Star Formation and Feedback I: The Physics of Star-Forming Clouds

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30th Jerusalem Winter School on Theoretical Physics

December 31, 2012

Philosophical Note

This school is about early galaxy formation. However, our knowledge of star formation and feedback in the early Universe is poor at best. My approach is therefore to develop models based on the local Universe, and then ask what the results imply about early galaxies.

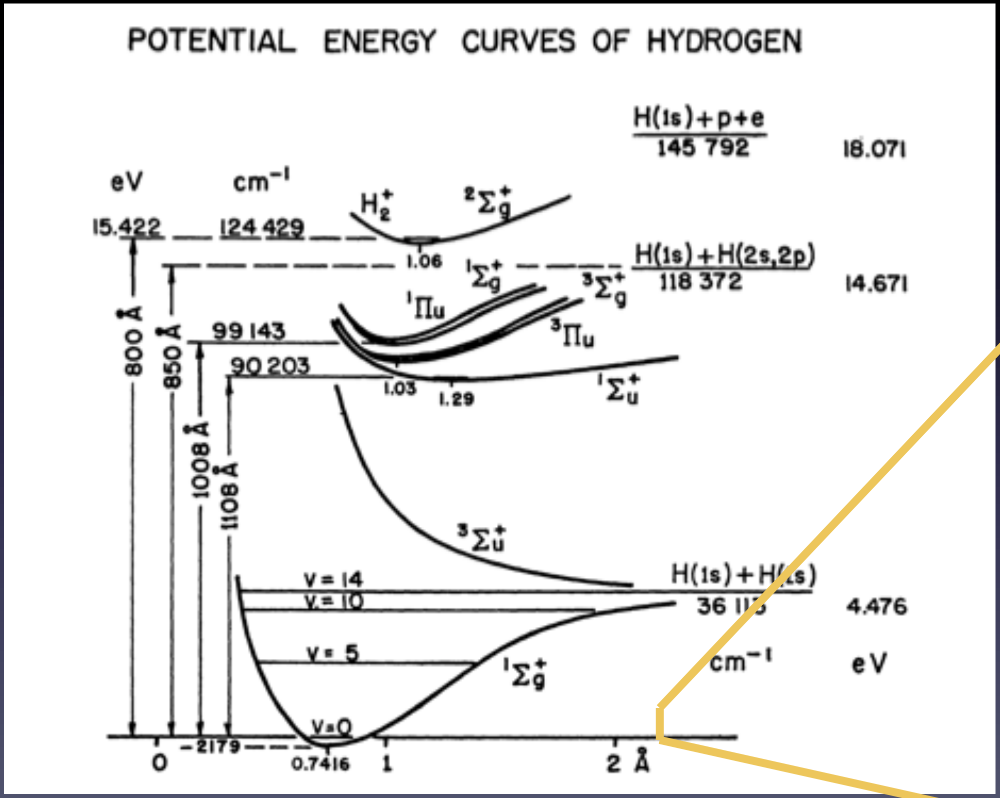
Outline

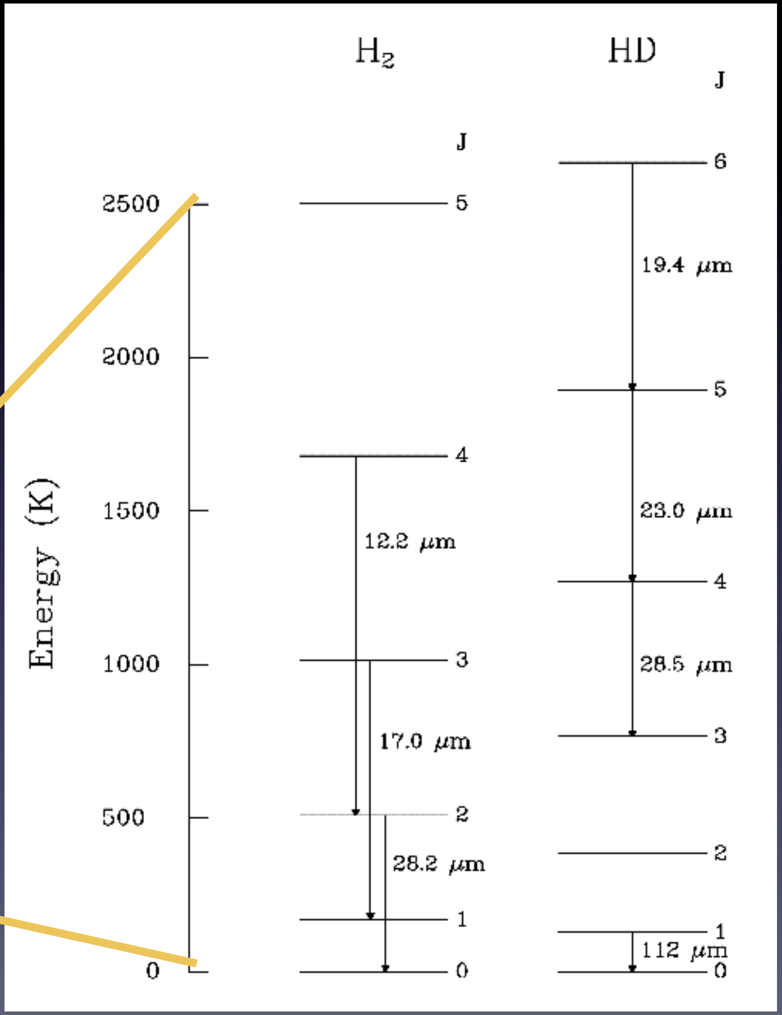
- Observing the cold ISM
  - H_2: proof that nature has a cruel sense of humor
  - CO: proof that astronomers are stubborn bastards
  - Density, velocity, and temperature measurement
- Properties of the cold ISM
  - Heating, cooling, and thermodynamics
  - Gas dynamics and turbulence
  - The virial theorem and gravitational collapse

General Observational Principles

- Star-forming gas is cold, so observations have to be in radio, mm, or far-IR
- Diffuse gas does not emit or absorb continuum radiation, so we must work with lines, or with dust mixed with the gas
- The star-forming ISM is mostly molecular

H_2 Level Structure





Why We Can't Observe H_2

- H_2 is most abundant species, but…
- Symmetric molecule ➔ no dipole moment ➔ no $\Delta J = 1$ transitions ➔ no emission from $J = 1$
- Level spacing for quantum rotor varies as $m^{-1/2}$, so H_2 $J = 2$ is 511 K off ground
- At $T = 10$ K, $\exp(-T_{level}/T) = 6 \times 10^{-23}$: very bad!

CO: the Next Best Thing

- O, C: two most abundant heavy elements
- CO usually dominant chemical species where H_2 is (**important exception**: low metallicity)
- CO has non-zero dipole moment ➔ $\Delta J = 1$ transitions occur
- CO $J = 1$ is only 5.5 K above ground

Quick Review of Two-Level Atoms

- Tracer species X of density n_X with non-degenerate levels 0, 1 separated by energy E
- Ambient gas is pure H_2 at density n_{H_2}, temp. T
- Level populations given by

$$\left(\frac{dn_1}{dt}\right)_{\text{coll. exc.}} - \left(\frac{dn_1}{dt}\right)_{\text{coll. de-exc.}} - \left(\frac{dn_1}{dt}\right)_{\text{emiss.}} = 0$$

$$k_{10} e^{-E/kT} n_{\mathrm{H}_2} n_{\mathrm{X},0} - k_{10} n_{\mathrm{H}_2} n_{\mathrm{X},1} - A_{10} n_{\mathrm{X},1} = 0$$

$$\frac{n_{\mathrm{X},1}}{n_{\mathrm{X},0}} = e^{-E/kT} \frac{1}{1 + n_{\mathrm{crit}}/n_{\mathrm{H}_2}}, \quad n_{\mathrm{crit}} = A_{10}/k_{10}$$

Implications for CO

- For $n_{H_2} >> n_{crit}$, population comes to LTE
- n_{crit} = (2200, 6800) cm^{-3} for CO J = (1, 2)
- For an optically thick cloud, effective value of A_{10} reduced by photon trapping ➔ lower n_{crit}
- Mass-weighted mean density in molecular clouds >~ 10^3 cm^{-3} ➔ first few J CO levels close to LTE

NB: molecular data all taken from the Leiden Atomic and Molecular Database (LAMDA, http://home.strw.leidenuniv.nl/~moldata/)

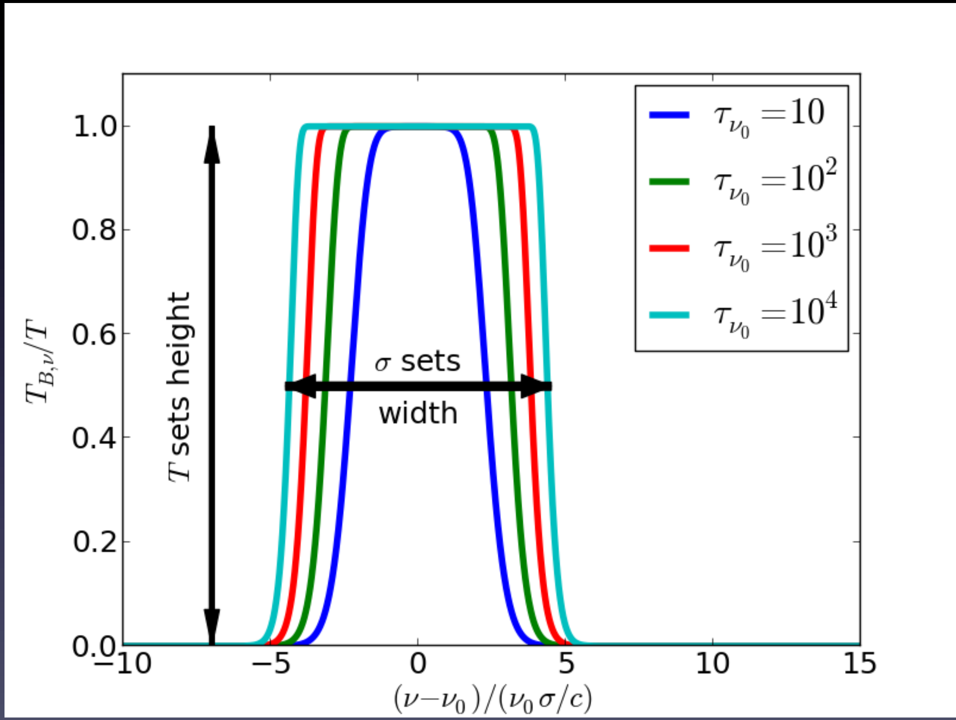
Mass Inference from CO I

- For an LTE emitter, emissivity is $B_\nu(T)$, intensity given by

$$I_\nu = \left(1 - e^{-\tau_\nu}\right) B_\nu(T)$$

- Optical depth set by velocity dispersion and line-center optical depth:

$$\tau_\nu = \tau_{\nu_0} e^{-(\nu-\nu_0)^2/2(\nu_0\sigma/c)^2}$$



Mass Inference From CO II

- Velocity-integrated intensity given by

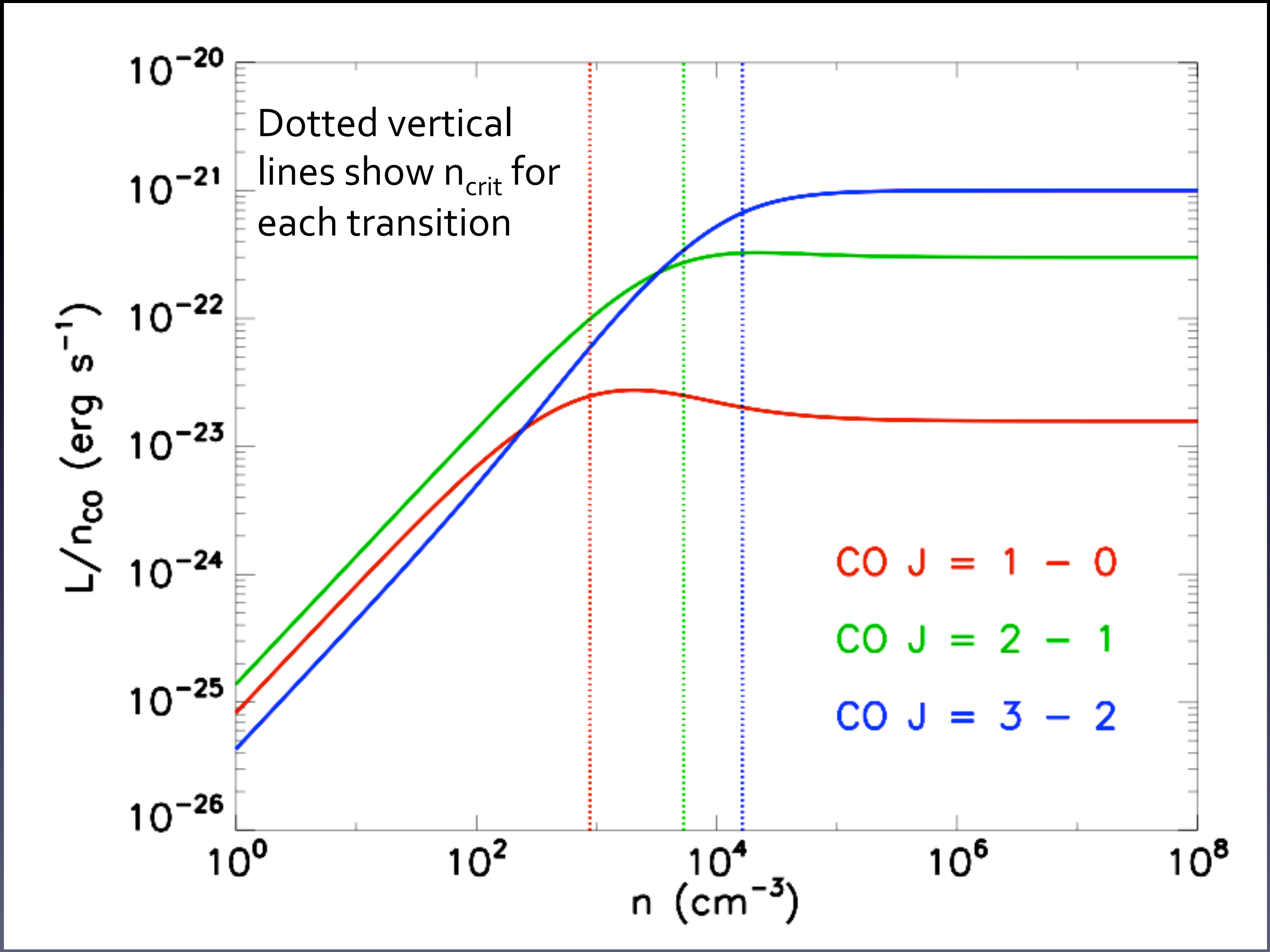
$$W_{\rm CO} = \int T_{B,\nu}\, dv = \int T_{B,\nu} \frac{c}{\nu_0}\, d\nu \approx \sqrt{8 \ln \tau_{\nu_0}}\sigma T$$

- To 1st order, if T ~ const, W_{CO} measures σ

- Let $n = 3M/(4\pi R^3 m_{H_2})$, $\alpha_{vir} = 2T/U = 5\sigma^2 R/GM$:

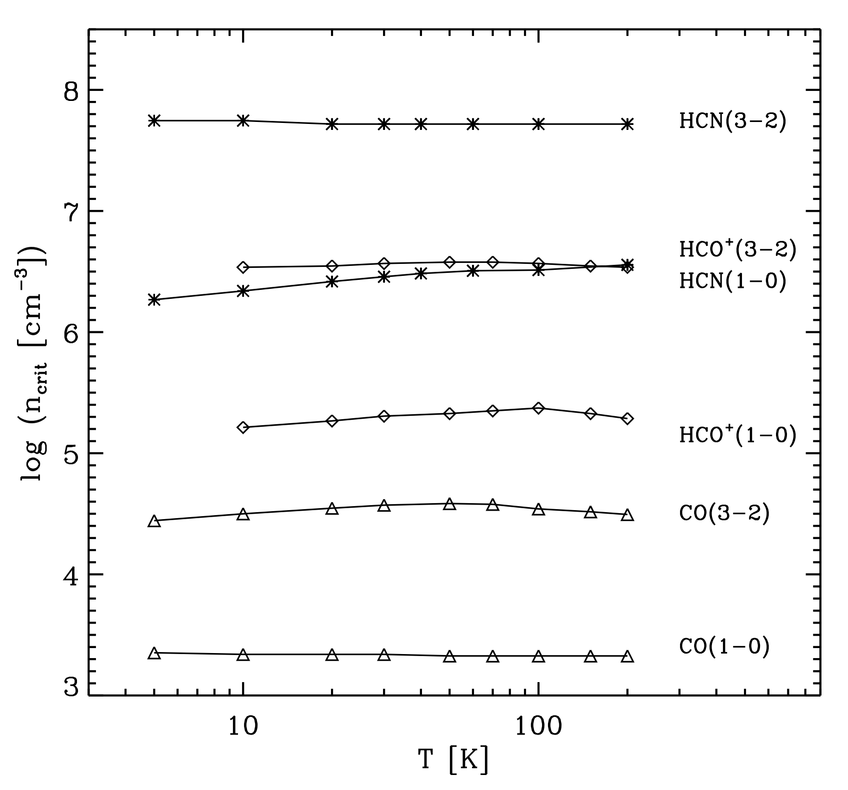
$$\Sigma = \sqrt{\frac{5n}{6\pi G m_{\rm H_2} \alpha_{\rm vir} T^2 \ln \tau_{\nu_0}}} W_{\rm CO} \equiv X_{\rm CO} W_{\rm CO}$$

Critical Density Effects



Density Distributions

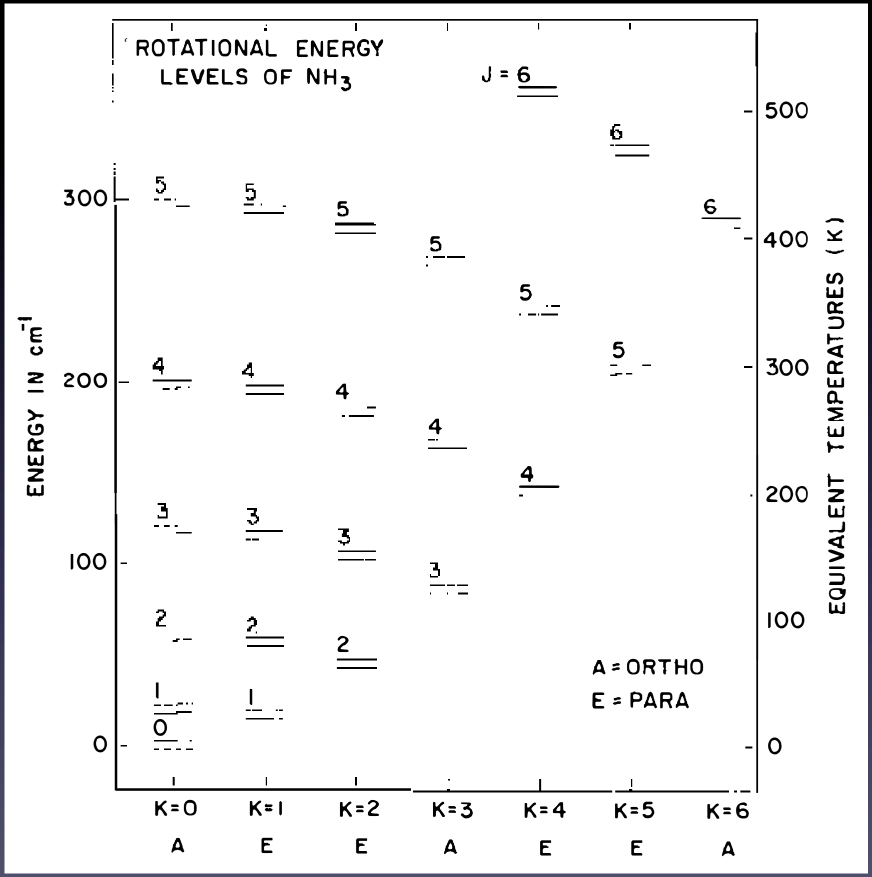
- CO nearly symmetric ➔ low dipole moment, low A, low n_{crit}
- Measuring multiple species with different n_{crit} probes the gas density distribution
- Most common example: HCN J=1
- Caveat: need to worry about temperature too



Critical density versus gas temperature for several lines (Juneau+ 2009)

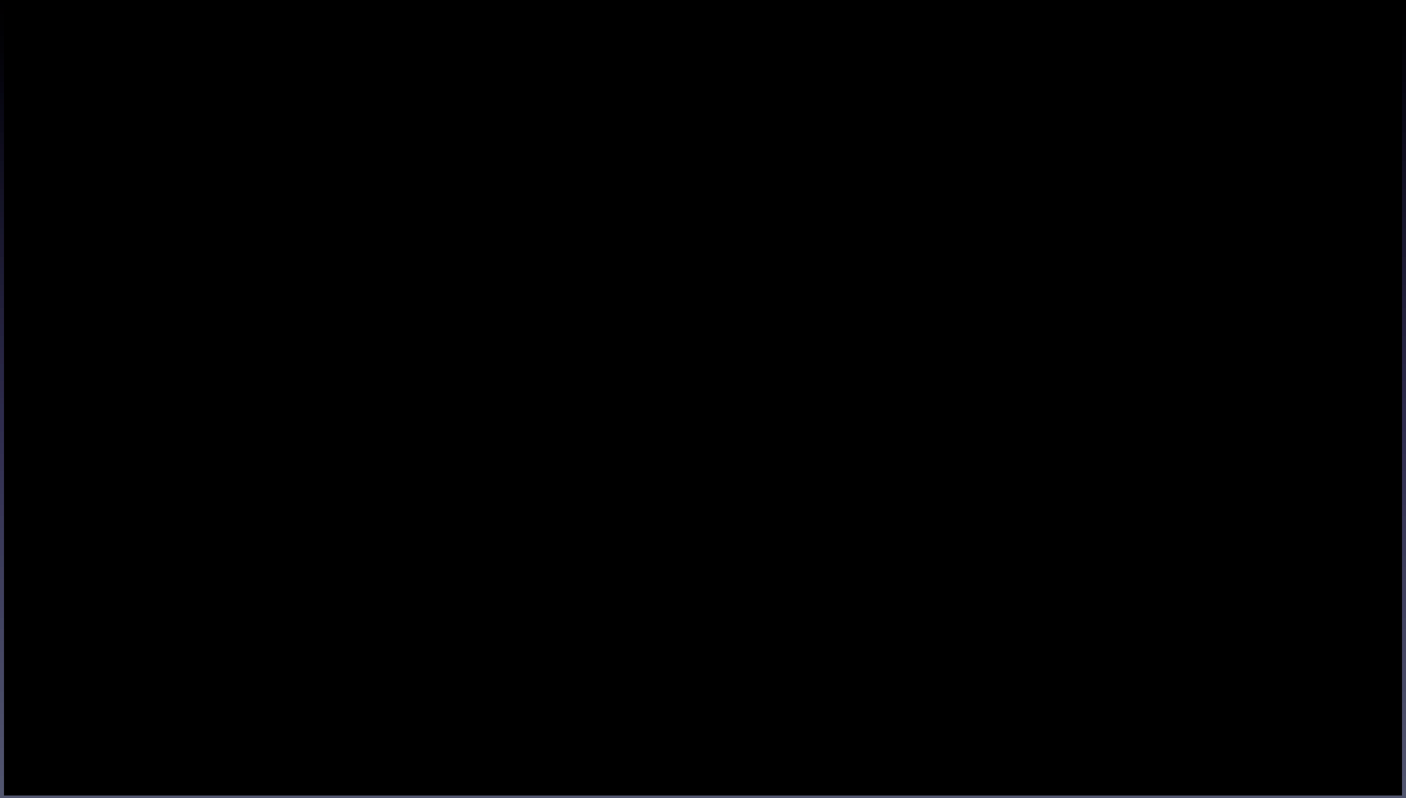
Velocity and Temperature

- To measure velocity: observe in an optically thin species, e.g. using a rare isotope (^{13}CO or C^{18}O in place of CO)
- To measure temperature: use a species with a particular level structure, shown at right (e.g. NH_3)



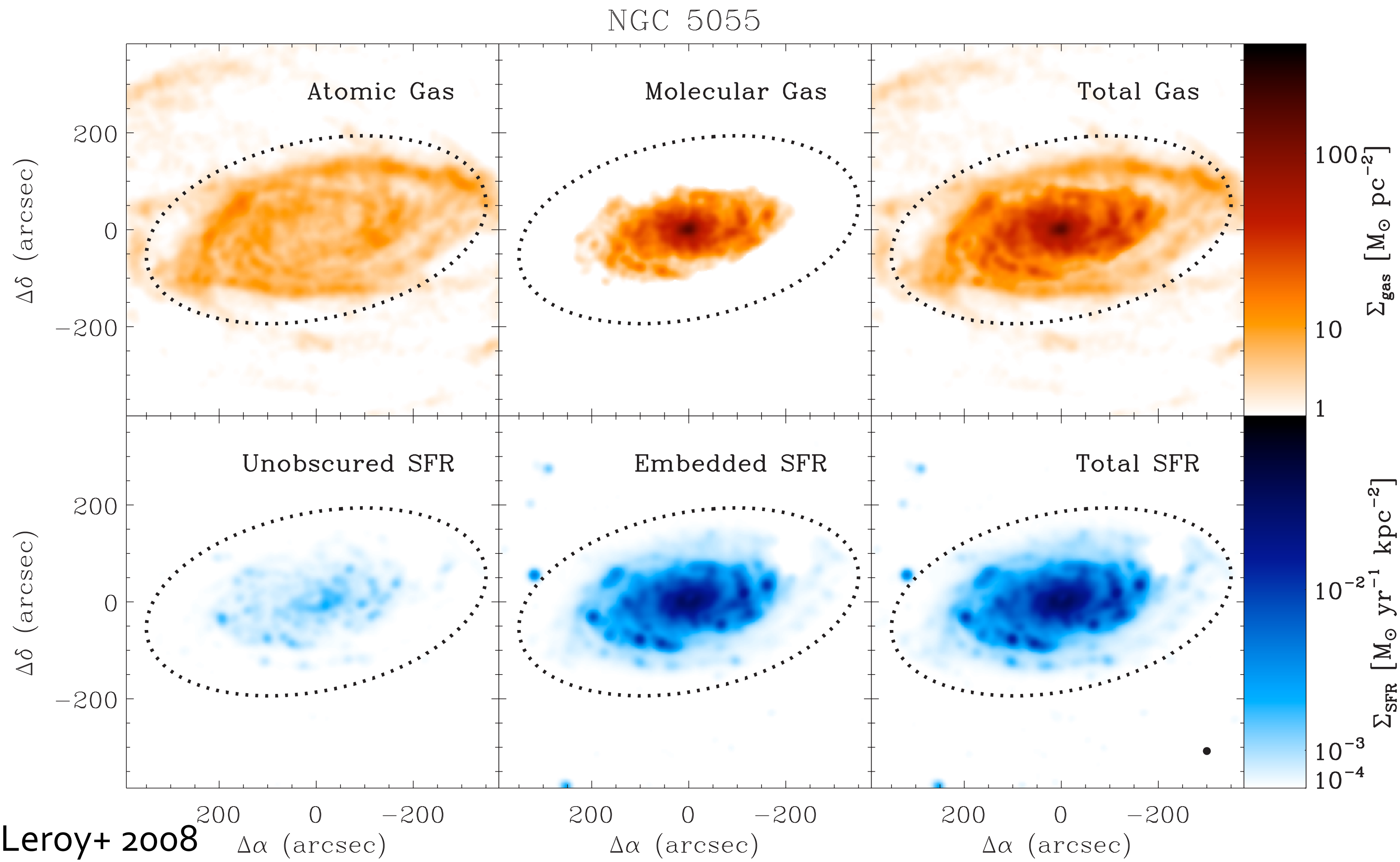
Level diagram for NH_3 (Ho & Townes 1983)

Example Milky Way Data



Position-velocity data in ^{12}CO and ^{13}CO in the Perseus cloud, from the COMPLETE survey (Ridge+ 2006)

Example Nearby Galaxy Data



Leroy+ 2008

Observed Cloud Properties

- Observationally-inferred properties of gas associated with star formation
  - Very cold: ~10 K in normal galaxies, at most < 100 K in starbursts
  - Very dense: column density $N >\sim 10^{22}$ cm^{-2}; volume density $n >\sim 100$ cm^{-3}, higher in starbursts and at high z
  - Very supersonic: typical velocity dispersion ~ 5 – 50 km s^{-1} ~30 – 300 times sound speed

Gas Thermodynamics

- Heating processes:
  - Adiabatic compression / viscous dissipation
  - EUV ionization / FUV photoelectric heating
  - Cosmic ray / x-ray heating
- Cooling processes
  - Adiabatic expansion
  - Atomic and molecular lines

Adiabatic / Viscous Heating (and Cooling)

- Consider material at density ρ
- Natural timescale for motions induced by gravity, or at virial velocity, is $t_{dyn} \sim (G\rho)^{-1/2}$
- Heating rate per atom:

$$\Gamma \sim -P\mu \frac{d}{dt}\left(\frac{1}{\rho}\right) \sim \mu c_s^2 \sqrt{4\pi G\rho}$$

$$\sim 10^{-29} n_2^{1/2} T_1 \text{ erg s}^{-1}$$

$n_2 = n$ / 100 cm^{-3}

$T_1 = T$ / 10 K

Ionization / Photoelectric Heating

- $N \sim 10^{22}$ cm^{-2}, $\sigma_{\text{pi-thresh}} = 6 \times 10^{-18}$ cm^{-2} ➔ for ionizing photons $\tau \sim 6 \times 10^{4}$ ➔ no ionization
- Grain PE heating dominated by ~1000 Å photons, $\sigma_{\text{dust}} \sim 10^{-21}$ cm^{-2} at $Z = Z_{\odot}$,

$$\Gamma \sim 1 \times 10^{-30} J_{\rm FUV} e^{-\tau_{\rm dust}/10} \text{ erg s}^{-1}$$

FUV field normalized to solar neighborhood value

$$N\sigma_{\rm dust}$$

Cosmic Ray / X-Ray Heating

- CRs and x-rays can penetrate high columns
- Heating processes: $\mathrm{H_2} + \mathrm{CR} \rightarrow \mathrm{H_2^+} + e^- + \mathrm{CR}$

$e^- + \mathrm{H_2} \rightarrow 2\mathrm{H} + e^-$

$e^- + \mathrm{H_2} \rightarrow \mathrm{H_2^*} + e^-$

$\mathrm{H_2^*} + \mathrm{H_2} \rightarrow 2\mathrm{H_2}$

$\mathrm{H_2^+} + \mathrm{H_2} \rightarrow \mathrm{H_3^+ H}$

$\mathrm{H_3^+} + \mathrm{CO} \rightarrow \mathrm{HCO^+} + \mathrm{H_2}$

$\mathrm{HCO^+} + e^- \rightarrow \mathrm{CO} + \mathrm{H}$

- Heating rate:

$$\Gamma_{\mathrm{CR}} \sim 10^{-27} \zeta \ \mathrm{erg\ s^{-1}}$$

CR / x-ray ionization rate normalized to Solar neighborhood value

CO Line Cooling

- CO molecule is a quantum rotor

Dipole moment μ = 0.112 D

$$E_J = hBJ(J+1) \qquad A_{J+1,J} = \frac{512\pi^4 B^3 \mu^2}{3hc^3}\frac{(J+1)^4}{2J+1}$$

Rotation constant B = 57 GHz

$$\Lambda_J = x_{\mathrm{CO}}(2J+1)\frac{e^{-E_J/k_B T}}{Z(T)}A_{J,J-1}(E_J - E_{J-1})$$

CO abundance

Partition function

- Most low J photons trapped, few high J photons emitted due to $e^{-E/kT}$ ➔ cooling dominated at intermediate J ~ 5
- For J = 5, $\Lambda \approx 10^{-27} e^{-8.3/T_1}\ \mathrm{erg\ s}^{-1}$

Thermodynamic Conclusions

- Collecting formulae in one place:

$$\Gamma_{\rm ad} \sim 10^{-29} n_2^{1/2} T_1 \text{ erg s}^{-1}$$

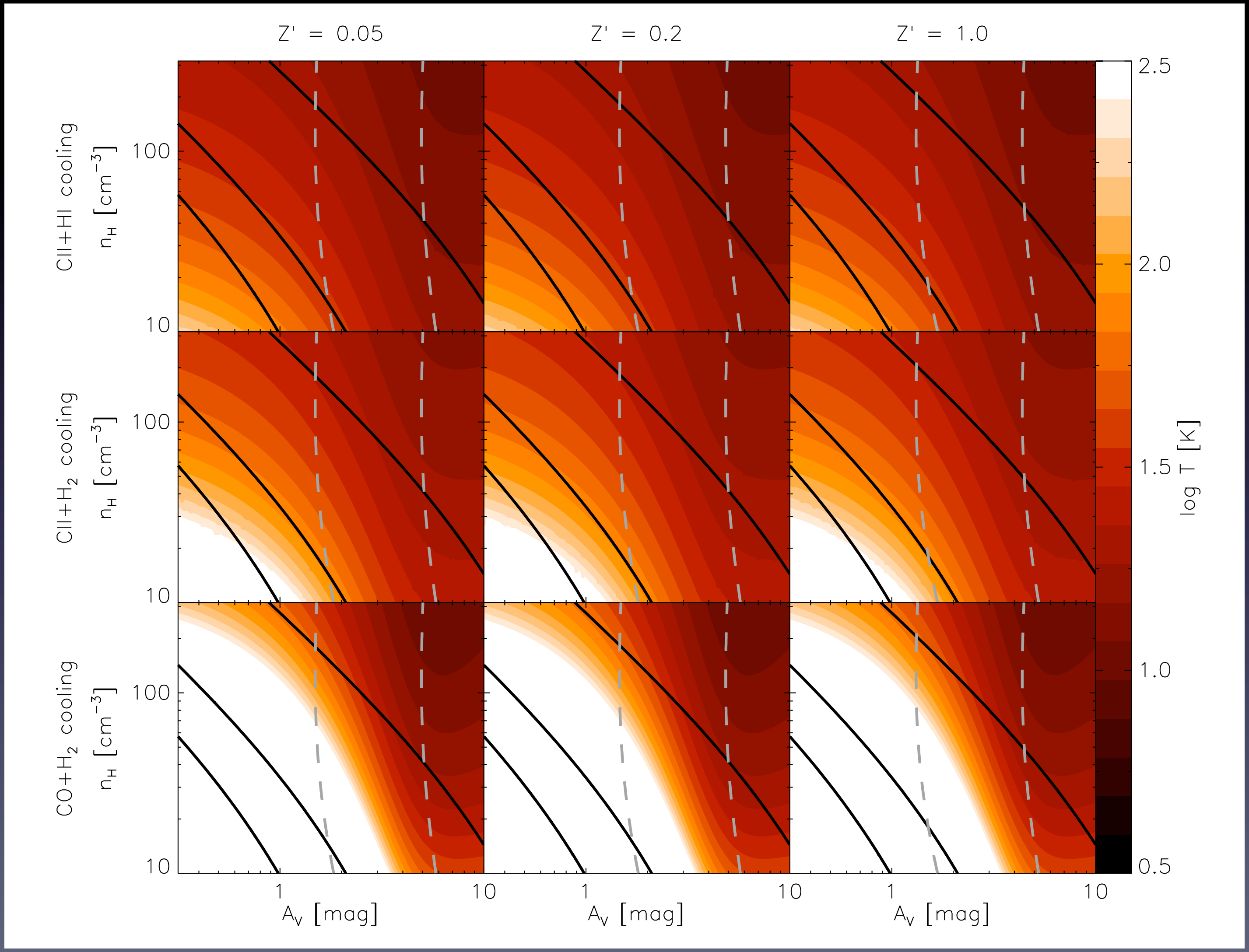
$$\Gamma_{\rm PE} \sim 10^{-30} J_{\rm FUV} e^{-\tau_{\rm dust}/10} \text{ erg s}^{-1}$$

$$\Gamma_{\rm CR} \sim 10^{-27} \zeta \text{ erg s}^{-1}$$

$$\Lambda_{\rm CO} \sim 10^{-27} e^{-8.3/T_1} \text{ erg s}^{-1}$$

- CR, CO dominant for n <~ 10^4 cm^{-3} (dust-gas collisions start to matter above this density)
- Heat released by compression lost ~ instantly
- Equilibrium T ~ 10 K, very hard to change

Parameter Space Survey of T



Krumholz, Leroy, & McKee (2011)

Gas Dynamics

- Since $\Gamma_{ad} << \Gamma_{CR} \sim \Lambda_{line}$, gas can be approximated as isothermal
- To understand behavior, estimate dimensionless numbers using characteristic values: L ~ 100 pc, V ~ 10 km s^{-1}, B ~ 10 μG

Equations of Motion

$$\frac{\partial}{\partial t}\left[\begin{array}{c}\rho\\ \rho\mathbf{v}\\ \mathbf{B}\end{array}\right] =$$

Pressure $P = \rho c_s^2$

Viscosity

$$-\left[\begin{array}{c}\nabla\cdot(\rho\mathbf{v})\\ \nabla\cdot(\rho\mathbf{v}\mathbf{v}) + \nabla P - \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} + \rho\nabla\phi - \rho\nu\nabla^2\mathbf{v}\\ \nabla\times(\mathbf{B}\times\mathbf{v} + \eta:\nabla\times\mathbf{B}\end{array}\right]$$

Resistivity tensor

Gravitational potential

To order of magnitude, $\nabla \to 1/L$, $(\partial/\partial t) \to L/v$

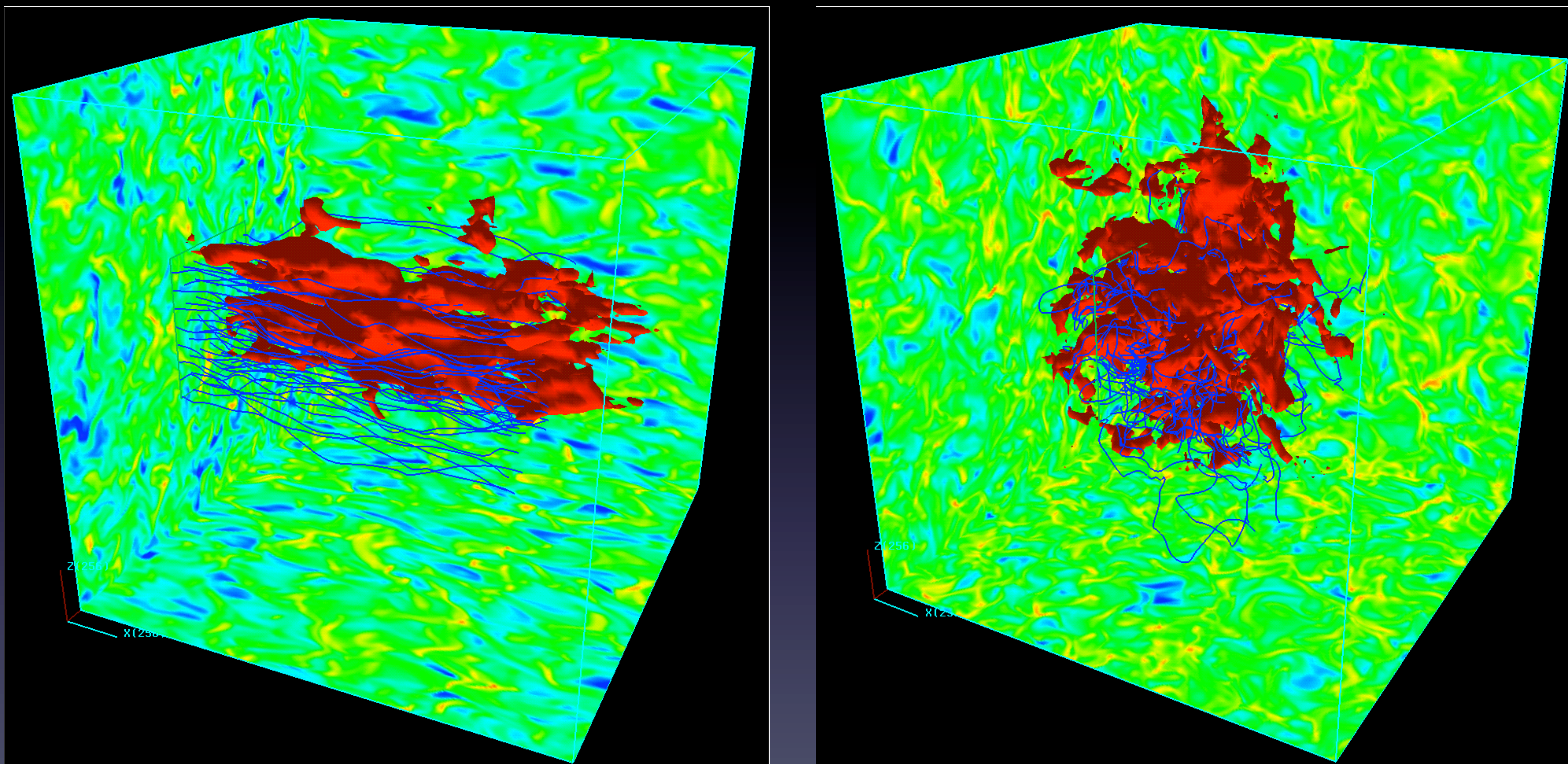
Mach Number(s)

$$\nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P - \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \nabla \phi - \rho \nu \nabla^2 \mathbf{v}$$

$$\boxed{\rho \frac{V^2}{L}} + \boxed{\rho \frac{c_s^2}{L}} + \boxed{\frac{B^2}{L}} + \rho \nu \frac{V}{L^2}$$

$$\mathcal{M} = \frac{V}{c_s} \gg 1 \quad \mathcal{M}_A = \frac{V}{B/\sqrt{4\pi\rho}} = \frac{V}{v_A} \sim 1$$

Low vs. High Alfvén Mach Number



Simulations of 3D MHD turbulence with $\mathcal{M}_A \sim 1$ (left) and $\mathcal{M}_A \gg 1$ (right) (Jim Stone, Princeton)

Reynolds Number(s)

$$\nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P - \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \nabla \phi - \rho \nu \nabla^2 \mathbf{v}$$

$$\boxed{\rho \frac{V^2}{L}} + \rho \frac{c_s^2}{L} + \frac{B^2}{L} + \boxed{\rho \nu \frac{V}{L^2}}$$

$$\mathrm{Re} = \frac{LV}{\nu}$$

$$\sim \frac{LV}{2 c_s \lambda_{\mathrm{mfp}}}$$

$$\sim 10^9$$

$$\nabla \times (\mathbf{B} \times \mathbf{v} + \eta : \nabla \times \mathbf{B})$$

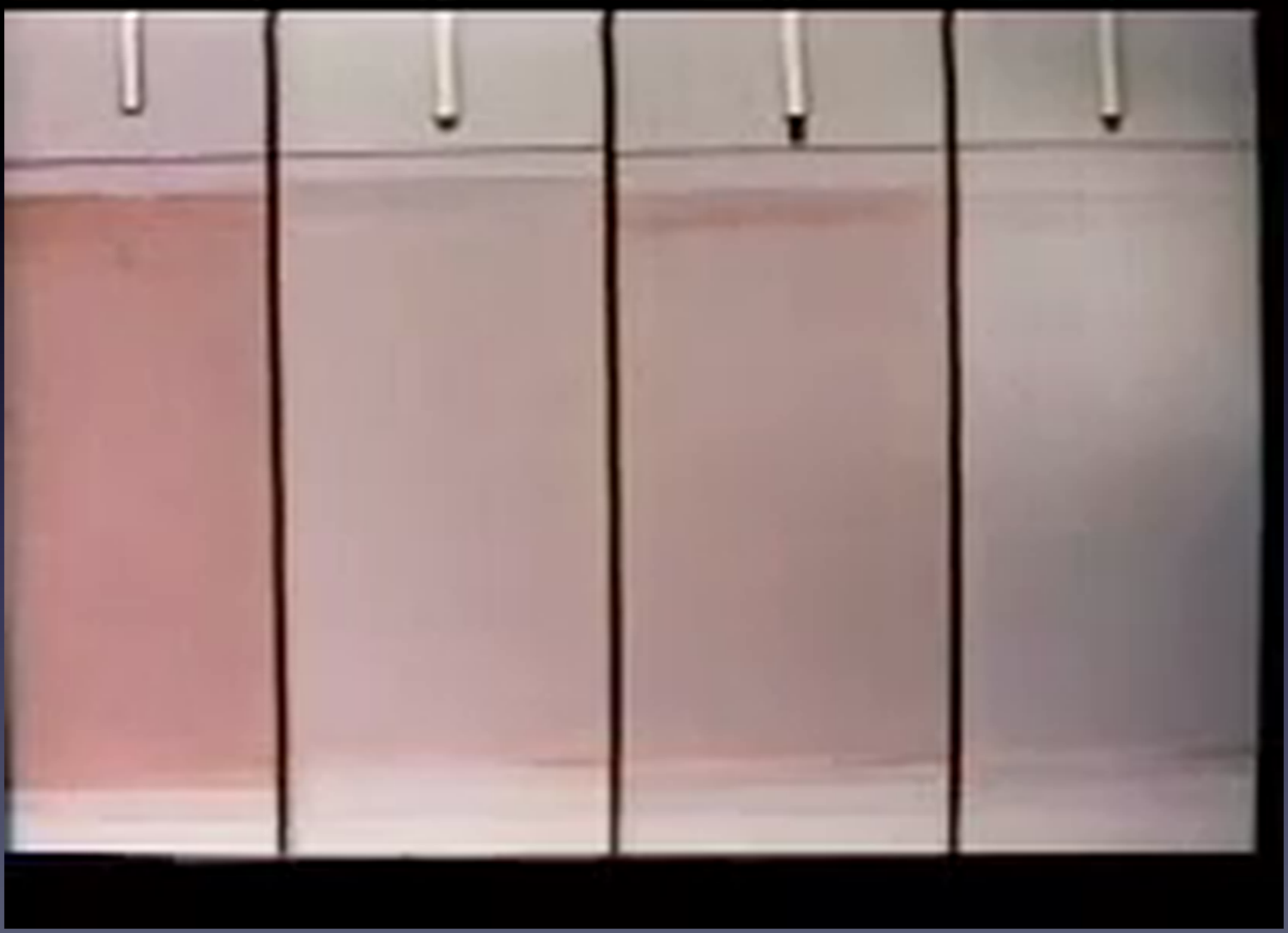
$$\boxed{\frac{BV}{L}} + \boxed{\eta \frac{B}{L^2}}$$

$$\mathrm{Rm} = \frac{LV}{\eta} \sim 50$$

Dynamical Conclusions

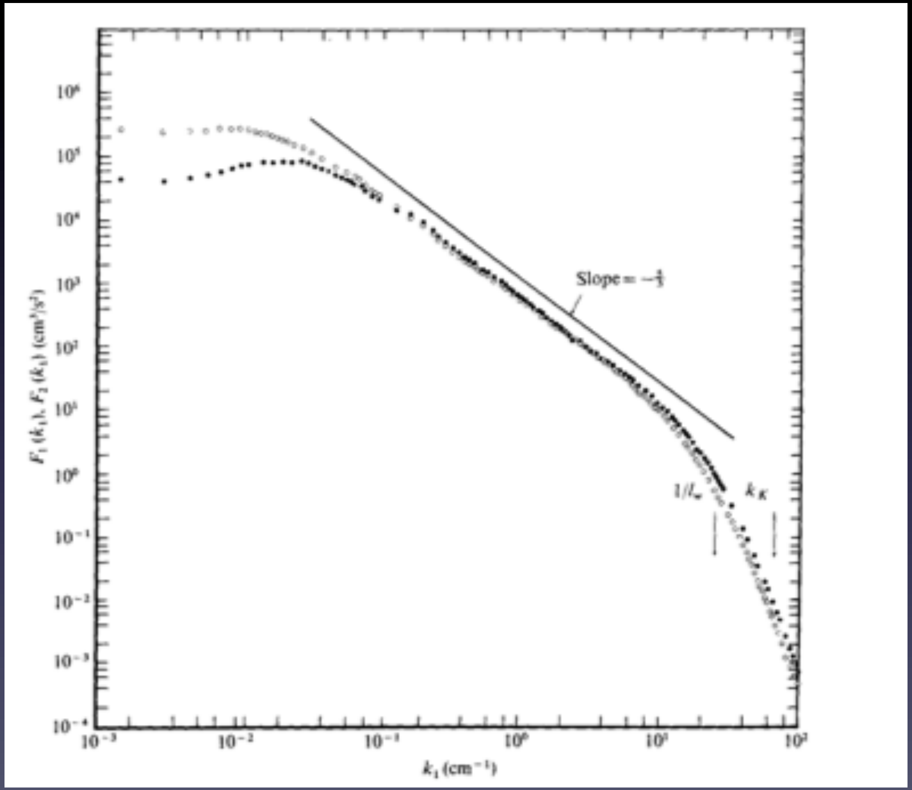
- $\mathcal{M} \gg 1$, so pressure forces unimportant on large scales, shocks inevitable, bulk kinetic energy >> thermal energy
- $\mathcal{M}_A \sim 1$, so magnetic forces non-negligible
- Rm > 1, so ideal MHD is an ok approximation, but breaks down on small scales
- Re >> 1, so gas is extremely turbulent

Why Re Matters

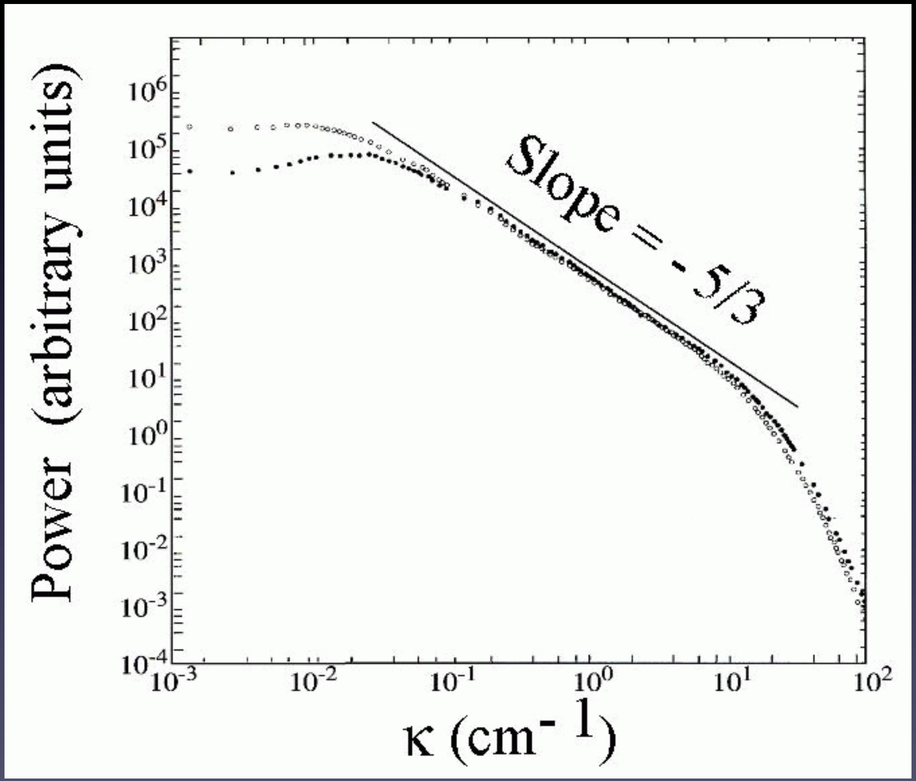


Re = 0.05 Re = 10 Re = 200 Re = 3000

Turbulence: Power Spectra

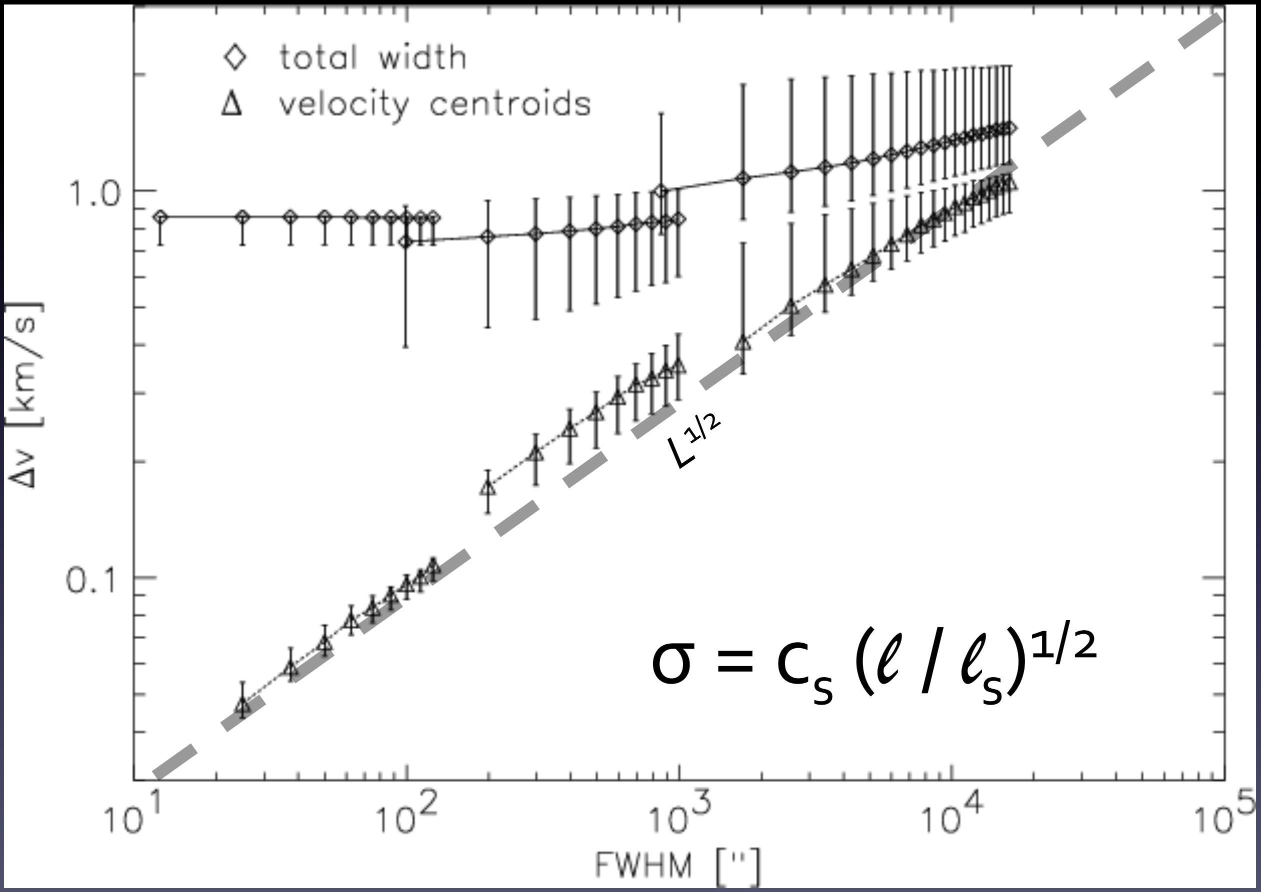


Power spectrum of 10 cm air jet in laboratory (J. Fluid. Mech., F. H. Champagne, 1978)



Power spectrum of atmospheric turbulence (G. Chanan, UC Irvine)

Linewidth-Size Relation



Velocity dispersion vs. beam size in the Polaris Flare cloud (Ossenkopf & Mac Low 2002)

LWS Relation vs. Power Spectrum

- Consider medium with $P(k) \sim k^n$; consider region of size L, wavenumber $k(L) = 2\pi / L$
- Total power from power spectrum is

$$P_{\rm tot} = \int_{k(L)}^{\infty} P(k)\, dk \propto k(L)^{n+1} \propto L^{-n-1}$$

- But we must also have $P_{\rm tot} \propto \sigma^2$
- Conclusion: $\sigma \propto L^{-(n+1)/2}$
- For supersonic turbulence $n = -2$, $\sigma \sim L^{1/2}$

The Virial Theorem: Sketch

(proof following McKee & Zweibel 1992)

- Start with conservation laws

$$\frac{\partial}{\partial t}\left[\begin{array}{c}\rho \\ \rho\mathbf{v}\end{array}\right] = -\left[\begin{array}{c}\nabla\cdot(\rho\mathbf{v}) \\ \nabla\cdot(\rho\mathbf{v}\mathbf{v}) + \nabla P - \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} + \rho\nabla\phi\end{array}\right]$$

- Rewrite in tensorial form

$$\frac{\partial}{\partial t}\left[\begin{array}{c}\rho \\ \rho\mathbf{v}\end{array}\right] = -\nabla\cdot\left[\begin{array}{c}\rho\mathbf{v} \\ \mathbf{T}_s - \mathbf{T}_M\end{array}\right] - \left[\begin{array}{c}0 \\ \rho\nabla\phi\end{array}\right], \qquad \begin{array}{l}\mathbf{T}_s = \rho\mathbf{v}\mathbf{v} + P\mathbf{I} \\ \mathbf{T}_M = \frac{1}{4\pi}\left(\mathbf{B}\mathbf{B} - \frac{B^2}{2}\mathbf{I}\right)\end{array}$$

- Write down moment of inertia, differentiate once, use mass conservation to simplify

$$I = \int_V \rho r^2\, dV \qquad \dot{I} = \int_V \frac{\partial\rho}{\partial t} r^2\, dV = -\int_{\partial V}(\rho\mathbf{v}r^2)\cdot d\mathbf{S} + 2\int_V \rho\mathbf{v}\cdot\mathbf{r}\, dV$$

- Differentiate again, use momentum conservation to simplify

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{M} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_{\partial V}(\rho \mathbf{v} r^2)\cdot d\mathbf{S}$$

$$\mathcal{T} = \int_V \left(\frac{1}{2}\rho v^2 + \frac{3}{2}P\right)$$

Kinetic and thermal energy: opposes collapse

$$\mathcal{T}_S = \int_S \mathbf{r}\cdot\mathbf{T}_S\cdot d\mathbf{S}$$

Surface pressure, ram pressure: promotes collapse

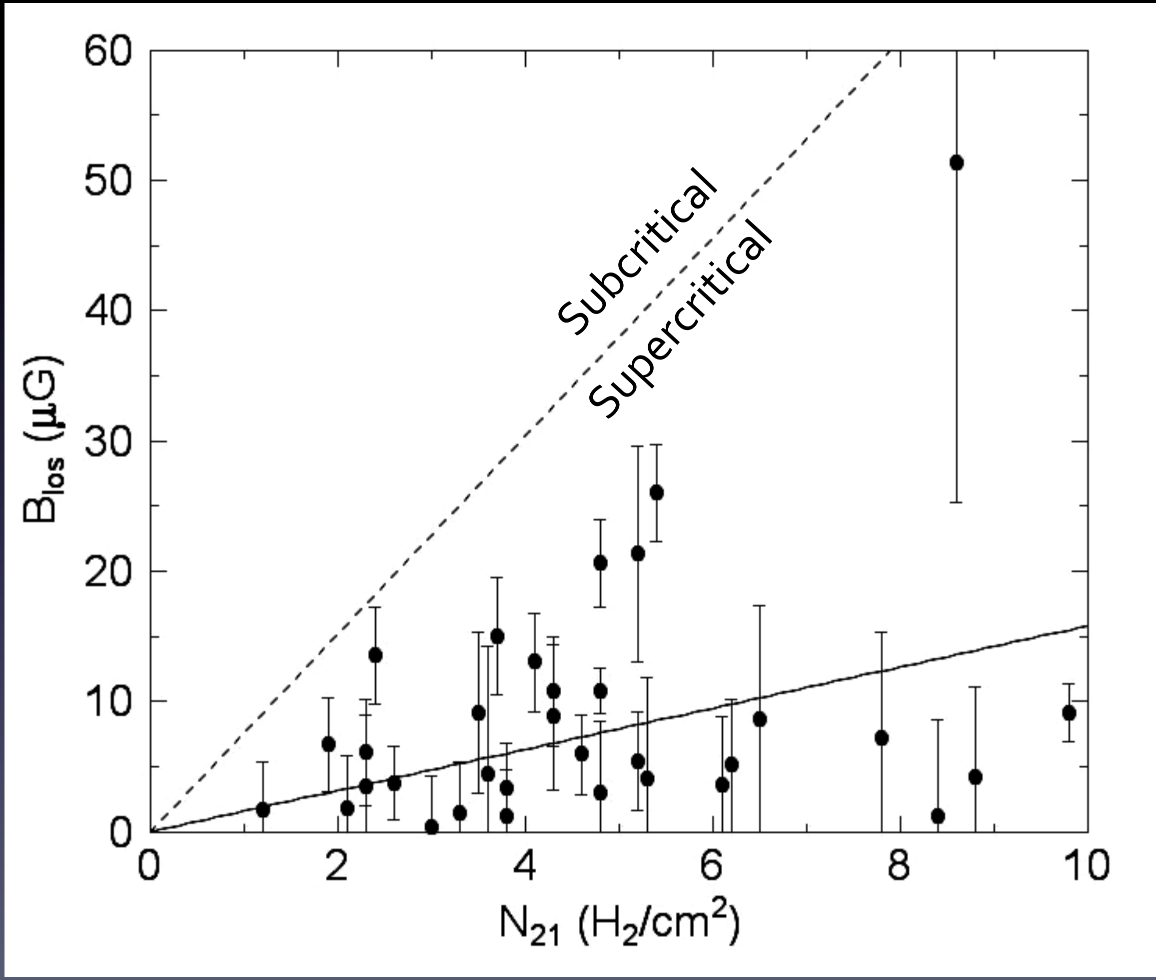
$$\mathcal{M} = \frac{1}{8\pi}B^2\,dV + \int_{\partial V}\mathbf{r}\cdot\mathbf{T}_M\cdot d\mathbf{S}$$

Magnetic pressure + surface tension: (usually) opposes collapse

$$\mathcal{W} = -\int_V \rho\mathbf{r}\cdot\nabla\phi\,dV$$

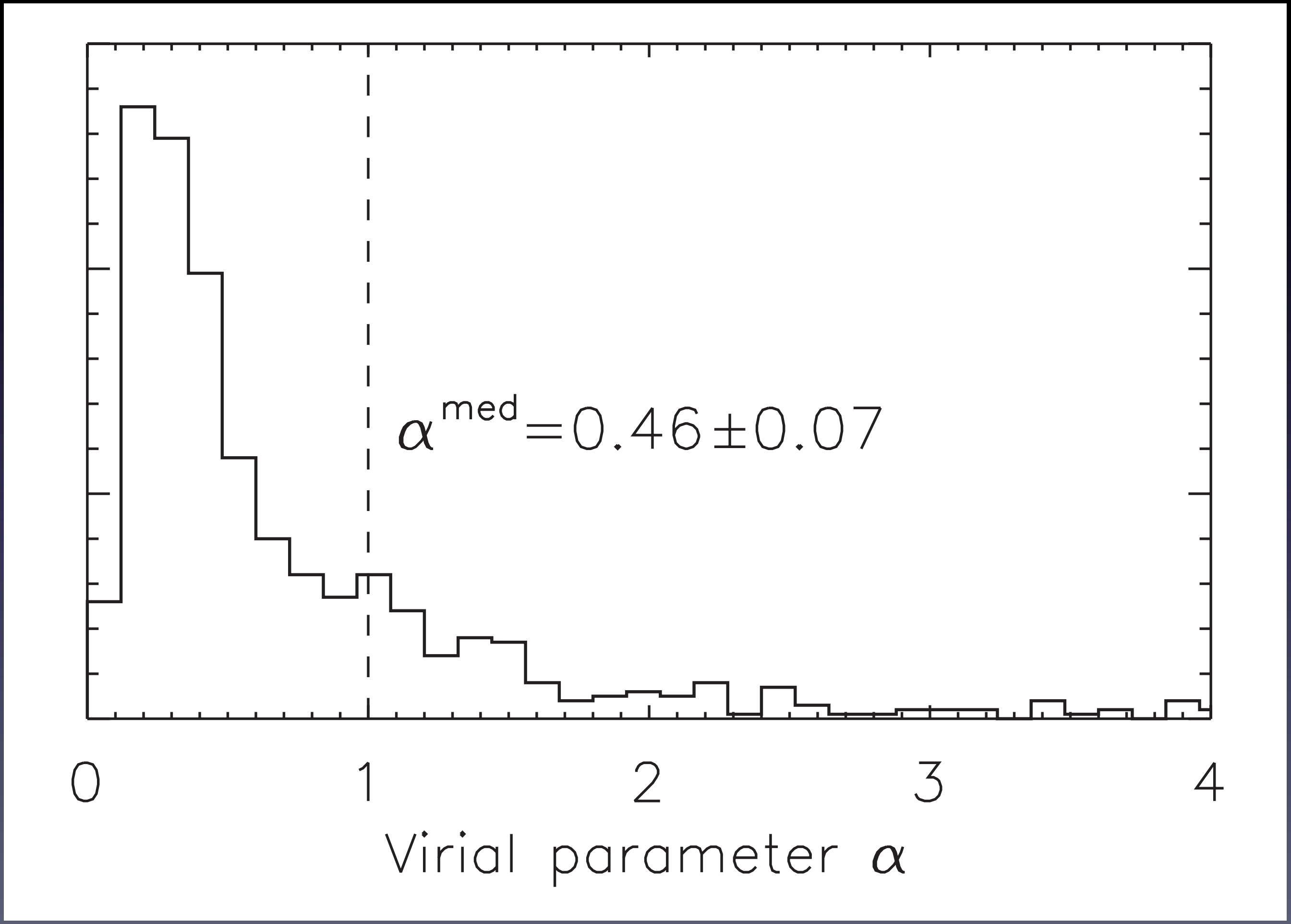
Self-gravity: promotes collapse

Gravity vs. Magnetic Fields



LOS magnetic field vs. column density for a sample of clouds for a sample of OH and CN Zeeman splitting measurements (Crutcher+ 2008)

Gravity vs. Turbulence



Virial ratio distribution in Milky Way GMCs (Roman-Duval+ 2010)

Implications of the VT

- Observed magnetic fields (slightly) too weak to prevent collapse: $\mathcal{M} < |\mathcal{W}|$
- On large scales $2\mathcal{T} \approx |\mathcal{W}|$ (equivalent to $\alpha_{vir} \sim 1$), so no collapse
- However, $\mathcal{T}$ is mostly bulk motion, which diminishes on small scales (LW-size relation)
- Only thermal pressure can prevent small-scale collapse

Thermal Pressure vs. Gravity

- Consider isothermal sphere of mass M, radius R, sound speed c_s, surface pressure P_s, at rest; no B field or turbulence
- VT for this object reads

$$\frac{1}{2}\ddot{I} = \frac{3}{2}Mc_s^2 - 4\pi R^3 P_s - a\frac{GM^2}{R}$$

- Condition for LHS to vanish is

$$P_s = \frac{1}{4\pi R^3}\left(\frac{3}{2}Mc_s^2 - a\frac{GM^2}{R}\right)$$

- If P_s exceeds this value, cloud contracts

The Bonnor-Ebert Mass

- $P_s(R)$ has a maximum at finite R

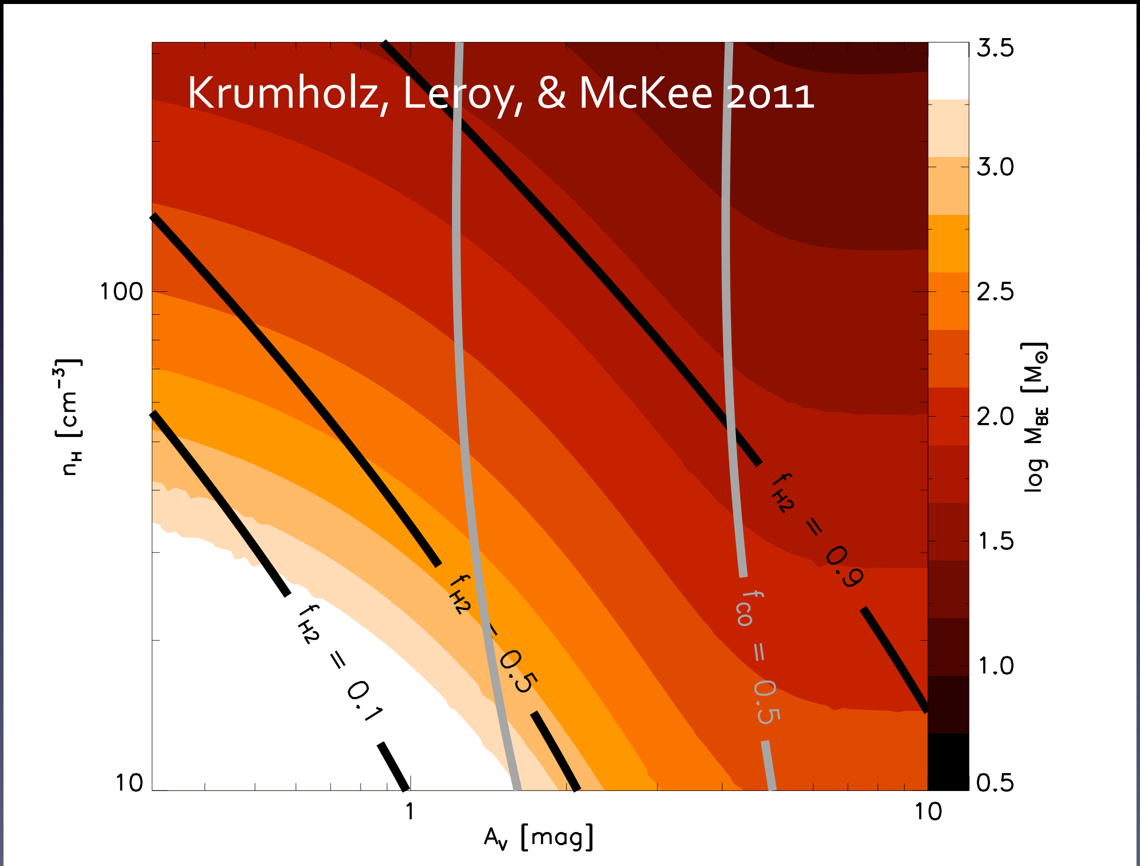
$$P_{s,\max} = \frac{3^7 c_s^8}{2^{14} \pi a^3 G^3 M^2}$$

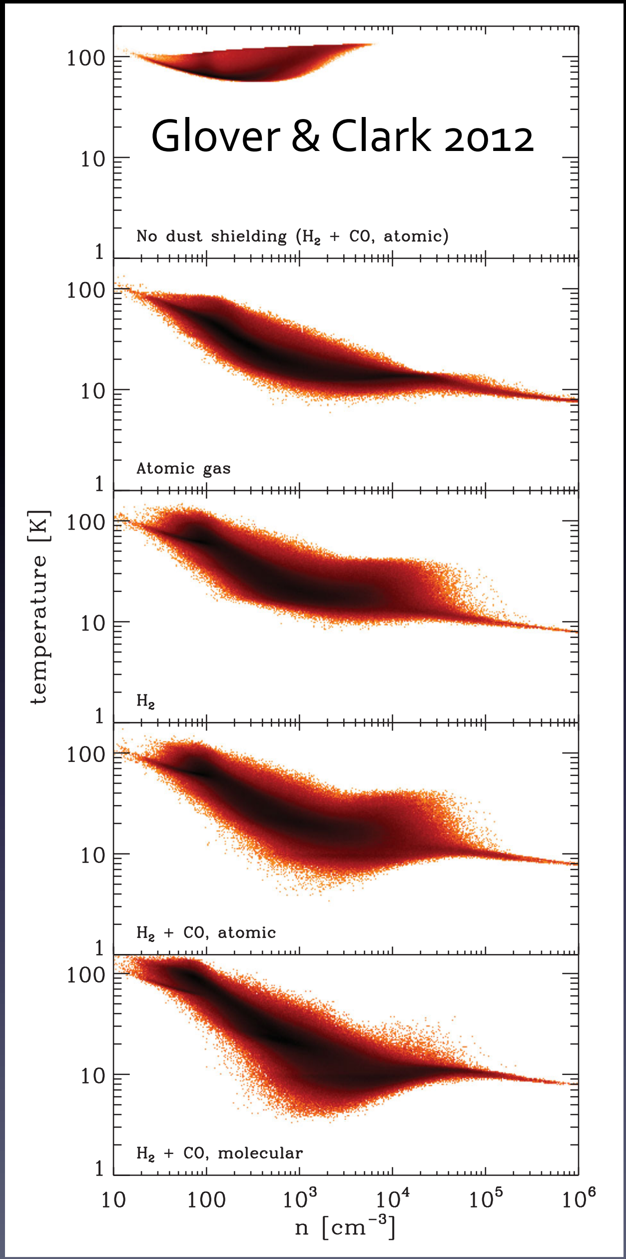
- If $P_s > P_{s,max}$ collapse is inevitable
- Can equivalently write in terms of mass:

$$M_{\mathrm{BE}} = 1.18 \frac{c_s^4}{\sqrt{G^3 P_s}} = 1.18 \frac{c_s^3}{\sqrt{G^3 \rho}}$$

- In GMCs in nearby galaxies, $P_s/k_B \approx 10^6$ K cm^{-3}, $c_s \approx 0.2$ km s^{-1} ➔ $M_{BE} \approx 0.4\ M_\odot$
- Outside GMCs, $P_s/k_B \approx 10^4$ K cm^{-3}, $c_s \approx 8$ km s^{-1} ➔ $M_{BE} \approx 10^7\ M_\odot$

Implications for Star Formation





Summary

- Observations of molecular lines constrain
  - Cloud masses
  - Densities
  - Temperatures
  - Velocity distributions
- Star-forming gas characterized by:
  - Low temperature, so M_{BE} can be small
  - Fast cooling, so gravitational contraction cannot heat gas up to halt collapse
  - Strong, supersonic turbulence, because cooling time << dynamical time