, clumps and cores for both simulations. Different colors represent different \( \Sigma \).
• No clear Larson relation is observed for the entire sample. It appears as a lower limit.

• Large scatter for low-$\Sigma$ objects. (We will come back to this)

• Some clumps selected by $\Sigma$ seem to follow $\sigma_v$-$R$ relation.
