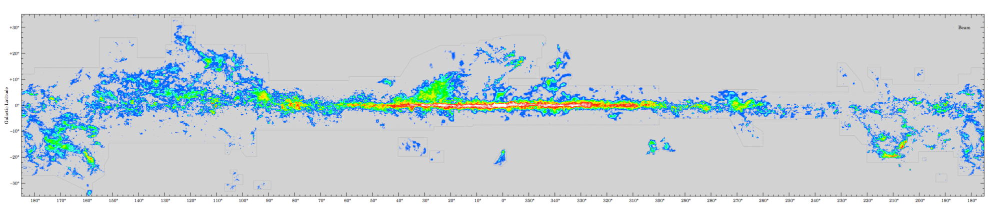
Lecture 26
Clouds, Clumps and Cores

1. Review of Dense Gas Observations
2. Atomic Hydrogen and GMCs
3. Formation of Molecular Clouds
4. Internal Structure
5. Observing Cores
6. Preliminary Comments on Core Stability

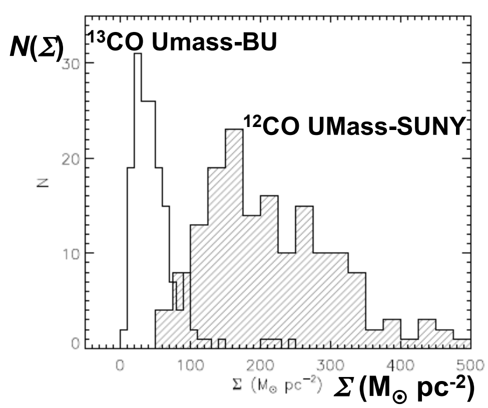
References

Bergin & Tafalla, ARAA 45 339 2007
Blitz & Williams, "Molecular Clouds"
Myers, "Physical Conditions in Molecular Clouds"
In Origins of Stars & Planetary Systems
http://www.cfa.harvard.edu/events/1999crete

Review of Molecular Clouds



Dame et al. (2001) CfA CO survey



recent star formation is associated with GMCs

empirical correlations

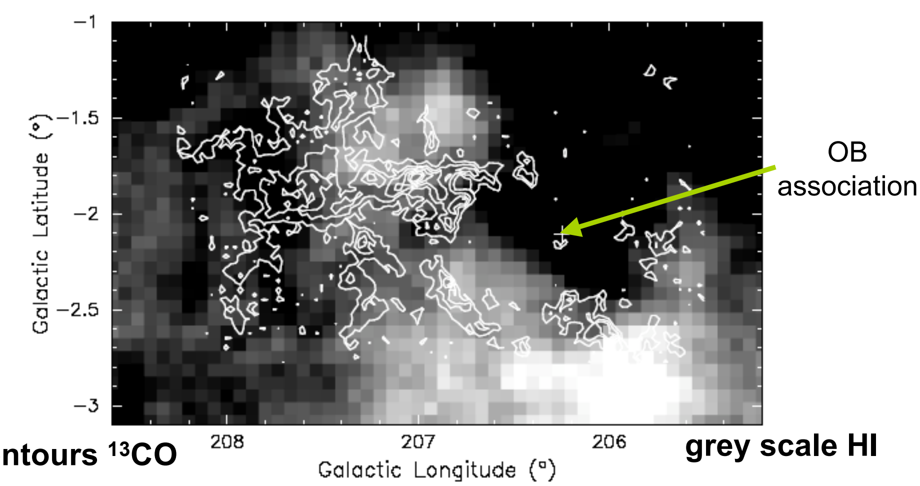
$$\sigma \approx N^{1/2} R^{1/2} \qquad \frac{M}{R} \approx \sigma^2$$

are not independent

2. HI Content of GMCs
Tentative Ideas

- HI envelopes around molecular clouds are probably common.
- Local GMCs may have comparable masses of HI and H_2
- HI is more spatially extended
- GMC HI probably varies throughout the Milky Way, e.g., HI merges into a continuous background in the 5-kpc ring.
- Origin of the HI in and near GMCs:
  Photodissociation of H_2?
  Remains of the GMC formation from HI?
- **Basic, interesting, and challenging topic for future study?**

HI and ^{13}CO in the Rosette Molecular Cloud



contours ^{13}CO **grey scale HI**

Figure 3. An HI envelope around the Rosette molecular cloud. The grayscale, range 450 to 620 K km s^{-1}, shows HI data from Arecibo observations by Kuchar & Bania (1993). Contours, beginning from and with increment 18 K km s^{-1}, are CO emission from Bell Labs observations by Blitz & Stark (1986). Emission has been summed over a velocity range $v = 4 - 25$ km s^{-1}. The cross marks the OB association that lies at the center of the Rosette nebula and has cleared out the neutral gas. The regions of strong HI emission (lighter colors) lie on the CO cloud boundaries, forming an envelope around the cloud.

Blitz & Williams 1999

3. Formation of Molecular Clouds

- Gravity must play a role: GMCs are self-gravitating, but not low-mass clouds ($M < 10^3\ M_\odot$), e.g., high-latitude clouds.
- GMCs may be short lived, as indicated by the age of the oldest sub-associations (10-20 Myr) still associated with GMCs.
- In principle, the age should be greater than the crossing time, but sound speeds are low. For purposes of estimation, use the original line width size relation:

$$R/\sigma \sim 2\ \text{Myr}\ (\sigma\ /\ \text{km s}^{-1}),$$

somewhat shorter than the above estimate of 10-20 Myr.

Formation is an Unsolved Problem

Many processes are involved – gravity, magnetic fields, turbulence, shocks, radiation, etc., but which is dominant?

Formation Mechanisms

Three are often discussed (e.g., Elmegreen in "Evolution of the ISM", ASP 1990)

- Collisional agglomeration of smaller clouds
- Formation from HI, e.g. by "gravo-thermal" instability
- Shocks in a turbulent ISM, generated by outflows from massive stars and SN remnants

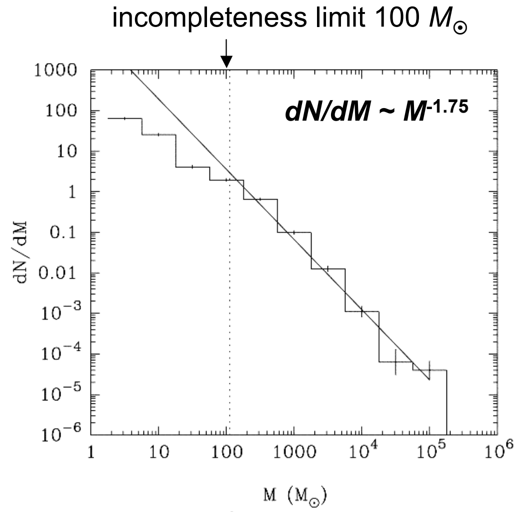
- **If GMCs are formed from the coalescence (agglomeration) of molecular fragments, where are they?**
- **Is it the chaff seen in spiral arms and in the vicinity of GMCs?**
- **How much precursor gas is preserved by star formation?**

Agglomeration

Blitz & Williams (1999)

The single power law indicates that the non-GMC "chaff" ($M < 10^3\ M_\odot$) belongs to the same population as GMCs and has possibly the same origin, I.e., agglomeration.

Blitz & Williams argue that, since formation and destruction time-scales are roughly the same (tens of Myr), the mass in low-mass MCs and GMCs should be about the same in steady state. They then argue that, this *not* being the case, GMCs form from HI and not by agglomeration. However, this steep distribution actually favors low-mass clouds.



Heyer & Terebey: 1500 clouds in the Perseus arm ApJ 502 265 1998):

4. Structure of Molecular Clouds

CO maps show that molecular gas is heterogeneous.

What is the topology of molecular clouds?

Is it useful to talk about discrete structures?

Blitz & Williams discuss three levels of structure: ***clouds, clumps, and cores***, illustrated by the following maps of the Rosette Molecular Cloud in CO, $C^{18}O$, and CS:

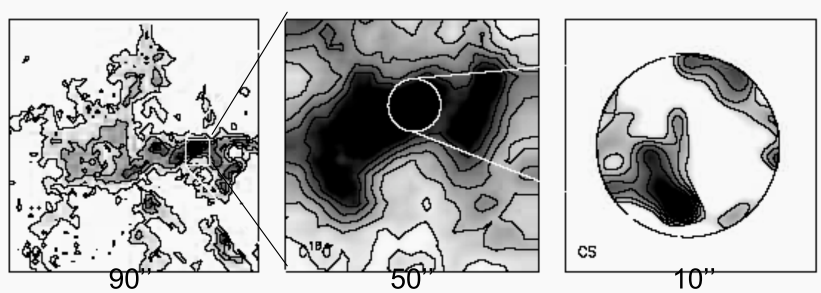


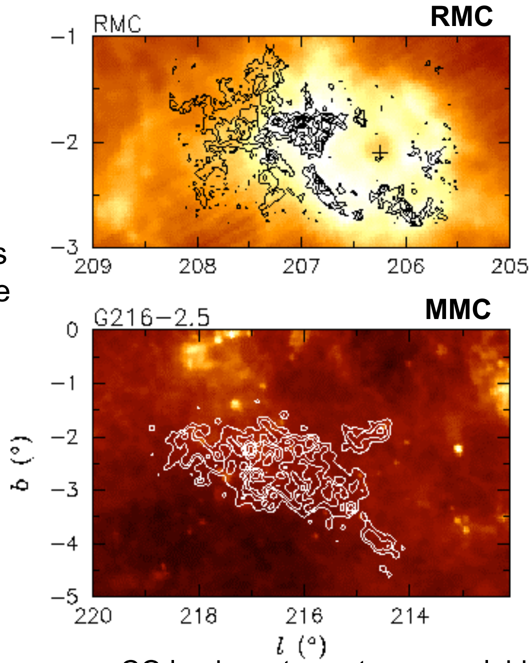
Figure 4. Hierarchical cloud structure. The three panels show a representative view from cloud to clump to core. The bulk of the molecular gas (cloud; left panel) is best seen in CO which, although optically thick, faithfully outlines the location of the H_2. Internal structure (clumps; middle panel) is observed at higher resolution in an optically thin line such as $C^{18}O$. With a higher density tracer such as CS, cores (right panel) stand out. The observations here are of the Rosette molecular cloud and are respectively, Bell Labs (90''), FCRAO data (50''), and BIMA data (10'').

Clumps in GMCs

Williams et al (ApJ 428 693 1994) analyzed ~ 100 ^{13}CO 1-0 clumps in the Rosette and the Maddalena molecular clouds

- These clouds have similar masses ~ 10^5 $M_\odot$, but orders of magnitude different star formation rates, as traced by FIR dust emission:
- Rosette: ~ 17 OB plus numerous embedded sources
- G216-2.5: no OB stars and L_{IR} / $M(H_2)$ < 0.07 $L_\odot/M_\odot$
- Star formation in the RMC occurs in gravitationally bound clumps; the MMC has none.

Why is there no star formation in MMC?

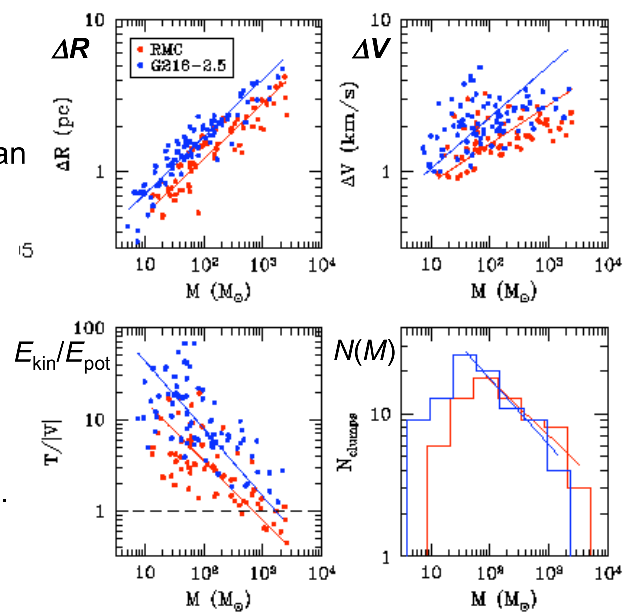


CO luminosuty contours overlaid On IRAS 100 μm intensity

Clump Properties of the RMC and MMC

Williams et al (ApJ 428 693 1994)

- Clump masses derived with an X-factor calibrated with ^{13}CO ~ 1/2 of the galactic average
- Spatial resolution for both clouds is similar ~ 0.7 pc.
- Clumps are similar, but those in MMC are bigger and have larger line widths.
- Both clouds are bound, but none of the MMC clumps are.



Properties of Dark Clods, Clumps and Cores

Bergin & Tafalla (ARAA 45 339 2007)

Table 1 Properties of dark clouds, clumps, and cores

	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_{\odot}$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent ($km\ s^{-1}$)	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph,	B213, L1709	L1544, L1498,
	Musca		B68

[a]Cloud masses and sizes from the extinction maps by Cambrésy (1999), velocities and temperatures from individual cloud CO studies.
[b]Clump properties from Loren (1989) (^{13}CO data) and Williams, de Geus & Blitz (1994) (CO data).
[c]Core properties from Jijina, Myers & Adams (1999), Caselli et al. (2002a), Motte, André & Neri (1998), and individual studies using NH_3 and N_2H^+.

5. Molecular Cloud Cores

- Star formation occurs in the densest parts of GMCs called molecular cloud cores.
- About 1/2 of known cores are luminous IR sources powered by newborn stars.
- Molecular core properties provide the initial conditions for star formation and may determine the properties of the stars they form.
- Keys to observing cores are molecular lines that trace high density rather than low density gas and IR measurements of warm dust heated by newborn stars

References

Bergin & Tafalla, ARAA 45 339 2007
Benson & Myers, ApJS 71 743 1989
Jijina et al. ApJS 125 161 1999

Some Dense Gas Tracers

Molecule	Transition	Frequency (GHz)	E/k (K)	n_{crit} (cm^{-3}) @ 10 K	n_{eff} (cm^{-3}) @ 10 K
CS	1-0	49.0	2.4	4.6×10^4	7.0×10^3
	2-1	98.0	7.1	3.0×10^5	1.8×10^4
	3-2	147.0	14	1.3×10^6	7.0×10^4
HCO^+	1-0	89.2	4.3	1.7×10^5	2.4×10^3
	3-2	267.6	26	4.2×10^6	6.3×10^4
HCN	1-0	88.6	4.3	2.6×10^6	2.9×10^4
	3-2	265.9	26	7.8×10^7	7.0×10^5
H_2CO	2_{12}-1_{11}	140.8	6.8	1.1×10^6	6.0×10^4
	3_{13}-2_{12}	211.2	17	5.6×10^6	3.2×10^5
	4_{14}-3_{13}	281.5	30	9.7×10^6	2.2×10^6
NH_3	(1,1)	23.7	1.1	1.8×10^3	1.2×10^3
	(2,2)	23.7	42	2.1×10^3	3.6×10^2

See Schoier et al. A&A 432 369 2005 for dipole moments etc.

Measurement of Core Temperatures

Although almost any optically-thick rotational ladder may work, the ***inversion spectrum*** of NH_3 is the most useful. The basic reference is Townes & Schawlow, Ch. 12.

In the ground state, the N atom Is located on either side of the 3 H atoms in the plane. To get to the other side, it has to tunnel through the potential barrier, whose height is ~ 2,000 cm^{-1}. The tunneling frequency is very small and is in the cm radio band.

Similar splittings occur for methanol (CH_3OH).

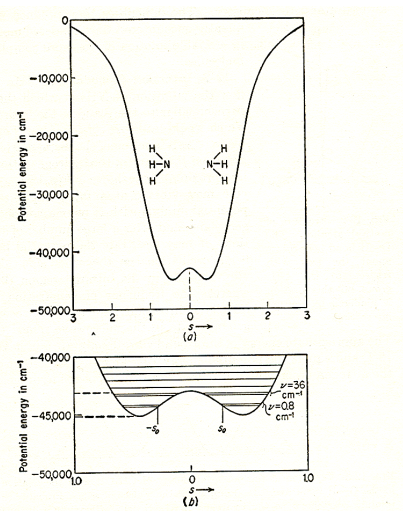


FIG. 12-1. Potential curve of NH_3. The variable s is a measure of the distance between the nitrogen and the plane of the hydrogens. (b) shows the lower part of the potential curve in more detail, and the energy levels.

NH_3 Temperature Measurement

NH_3 is a symmetric rotor with a dipole moment of 1.48 D.
The allowed *rotational* transitions satisfy $|\Delta J| = 1$ and $\Delta K = 0$,
but the frequencies are so high they require space observations.

But the levels are split by tunneling in the 25-GHz band that depends on (J,K). The transitions usually observed are at the bottom of each K-ladder. The splittings of these (K,K) levels are:

(1,1)	23.694 GHz
(2,2)	23.723
(3,3)	23.870
(4,4)	24.139
(5,5)	24.533
(6,6)	25.056

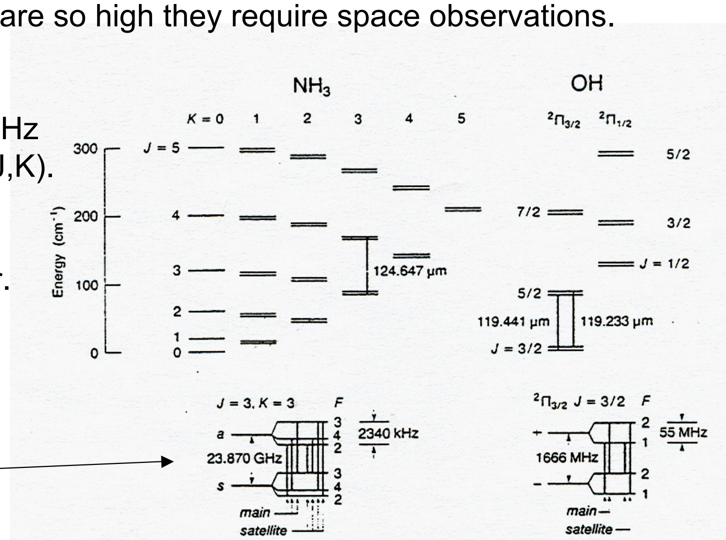


Fig. 5. Rotational levels of NH_3 (left) and OH (right) (adapted from Watson 1982)

The hyperfine splittings are also shown.

NH_3 Temperatures

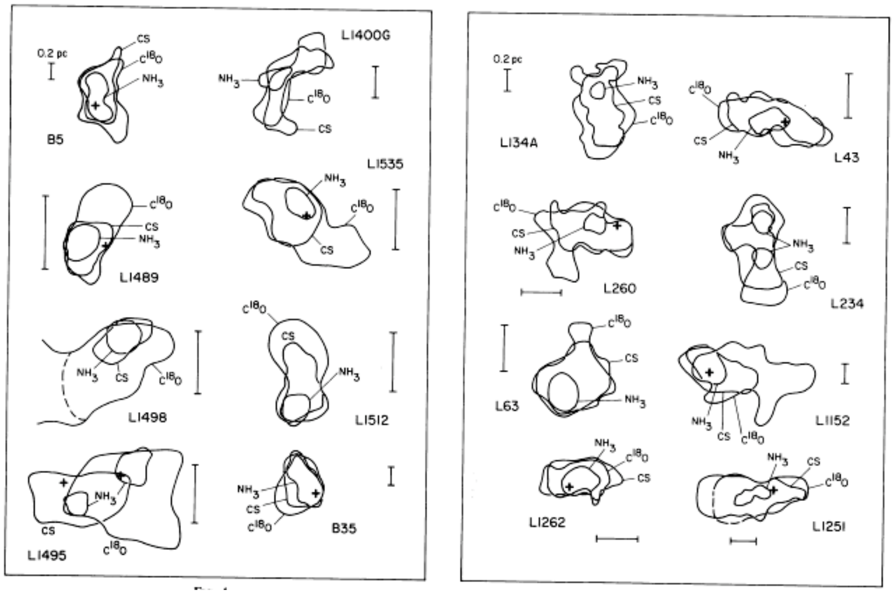
The beauty of measuring the inversion transitions of the NH_3 (*K,K*) levels is that they span a large range of excitation temperature but require measurements in just one radio band (using the same instrumentation for all transitions). The transitions listed above cover the temperature range up to 500 K.

This is to be contrasted with a non-hydride rotor like CO where a large range of excitation temperatures can only be achieved by using different telescopes with different resolution.

The often used (J,K)=(1,1) level occurs at 1.27 cm and has a moderate critical density.

Shapes of Molecular Cloud Cores

Myers et al. 376 561 1991



Notice the different map sizes for CO, CS and NH_3, and the elongation in the case of $C^{18}O$

Survey of 264 NH_3 Cores

Jijina et al. ApJS 126 161 1999

NH_3 Column Radius Aspect Ratio

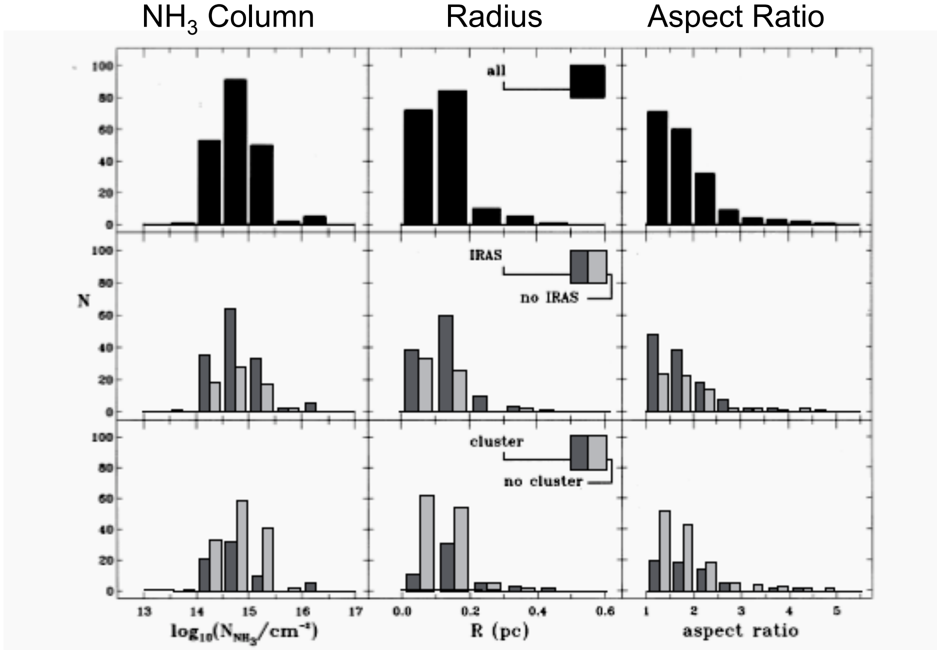


FIG. 1.—Distributions of the core gas properties: column densities, N_{NH_3} (cm^{-2}), core sizes, R (pc), and aspect ratios, a/b, for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

Jijina et al. NH_3 Core Survey

Line width Temperature Velocity gradient

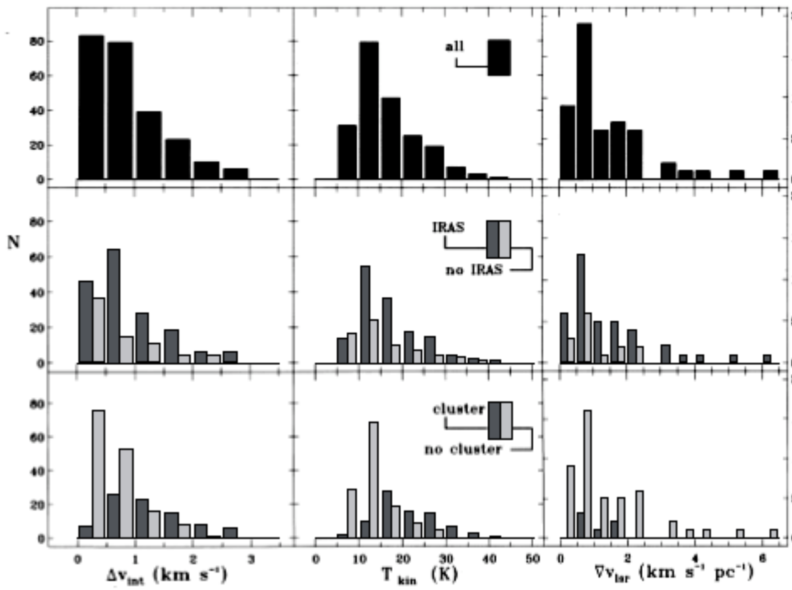


FIG. 2.—Distributions of the core gas properties; intrinsic velocities, Δv_{int} (km s^{-1}), kinetic temperatures, T_{kin} (K), and velocity gradients, ∇v_{lsr} (km s^{-1} pc^{-1}), for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

Jijina et al. NH_3 Core Survey
Mass distribution

10 100

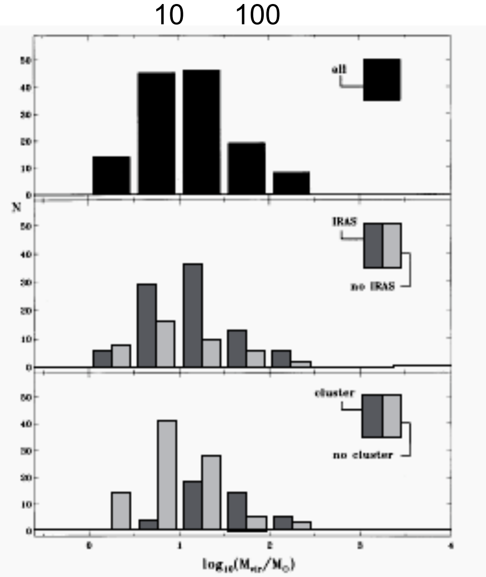
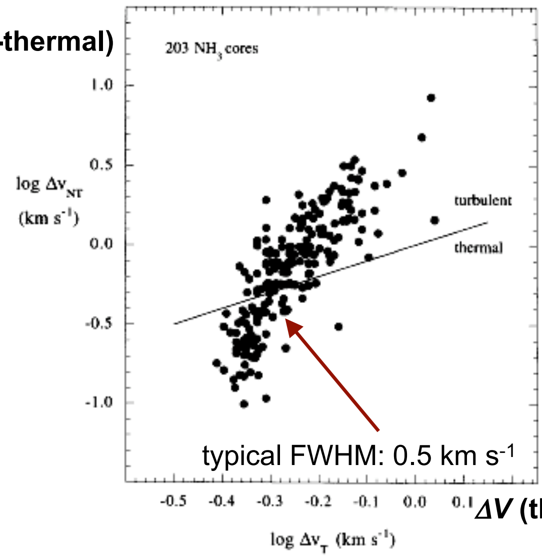


FIG. 3.—Distributions of the core mass distribution, $M_{vir}/M_\odot$, for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

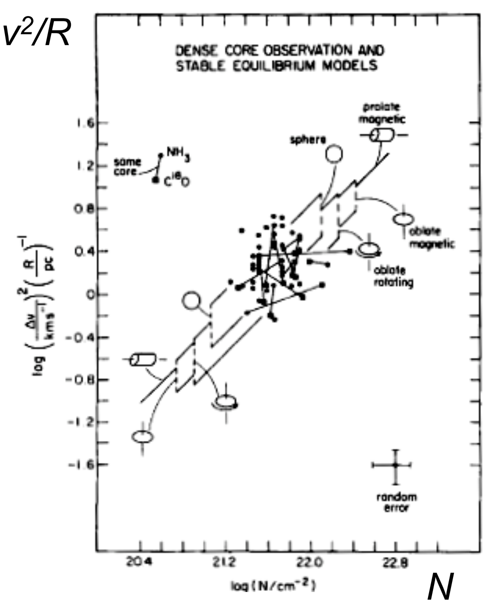
Non-Thermal vs. Thermal Core Line Widths

Myers (Crete 1999)



Turbulent cores are warmer than quiescent cores

Consistency of Cores and Virial Equilibrium



gravitational energy per unit mass vs. column density

- Models of virial equilibrium (funny symbols) easily fit the observations (solid circles [NH_3] and squares [$C^{18}O$]).
- The Larson/Solomon relations would imply that both the ordinate and abscissa are near constant. Myers' data seemed to illustrate this approximately for a diverse sample of cores.
- Linewidth-size relations have been found for the larger cores

  $\Delta v \sim R^p$ **0.3 < p < 0.7**

  until the cores are dominated by thermal rather than turbulent motions (Goodman et al. ApJ504 223 1998)

Observed Core Properties

1. associated with star formation: 50% or more have embedded protostars (*Spitzer* found a few more)
2. elongated (aspect ratio ~ 2:1)
3. cold: T ~ 6 – 30 K
4. internal dynamics dominated by thermal or turbulent motion: Myers' NH_3 cores are roughly equally split between thermal and non-thermal.

$$\Delta v_{\rm FWHM}{}^2 = \Delta_{\rm turb}{}^2 + 8\ln 2\,(\frac{kT}{m})$$

$$\Delta v_{\rm th} = \sqrt{8\ln 2\,(\frac{kT}{m})} = 0.675\ {\rm km\ s^{-1}}\sqrt{\frac{m_{\rm H}}{m}(\frac{10{\rm K}}{T})}$$

5. typical size: R ~ 0.1 pc
6. ionization: $x_e \sim 10^{-7}$

Observed Core Properties

7. approximate virial equilibrium
8. size-linewidth relation may apply
   An interesting exception is the
   Pipe Nebula (Lada et al. 2008)
9. mass spectrum similar to GMCs

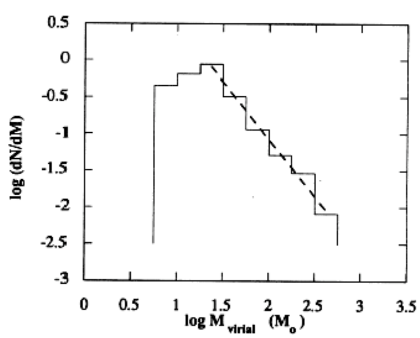


Figure 6. The mass spectrum of dense cores in the L 1630 cloud from the study of LBS. The spectrum can be characterized by a power law with an index of -1.6.

fact that different definitions of clumps were employed in each case [20, 122].

6. Comments on Stability of Cloud Cores

Summary of molecular cloud core properties,
Many of which still need to be quantified

1. Location of star formation
2. Elongated (aspect ratio ~ 2:1)
3. Internal dynamics dominated by thermal or by turbulent motion
4. Often in approximate virial equilibrium
5. Temperature: $T \sim 5 – 30$ K
6. Typical size: $R \sim 0.1$ pc
7. Ionization fraction: $x_e \sim 10^{-7}$
8. Size-line width relation may apply
9. Mass spectrum similar to GMCs.

First Consideration of Core Stability

- Virial equilibrium might be an appropriate state from which cores proceed to make stars. However, a significant fraction of cores have embedded protostars (IRAS observations). They can’t be quiescent forever.

- Core stability is an important issue, e.g., why are they stable (if they are), and how do they become de-stabilized and collapse under gravity to form stars?

- Although Myer’s data suggest thermal and/or non-thermal) pressure may stabilize cores against collapse, other possibilities need to be considered, in particular rotation and magnetic fields.

Effects of Rotation

Molecular cloud cores have *modest* velocity gradients,

0.4 - 3 km s^{-1} pc^{-1}

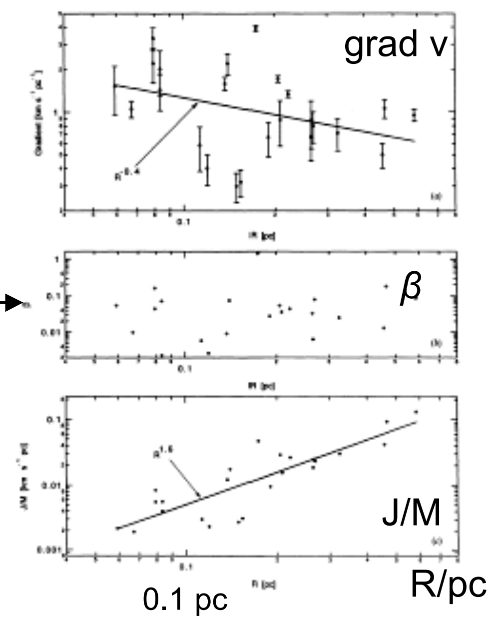
and angular speeds

$\Omega \sim 10^{-14}$ - 10^{-13} rad s^{-1}.

$\beta = E_{rot} / E_{grav} \sim 0.02$

Cores do not appear to be supported by rotation.

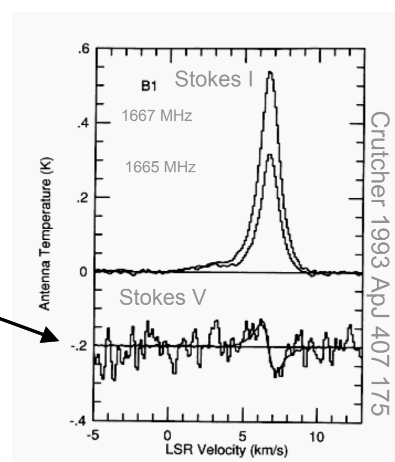
NB Not all of the observed gradients correspond to the overall rotation of the core



Goodman et al. ApJ 406 528 1993

Magnetic Fields

- Magnetic fields are difficult to measure in cloud cores with the Zeeman effect
- Example of dark cloud B1:
  $|\mathbf{B}| \cos \theta \approx -19 \pm 4$ μG
  $B^2/8\pi \sim 3 \times 10^5$ K cm^{-3}
- This value of $B^2/8\pi$ is much greater than the thermal pressure of a 10 K core with n ~ 10^3 cm^{-3}. Cores do have higher densities, whereas OH probes $n_H \approx 10^3$ cm^{-3}.
- Magnetic fields are potentially important.



B1 - First dark cloud OH Zeeman measurement