STARLESS CORES

Mario Tafalla
(Observatorio Astronómico Nacional, Spain)

Outline:

1. ***Internal Structure***
   a. ***Introduction***
   b. ***How to characterize the internal strcuture of starless cores***
   c. ***L1498 & L1517B: two intermediate-stage cores***
2. ***Evolution of cores***
   a. ***How can we trace core evolution?***
   b. ***Searching for young cores***

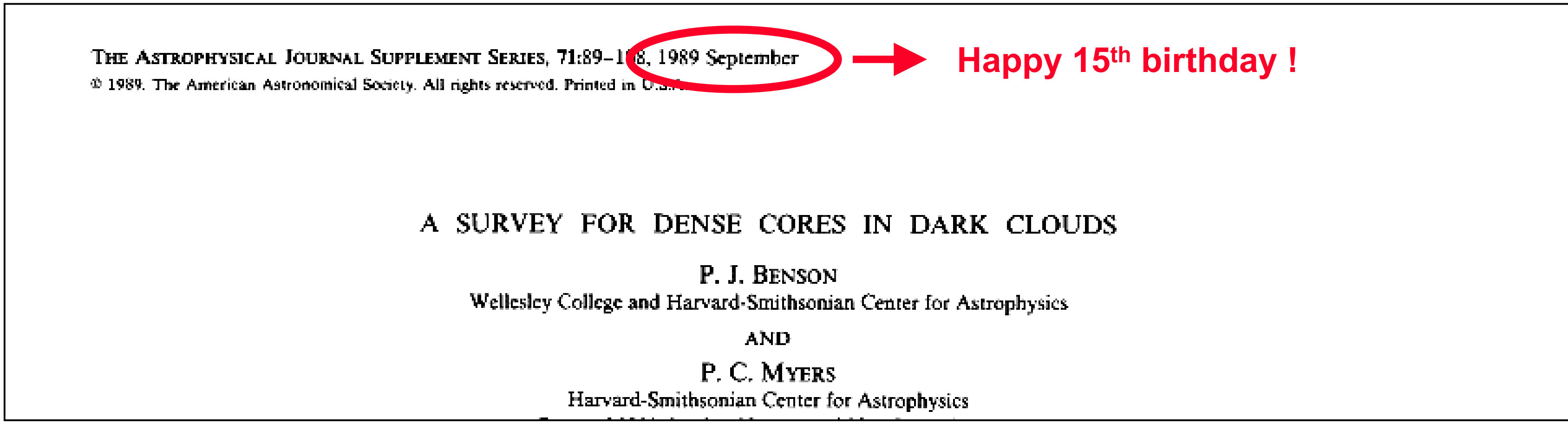
Why do we study dense starless cores?

- **Taurus-like cores do not**
  - form high or intermediate-mass stars
  - form clusters
  - represent dominant mode of star formation
- **Taurus-like cores do**
  - represent the simplest sites where Sun-like stars are born
  - constitute the most nearby star-forming regions
  - form ``complete´´ systems: disks, outflows, binaries

Hope: star formation in a core contains most of the basic physics of star formation

From cores to clusters (of 1 star/binary)

Global core properties


THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 71:89–1[illegible]8, 1989 September
© 1989. The American Astronomical Society. All rights reserved. Printed in U.S.A.

A SURVEY FOR DENSE CORES IN DARK CLOUDS

P. J. BENSON
Wellesley College and Harvard-Smithsonian Center for Astrophysics

AND

P. C. MYERS
Harvard-Smithsonian Center for Astrophysics

- Global properties well known since late eighties
- Determined from
  - low resolution observations (> arcminute)
  - single line tracer (NH_3)
  - observation of a large number of objects (>100)
- Global properties are averages
  - but cores are not homogeneous

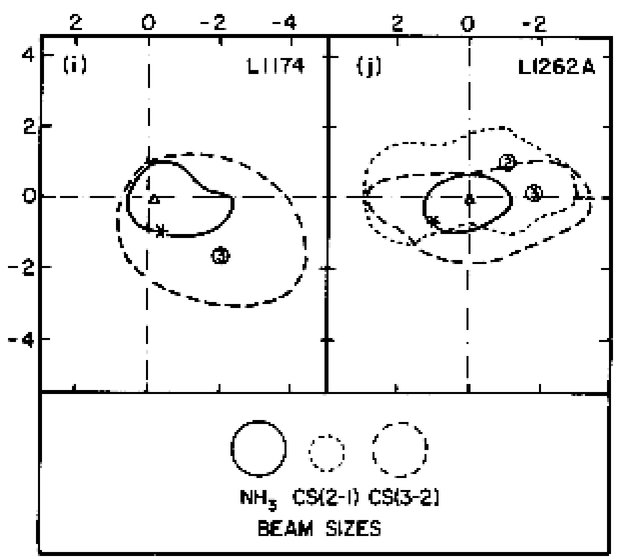
Problems already: something missing...

THE ASTROPHYSICAL JOURNAL, 346:168–179, 1989 November 1

→ Happy 15th birthday too !

A CS SURVEY OF LOW-MASS CORES AND COMPARISON WITH NH_3 OBSERVATIONS

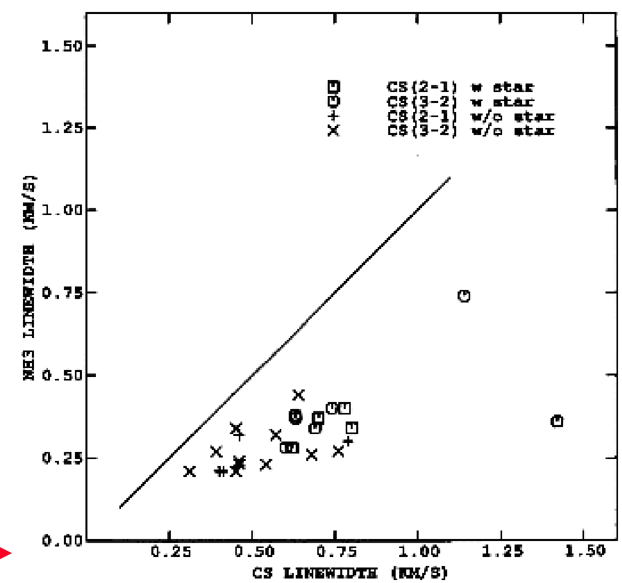
SHUDONG ZHOU, YUEFANG WU,[1] AND NEAL J. EVANS II
Department of Astronomy and Electrical Engineering Laboratory, University of Texas at Austin
GARY A. FULLER
Astronomy Department and Radio Astronomy Laboratory, University of California, Berkeley
AND
PHILIP C. MYERS
Harvard-Smithsonian Center for Astrophysics



G. 3.—The peak positions and the FWHM contours of NH_3 and CS line

CS maps 2x larger than NH_3 maps. Peaks do not coincide. ←

CS lines 2x wider than NH_3 lines. →



2004: 15 years later

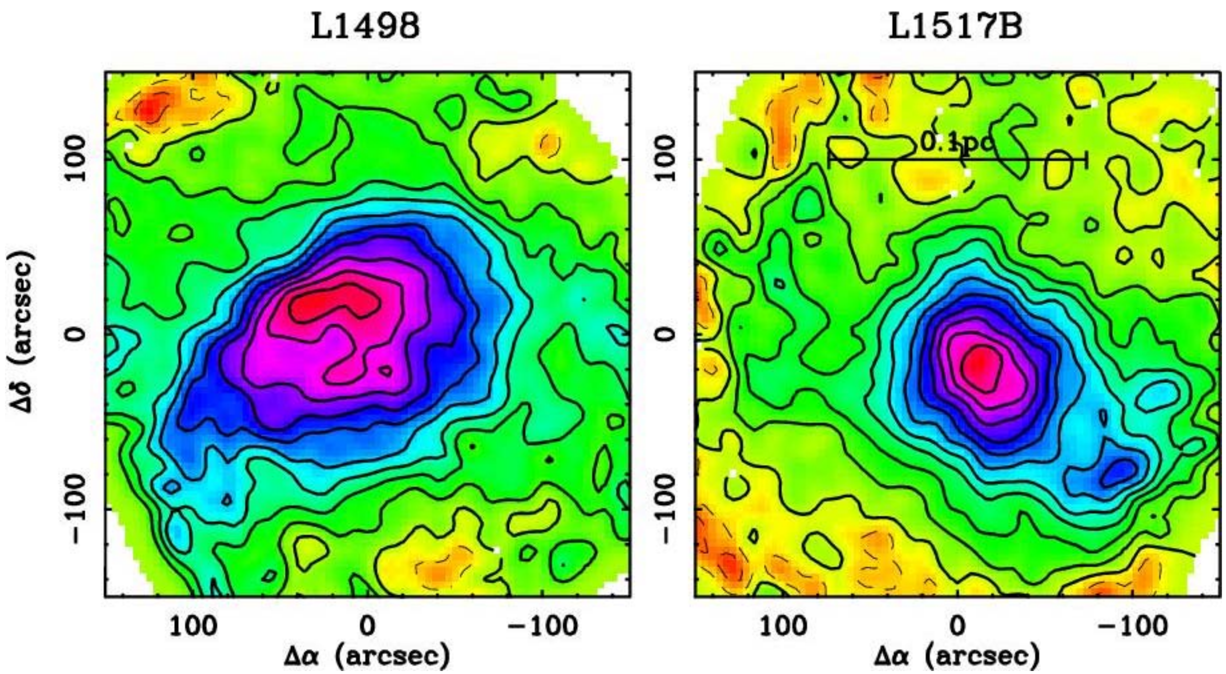
- Increase in resolution (< 1arcmin): IRAM 30m, JCMT
- mm/sub-mm dust continuum (SCUBA, MAMBO)
  - Ward-Thompson et al. (1994), André et al. (1996)
- NIR extinction measurements
  - Lada et al. (1994), Alves et al. (2001)
- Mid-IR absorption images
  - Bacmann et al. (2000)
- Identification of depletion/freeze out as a key element in dense core chemistry
  - Kuiper et al. (1996), Kramer et al. (1999), Caselli et al. (1999)

It has become finally possible to model consistently the interior of dense cores

Deriving core internal structure

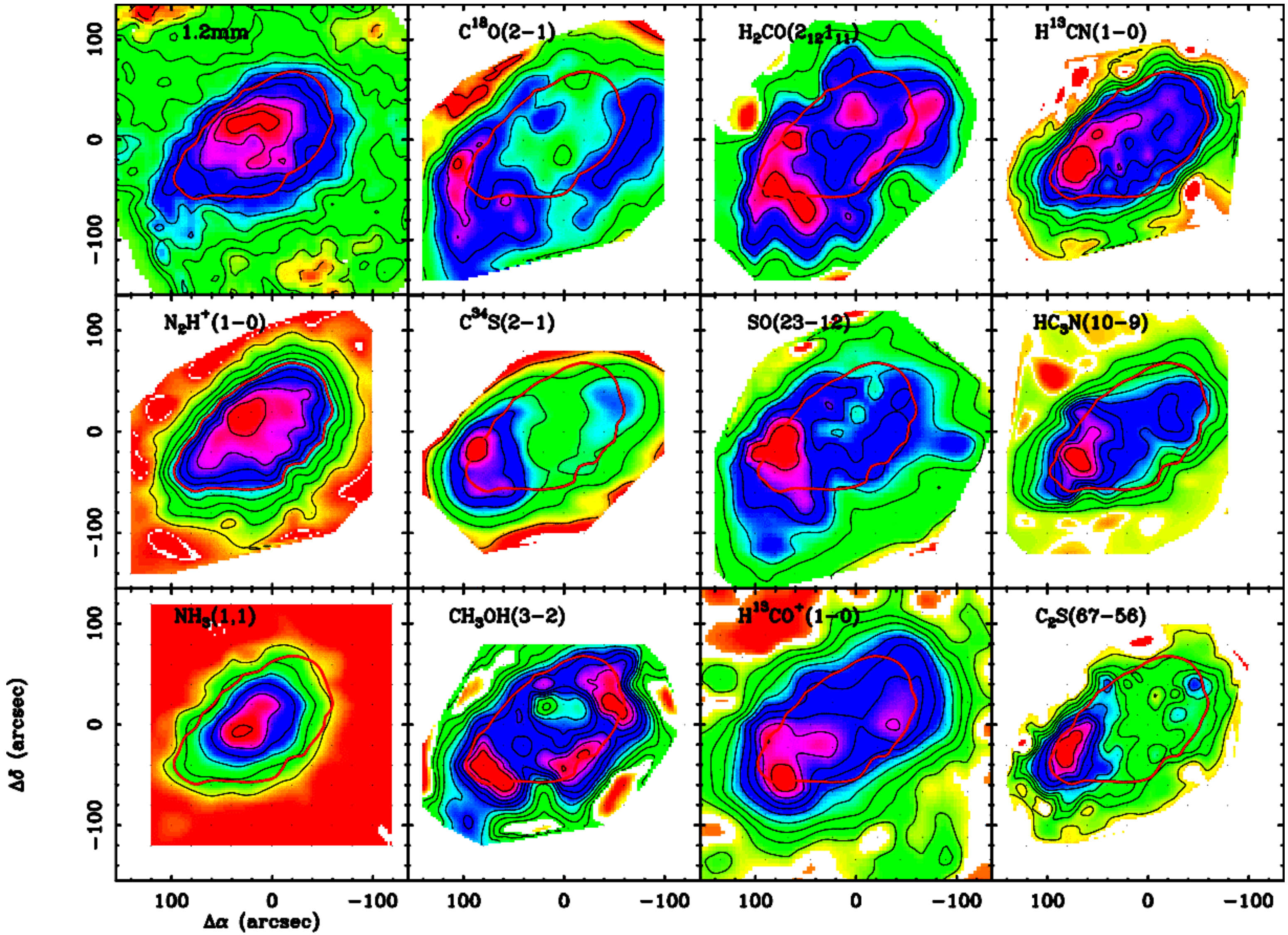
- Parameters: n(r), T(r), sigma_v(r), v(r), X_i(r), (B?)
- Assumption of spherical symmetry
  - observed deviations: oblate-prolate?
- Radiative transfer. Dust
  - optically thin at mm/submm
  - factor of 2 uncertainty in emissivity a mm/sub-mm wavelength
  - uncertain dust temperature profiles (see Malcolm´s talk)
- Radiative transfer. Lines
  - no LTE ($n<n_{cr}$)
  - no LVG (sigma_v is small)
  - Monte Carlo (e.g., Tafalla et al. 2002), ALI (Keto et al. 2004)

The internal structure of L1498 & L1517B

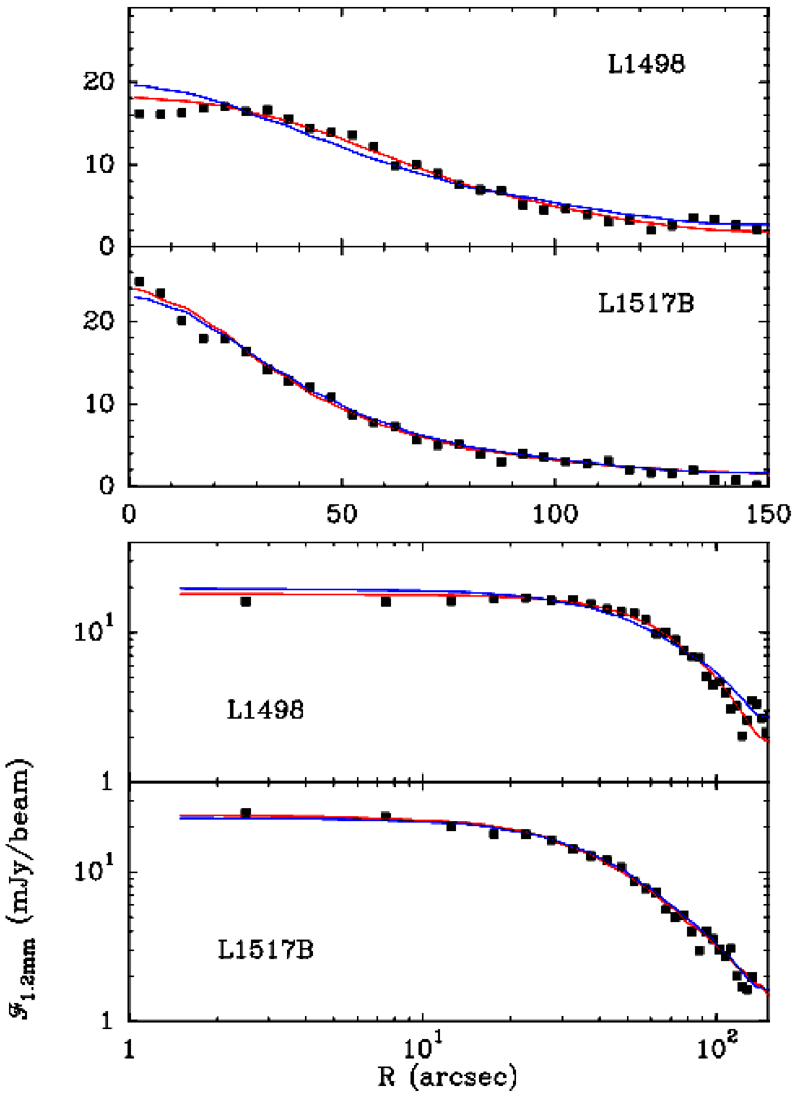


- Two Taurus/Auriga cores
  - no evidence for star formation (2MASS, IRAS)
  - close to round shape
- Probably at intermediate stage in evolution (see later)
- Tafalla, Myers, Caselli, Walmsley (2004) + in prep.

Molecular data for L1498

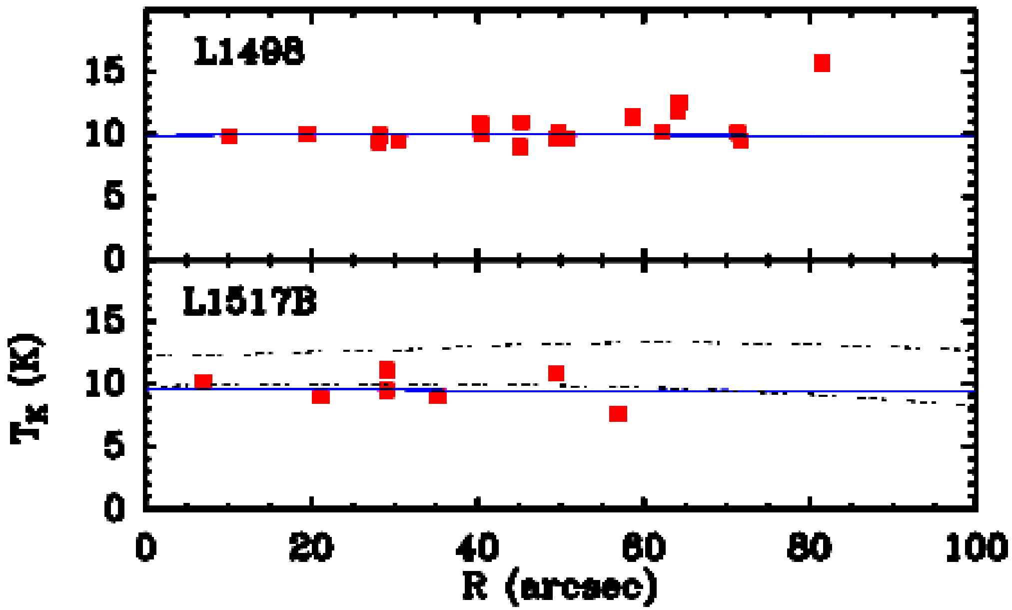


Core density profiles



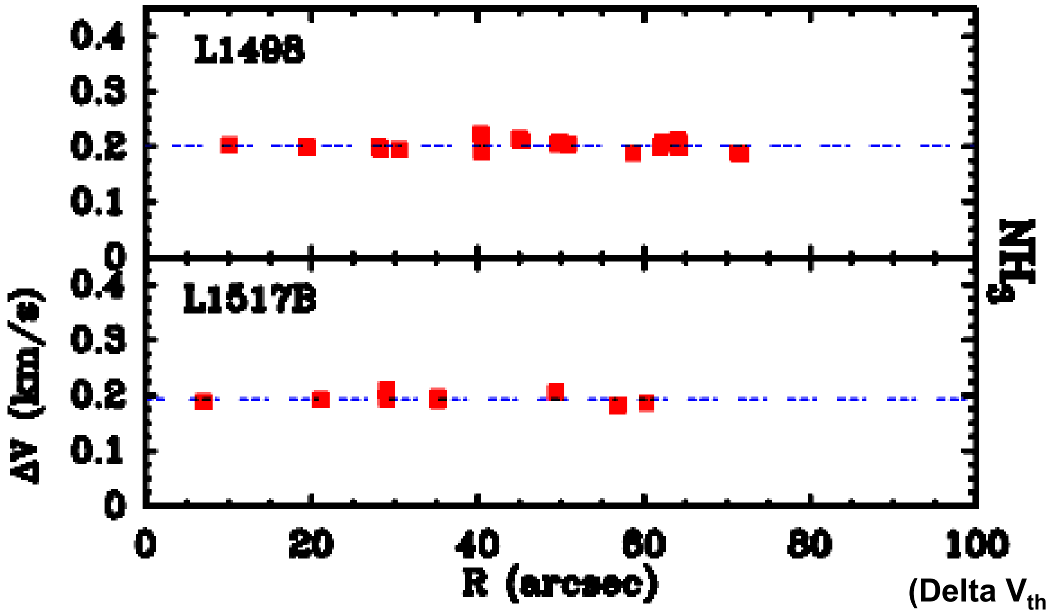
- T_d = 10K, $k_{1.2mm}$ = 0.005 cm^2/g
- Analytical models:
  - red lines
  - $n(r) = n_0 / (1 + (r/r_0)^a)$
  - n_0 = 1-2 10^5 cm^{-3}
  - r_0 = 5,000-10,000 AU
  - a = 2.5-3.5
- Isothermal (Bonnor-Ebert) models:
  - blue lines
  - indistinguishable from a=2.5 (L1517B)
  - R_{max} close to critical

Core temperature



- (1,1)-(2,2) analysis for each point
  - create radial profile of gas temperature
- Excellent fit with constant temperature
  - close to 10 K
- Possible central gas temperature drop?
  - dust temp. expected to drop at center (bc UV attenuation)
  - dust/gas thermal coupling at densities 10^5 cm^{-3}
- Compare with models by Galli et al. (2002)
  - drop seems less than 1 K (3K increase doubles (2,2) emission)

Linewidth: thermal and non thermal



(Delta V_{th} = 0.16 km/s for 10 K)

- **Hyperfine analysis** corrects for optical depth
- Radial profile of NH_3 **intrinsic linewidth**
  - constant, very low scatter (consistent w. noise). No linewidth-size relation
  - non thermal component FWHM < 0.1 km/s ($sigma_{NT}$ = 0.04 km/s)

$$\frac{P_{NT}}{P_T} = \frac{\sigma_{NT}^2}{(kT/m)} \approx 0.05$$

→

Pressure support by turbulent component is negligible in central 0.1 pc

Equilibrium state of L1498 and L1517B

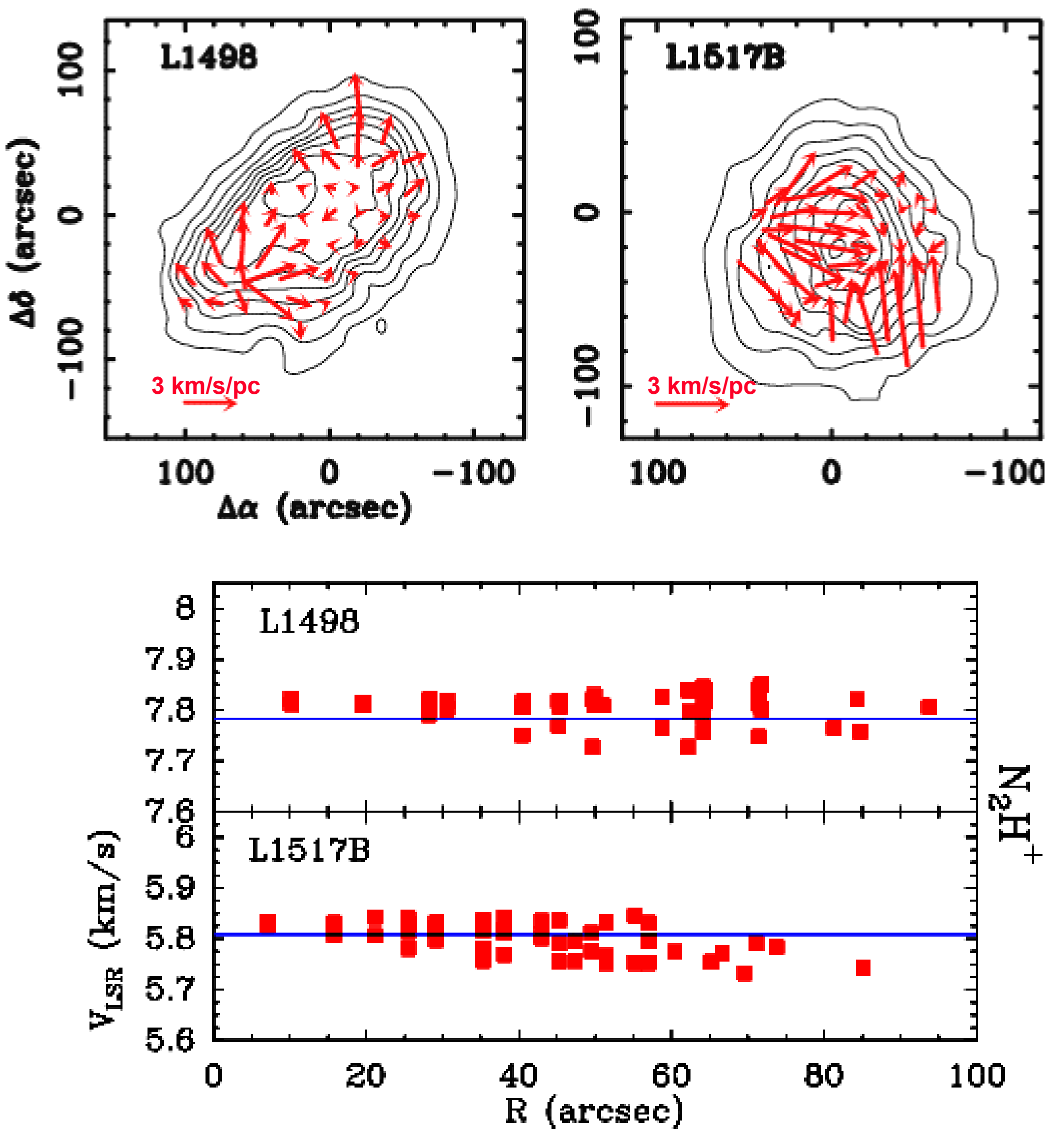
- Cores seem isothermal (T=10K)
- Linewidth is constant
  - non-thermal contribution to pressure is negligible (5% of thermal)
- Density profiles are very close to Bonnor-Ebert profiles

Are L1498 and L1517B in equilibrium?

- Compare measured velocity dispersion (0.185 km/s) with predicted by BE fit
  - L1498: 0.32 km/s
  - L1517B: 0.27 km/s
- Caveat: BE-fit dispersion depends on assumed emissivity
  - if kappa is twice assumed, L1517B is in equilibrium
- Magnetic field?
  - L1498 not spherical

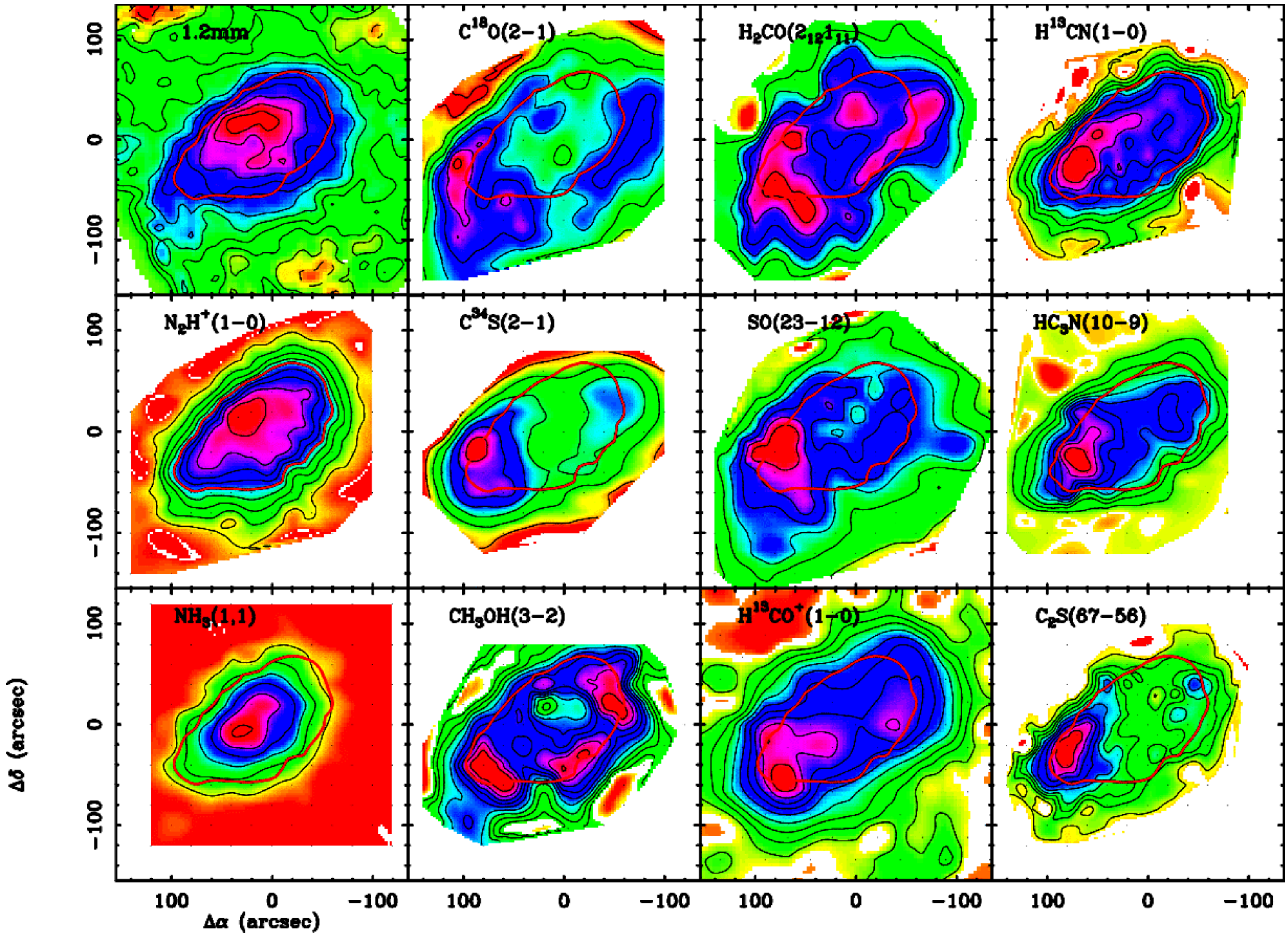
Unclear: study kinematics...

Velocity structure

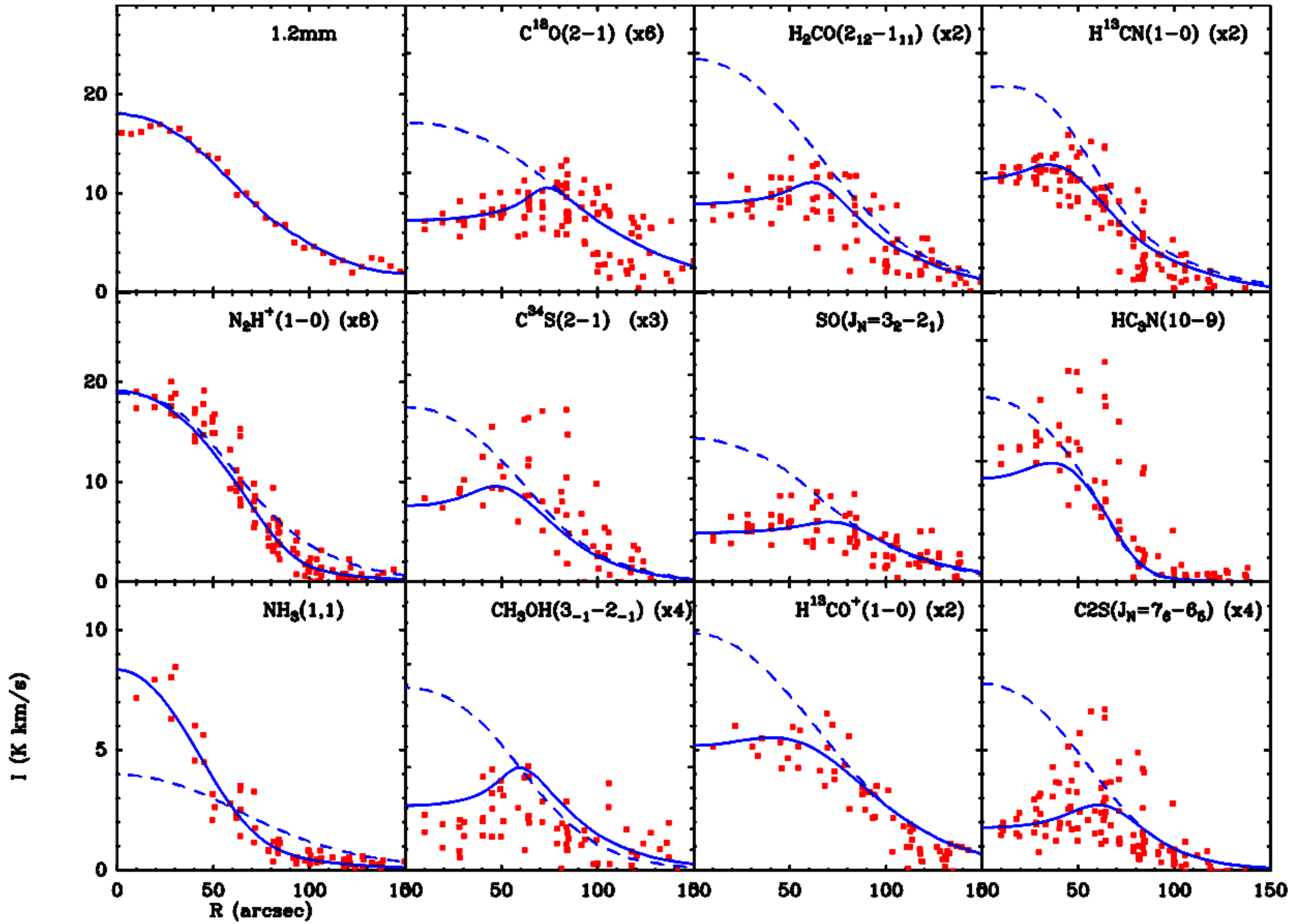


- No clear global pattern (cf. B68, Lada et al. 2003)
  - no rotation
  - not perfect equilibrium
- Radial profile of V_{LSR}
  - N_2H^+ and NH_3 agree
  - much larger than noise propagation
  - rms approx 0.03 km/s
  - too small for turbulent scenario (Klessen et al.)
- Time escale
  - v = 0.1 km/s, r = 0.1 pc
  - t = 1 Myr
  - typical of contraction motions (Lee et al. 1999)

Molecular composition. L1498.



Molecular radial profiles



Monte Carlo models for L1498

NO/INNER DEPLETION

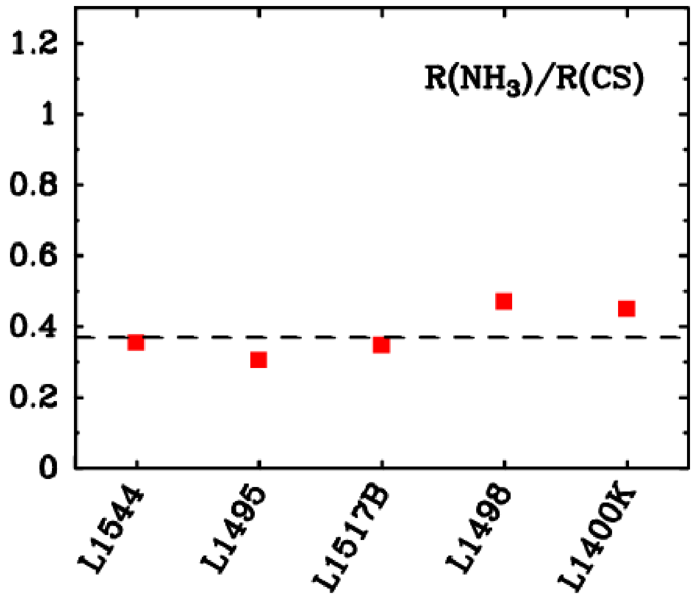
MOLECULE	X_0	R_{hole} (cm)
NH_3	1.4×10^{-8}	–
N_2H^+	1.7×10^{-10}	–
DCO^+	5.0×10^{-11}	0.65×10^{17}
HCN	9.0×10^{-9}	0.8×10^{17}
HC_3N	5.0×10^{-10}	0.8×10^{17}
CS	3.0×10^{-9}	1.0×10^{17}

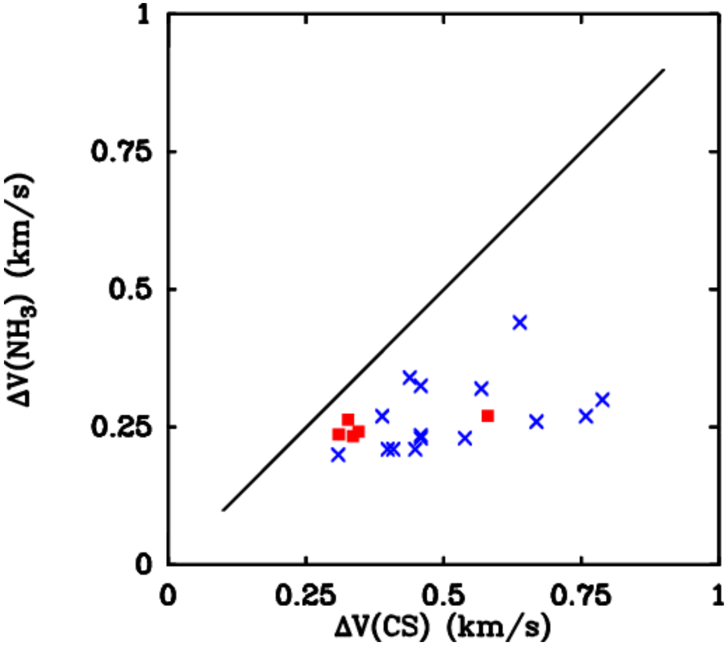
OUTER DEPLETION

MOLECULE	X_0	R_{hole} (cm)
$o\text{-}C_3H_2$	1.2×10^{-9}	1.1×10^{17}
HCO^+	3.0×10^{-9}	1.15×10^{17}
CH_3OH	3.0×10^{-10}	1.2×10^{17}
$o\text{-}H_2CO$	4.0×10^{-10}	1.25×10^{17}
CCS	4.0×10^{-10}	1.25×10^{17}
SO	1.4×10^{-9}	1.5×10^{17}
$C^{18}O$	0.5×10^{-7}	1.5×10^{17}

- **Step** models: constant abundance X_0 + central hole R_{hole}
- Size of **central hole** varies with molecule
  - differentiated (onion-like) abundance pattern
  - most tracers insensitive to inner gas (r<5,000 AU=0.75 10^{17}cm)
- Central abundance drops explained by molecular **freeze out**
  - N-bearing species favored at center due to low binding energy of N_2 (Bergin & Langer 1997, Aikawa et al. 2003)
- Central NH_3 **enhancement** not well understood

NH_3-CS discrepancy explained

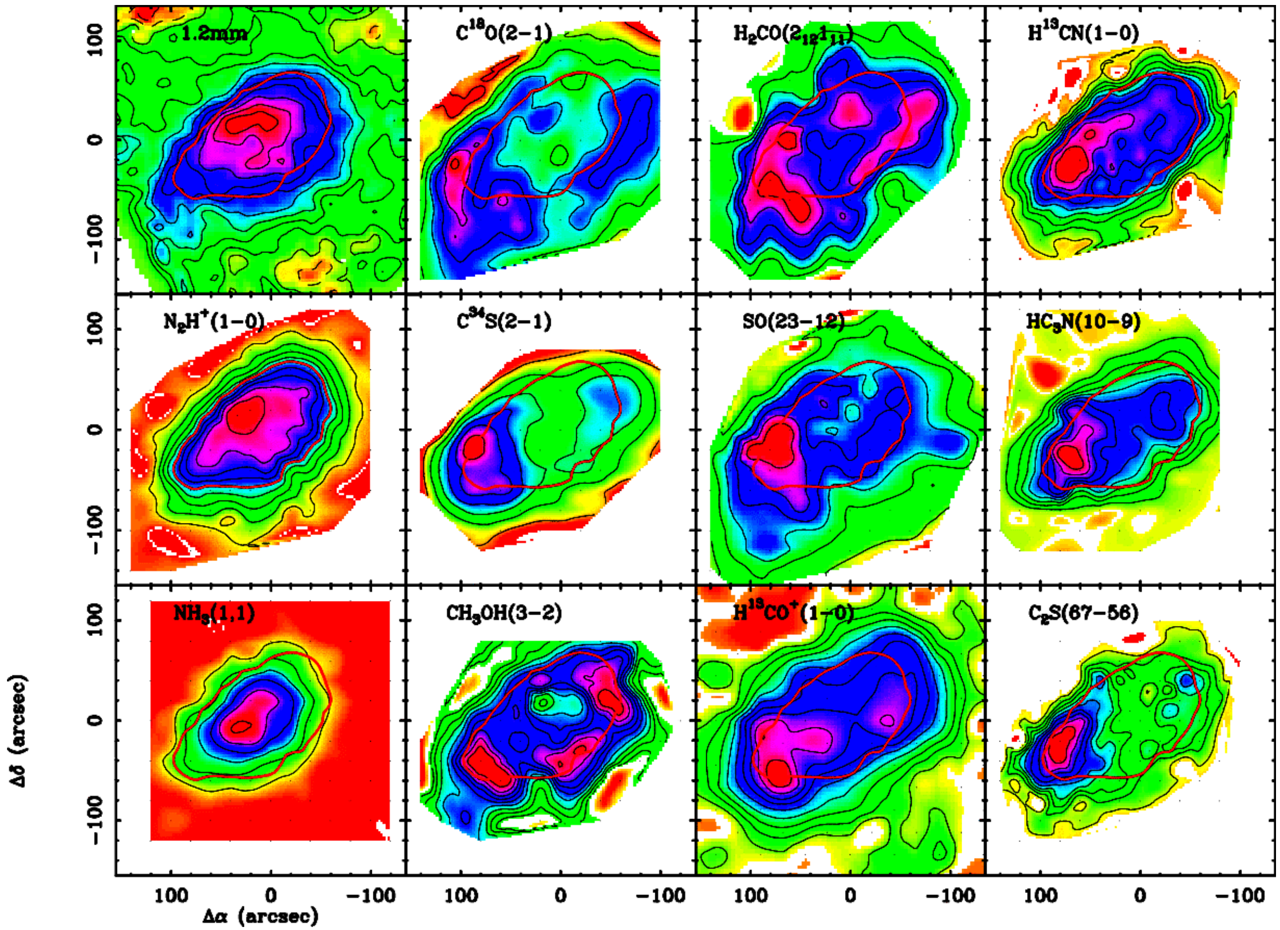




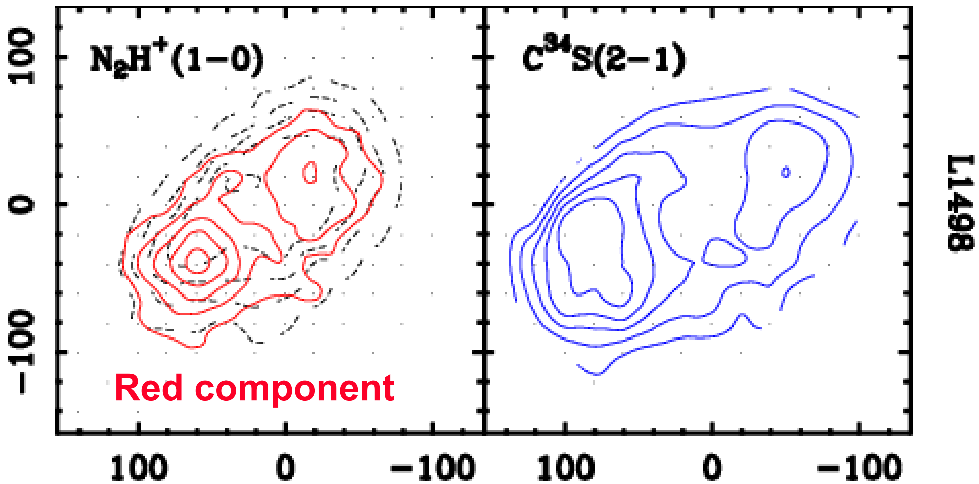
- Our models reproduce NH_3-CS discrepancy
  - they contain key ingredients to explain it
- 2x larger CS maps (+ different peak position): depletion effect
  - absence of CS at core center truncates map and increases HM radius
- 2x wider CS lines: optical depth effect
  - CS lines systematically self absorbed

Depletion, tracer of core contraction?

- **Superposed to order-of-magnitude radial abundance drops in CO and CS, factor-of-two azimuthal variations**



Depletion, tracer of core contraction?



- Regions with higher CO and CS abundance
  - probably less depletion
  - probably less time at high densities: younger
- Younger regions correlated with "high velocity" N_2H^+ (also NH_3)
- If contraction: no spherical symmetry (Myr time scale)
- Effect observed in L1498 & L1517B. We still need more cases

Tracing core evolution using depletion

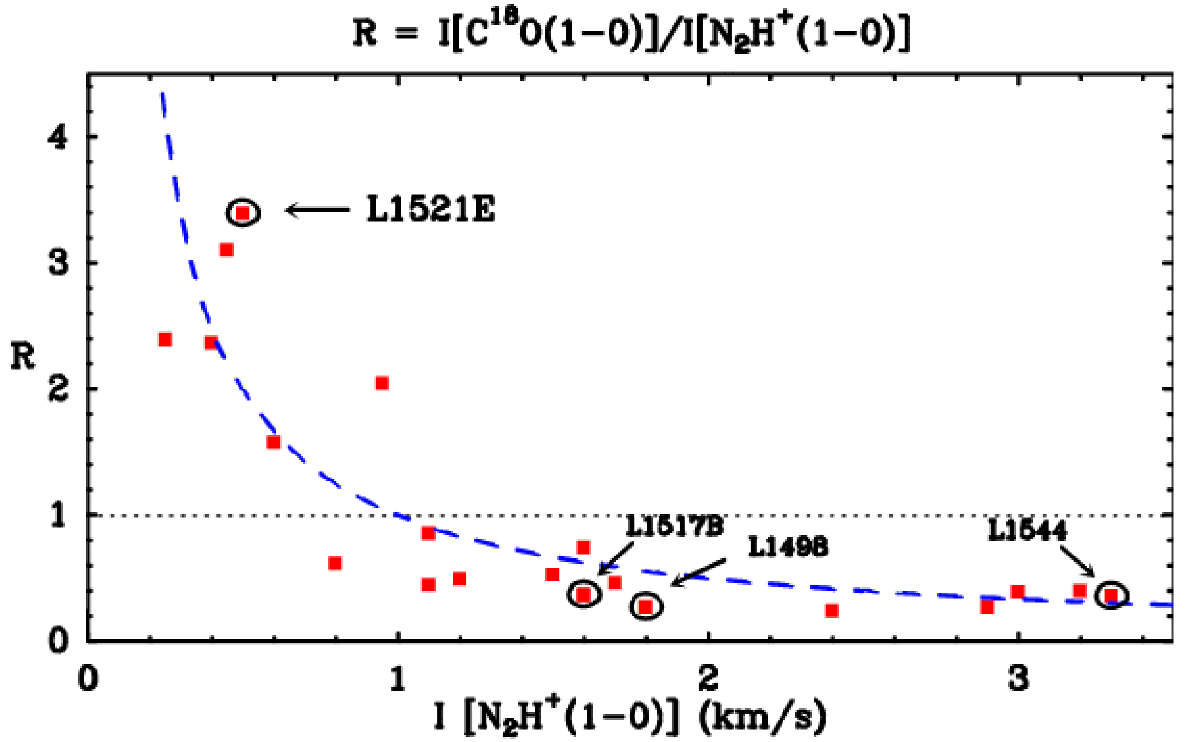
- We don´t understand all the details of core chemistry, but some basic processes are clear
- As a core contracts, freeze out increases with time
- If a core stays cold and dense
  - freeze out is irreversible and progressive
  - it can be used as a clock to time contraction
- "Depletion for dummies:"
  - young core, little CO depletion
  - old core, strong CO depletion
- Define depletion indicator comparing CO and N_2H^+ emission

$$R = I[C^{18}O(1-0)]/I[N_2H^+(1-0)]$$

(measured at core center)

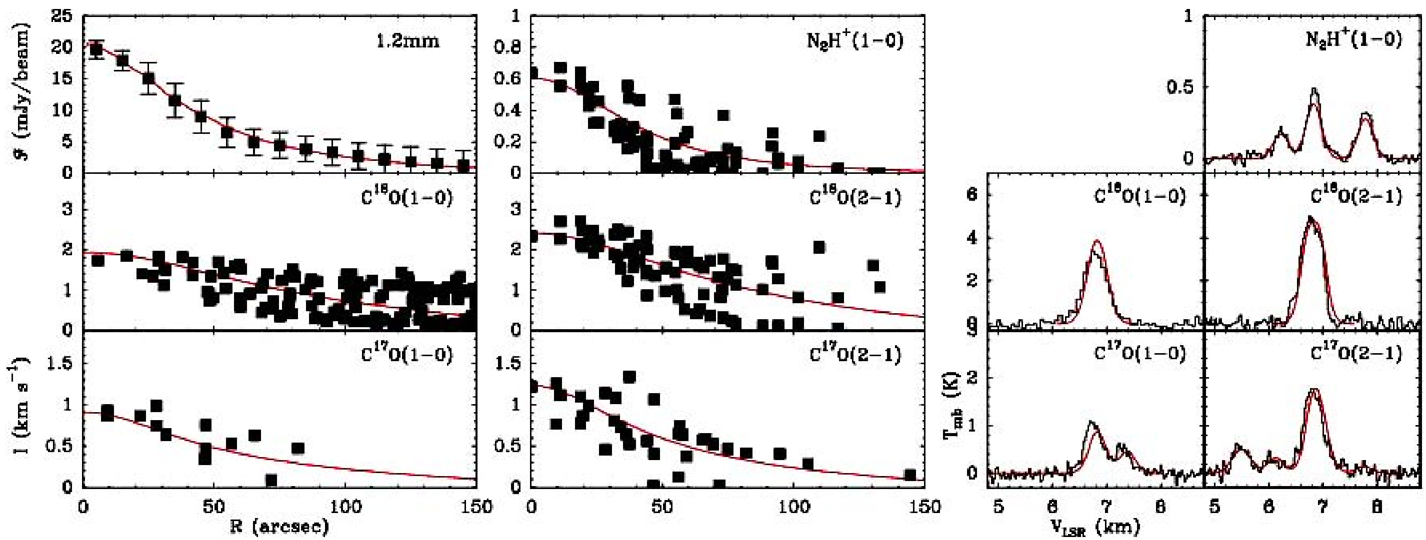
- Young core: little CO depletion, high R
- Old core: strong CO depletion, low R
- Behavior is reinforced because N_2H^+ is a late-time molecule

Tracing core evolution with CO depletion



- 21 cores fully mapped in $C^{18}O(1\text{-}0)$ and $N_2H^+(1\text{-}0)$ with FCRAO
- R = 1 boundary CO depletion/no depletion
  - Monte Carlo radiative transfer models
- Non trivial search for cores with R > 1
  - standard "Benson & Myers" cores have R<1 (NH_3-bright selected)

L1521E: the youngest core?



Tafalla & Santiago (2004)

- **Radiative transfer (Monte Carlo)**
  - **consistent with no CO depletion**
  - **N_2H^+ abundance is 8 times lower than in L1498 & L1517B**
- **Chemical composition suggestive of extreme youth**
  - **< 150,000 yr (crude depletion time scale)**
- **But central density similar to L1517B & L1498 (3 10^5 cm^{-3})**
- **Fast contraction? We need more examples**

Summary

- Combination of new techniques and higher angular resolution over the last 15 years
  - has allowed true mapping of dense core material (dust)
  - has shown that chemical differentiation is a major factor
- Detailed radiative transfer modeling of cores now
  - can explain old discrepancies between tracers
  - reveal a more clear picture of core internal structure
- From L1498 and L1517B analysis
  - quasi Bonnor-Ebert density distributions
  - spatially constant temperature and turbulence
  - onion shell molecular composition
  - possible residual motions from asymmetric core contraction
- Extending analysis to other cores
  - we can search for cores of different age
  - attempt to reconstruct history of core contraction
- We can look forward to another exciting 15 years of core research