“Turbulence and star formation in molecular clouds”

Richard Larson, 1981

Presenter: Jeff Mankey

Molecular clouds

Image: Evaporating molecular cloud near Carina nebula. Hubble Telescope, 1999.

Molecular clouds

- Colder and more dense than the rest of the ISM
- Hydrogen exists as H_2
- Large range of size, density and total mass

Table 32.2 Terminology for Cloud Complexes and Their Components

Categories	Size (pc)	n_H (cm^{-3})	Mass ($M_\odot$)	Linewidth ($km\,s^{-1}$)	A_V (mag)	Examples
GMC Complex	25 – 200	50 – 300	$10^5 - 10^{6.8}$	4 – 17	3 – 10	M17, W3, W51
Dark Cloud Complex	4 – 25	$10^2 - 10^3$	$10^3 - 10^{4.5}$	1.5 – 5	4 – 12	Taurus, Sco-Oph
GMC	2 – 20	$10^3 - 10^4$	$10^3 - 10^{5.3}$	2 – 9	9 – 25	Orion A, Orion B
Dark Cloud	0.3 – 6	$10^2 - 10^4$	5 – 500	0.4 – 2	3 – 15	B5, B227
Star-forming Clump	0.2 – 2	$10^4 - 10^5$	$10 - 10^3$	0.5 – 3	4 – 90	OMC-1, 2, 3, 4
Core	0.02–0.4	$10^4 - 10^6$	$0.3 - 10^2$	0.3 – 2	30–200	B335, L1535

Draine, pg. 358

Larson's Big Idea

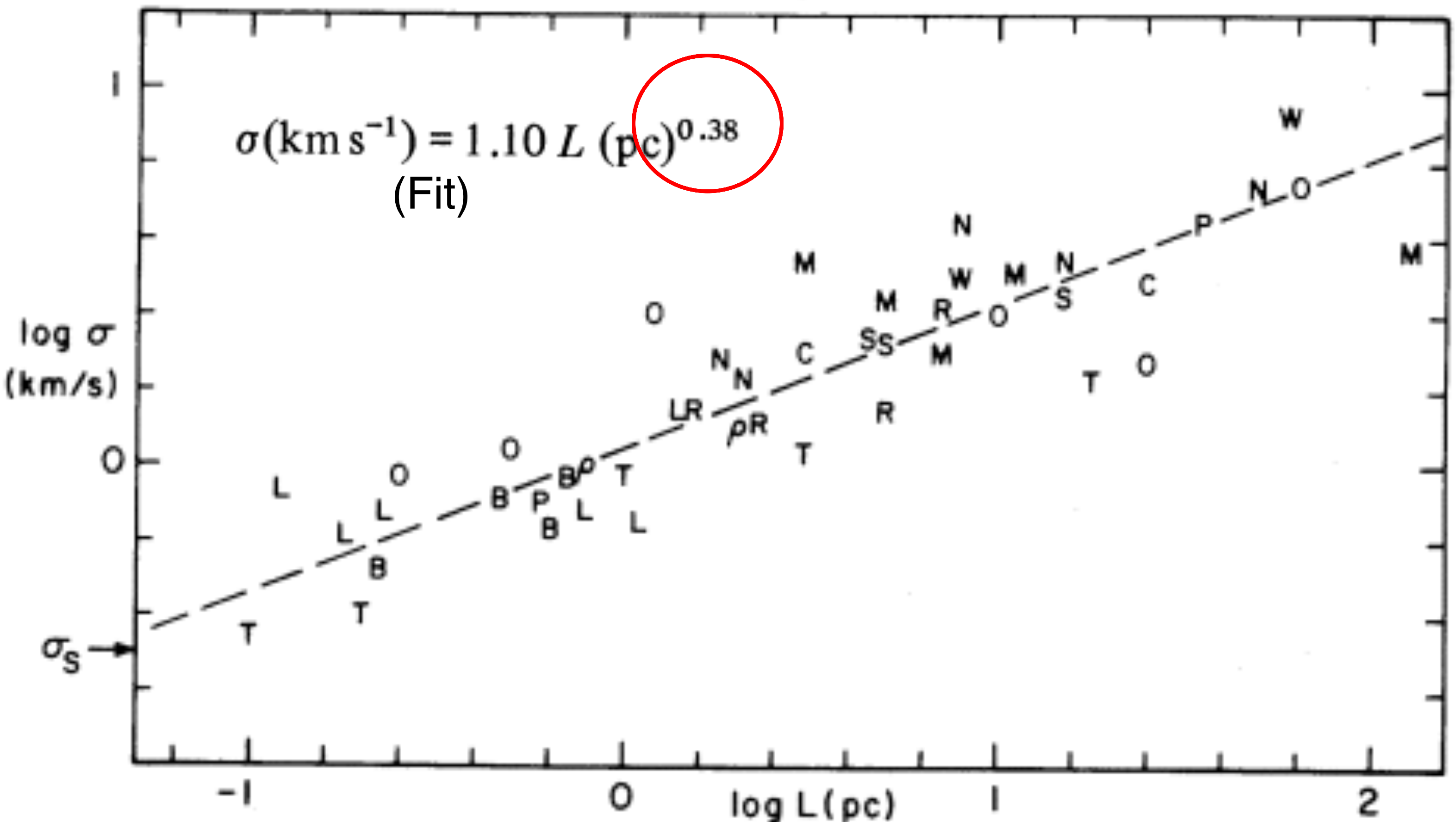
TURBULENCE!

- Previous models had been based on:
  - Simple gravitational collapse and fragmentation (radial only)
    Jeans (1929), Hoyle (1953), Hunter (1967)
  - Collapse and fragmentation including other means
    Woodward (1978), Bodenheimer & Black (1978)
- Reality doesn't reflect these models
  - Observed turbulent-like structures (filaments, clusters, etc.) that are typical to shear stress, strain
  - No large homogeneous clouds beginning to fragment observed

Methodology

- Larson performed a literature review to gather data on
  ~ 62 molecular clouds
- He computed the size (L), velocity dispersion (σ), mass (M), and H_2 density (n_{H2}) for each
- Performed statistical analyses of correlations
- Generally, ^{13}CO emission line used as tracer
  - σ determined from Doppler broadening
  - M and n_{H2} quoted, generally determined from ^{13}CO luminosity
  - L determined geometrically from visible ^{13}CO extent

Results: σ vs. L

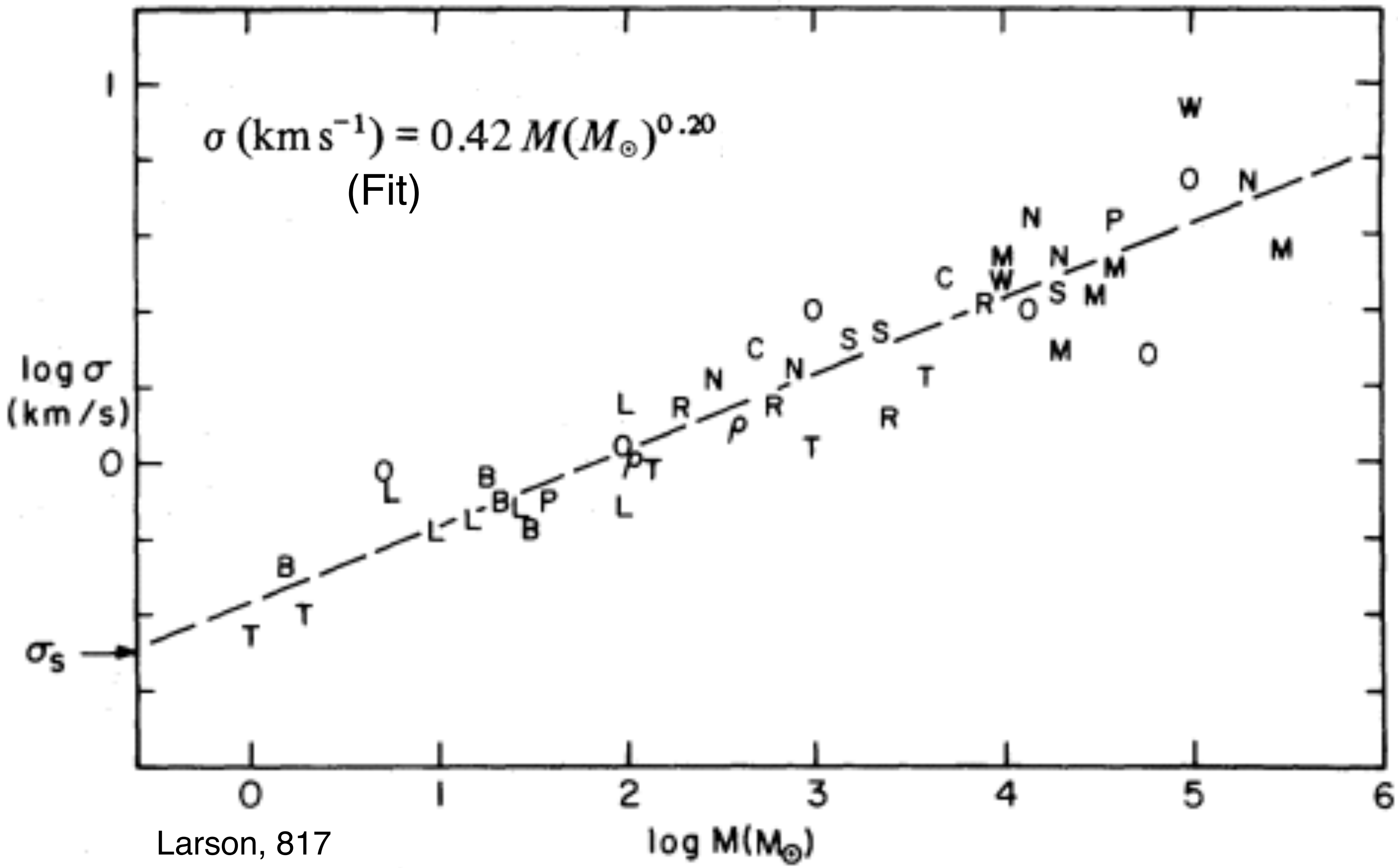


Larson, 814

Results: σ vs. L

- Power law dependence, with no preferred scale; this suggests a turbulent model
- Kolmogorov law: $\sigma \sim L^{1/3}$
- For molecular clouds, typical velocities are between 0.6 and 10 km/s ; for H_2 ideal gas, c_s is ~0.36 km/s => <u>supersonic</u>
- Energy should be lost directly due to viscous shock dissipation at high velocities (i.e. larger scales), leaving less to be cascaded to smaller scales => <u>steeper slope</u>

Results: σ vs. M



Larson, 817

Results: σ vs. M

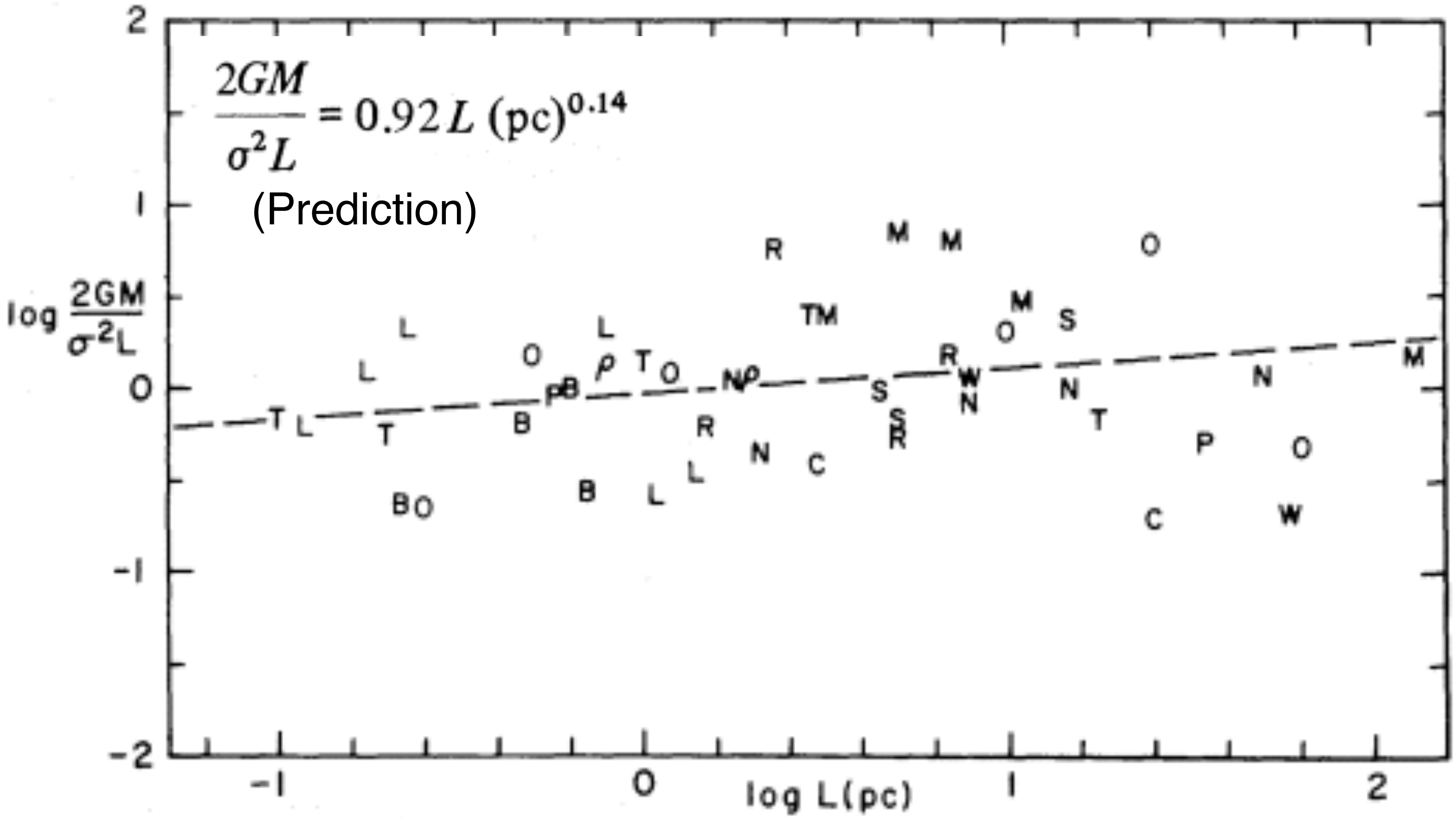
- Virial theorem: Balance between kinetic energy (velocity dispersion) and gravitational potential energy

$$M\sigma^2 \sim \frac{2GM^2}{L} \longrightarrow \sigma^2 \sim \frac{2GM}{L}$$

- Assuming virial equilibrium, the earlier fits lead to the prediction:

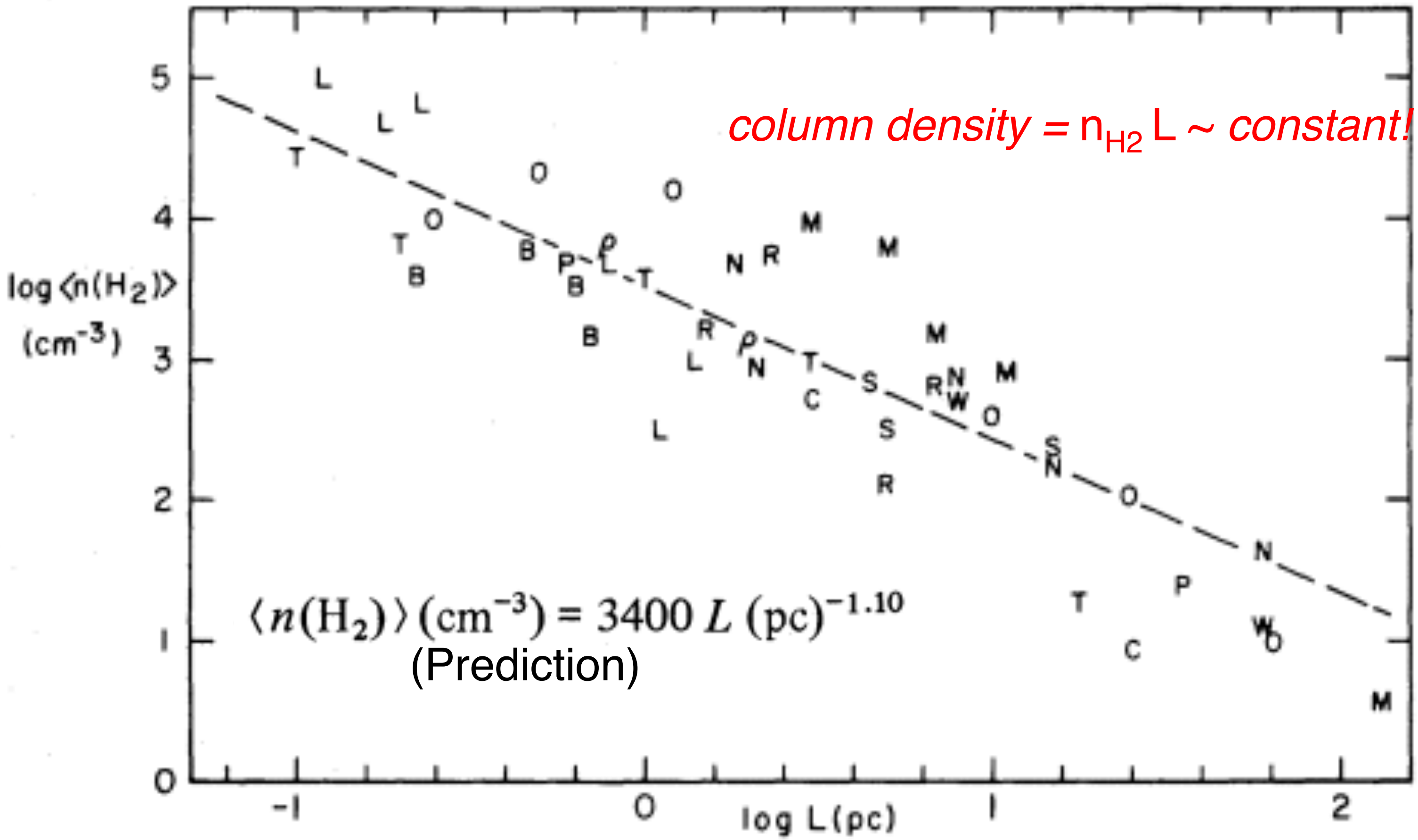
$$\frac{2GM}{\sigma^2 L} = 0.92\,L\,(\mathrm{pc})^{0.14}$$

Results: σ vs. M



Larson, 817

Results: n_H vs. L



Larson, 819

Results: Analysis

- Most of the clouds are in approximate virial equilibrium, and gravitationally bound
- The few that deviate are those that appear to be in gravitational collapse/star formation

Larson's model

- Turbulent (and generally supersonic) fluid-driven shocks creates high densit regions, which then may become gravitationally bound

- If the region becomes dense enough, it may decouple from its surrounding environment and collapse independently into a star (like liquid/gas interface)
- A hierarchy of scales develops as kinetic energy is transferred from large to small scales
- In complement to 2-phase model

Predictions of this model

- Smallest stars form from structures/substructures at the bottom of the hierarchy
- If we assume that subsonic speeds will not form structures, **a minimum size and mass can be calculated based on the speed of sound**
- This seems to correctly predict the IMF minimum of $\approx 0.1\ M_{solar}$
- Largest stars will form by accretion of clumps that develop through turbulent processes

Predictions of this model

- Massive stars form only in the densest parts of largest clouds, while smallest stars form in clouds of all sizes (consistent with observations)
- We can predict a time scale associated with large-scale changes to the cloud's density structure,

$$t \sim L / \sigma$$

  - t ranges from ~0.2 My (for L≈0.1 pc) to ~15 My (L≈100 pc)
  - This is consistent with observations; molecular clouds not typically observed around stars older than ~10 My

Summary

- Purely fluid turbulent model that predicts hierarchy of scales, velocities, and densities
- Predictions match the initial mass function for developing stars, as well as observed variations in above parameters
- Virial equilibrium of most molecular clouds suggests balance between turbulent flow and gravitational stability
- In reality, velocity dispersion is likely the result of turbulence, MHD, external forces, and thermal processes all working together; however, these results suggest turbulence is the dominant process at work

Subsequent work

- Solomon, et al. (1987) performed a more rigorous survey using data for 283 molecular clouds from Massachussets-Stony Brook CO Galactic Plane Survey
  - They found **γ = 0.5** ; farther from subsonic Kolmogorov gamma of 1/3, but not unexpected due to greater role of hydrodynamic shock dissipation
- Heyer and Brunt (2004) performed a Monte Carlo analysis based on 27 clouds (all GMCs!) and found gamma = 0.59
- There is a great deal of uncertainty in determining this relationship, particularly in identifying and measuring cloud substructures; hence the role of turbulence vis à vis other processes remains debated

Image: Eagle Nebula.

Questions?

Backup slides

Jeans instability

- If sufficiently dense and with insufficient pressure to support it, a free cloud of gas will self-gravitate and collapse
- There is a critical density at which the gas will gravitationally collapse:

$$M_J = \left(\frac{4\pi}{3}\right)\rho R_J^3 = \left(\frac{\pi}{6}\right)\frac{c_s^3}{G^{3/2}\rho^{1/2}} \simeq (2\ \mathrm{M}_\odot)\left(\frac{c_s}{0.2\ \mathrm{km\ s^{-1}}}\right)^3\left(\frac{n}{10^3\ \mathrm{cm^{-3}}}\right)^{-1/2}.$$

- Or, alternatively there is a critical size below which a gas will gravitationally collapse:

$$\lambda_J = \sqrt{\frac{15 k_B T}{4\pi G \mu \rho}},$$

- The gas will heat as it collapses, until this generates sufficient pressure to reverse the instability