New Opportunities for Molecular Research

Al Wootten

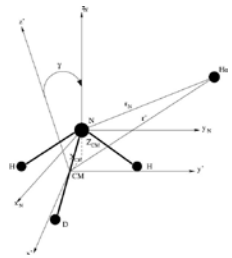
NRAO, ALMA Program Scientist NA

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

Opportunities

- After 50 years, what new opportunities are there?
  - Take advantage of higher sensitivity telescopes
  - Broader band spectrometers, complement other programs
- Centimeter range is usually thought of as a green pasture for large perhaps prebiotic molecules.
  - During the dense core phase, large molecules stick onto grains, forming icy agglomerates, the building blocks of planets, infused with a rich panoply of molecules which are released as the new stars warm them
  - For large molecules (eg glycine), even in the cm range confusion can be reached quickly, though there are often many transitions
  - One can combine knowledge (eg kinematic) of a source gained through higher resolution observations to inform other lower resolution observations
- Specific example: deuteroammonia, a molecular fossil from a cloud's icy past
  - Most transitions are in the submm; those may have high optical depth (Neill et al 2013)
  - An accident of nature, however, provides a wealth of lines in the cm



Why NH_2D?

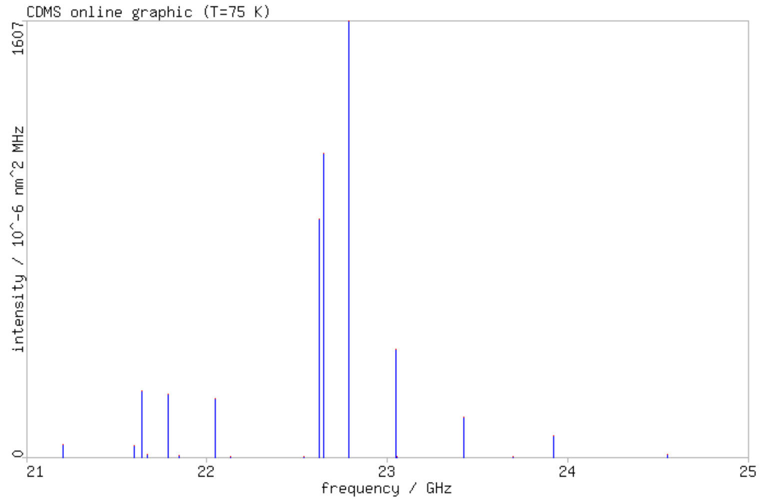
An **NH_2D**Molecule

- NH_3 is a key molecule in the initiation of nitrogen chemistry in the interstellar medium
- Its inversion lines occur near 1cm and offer a well-known thermometer; while they are many they offer limited potential for measuring density; also the fundamental lines are in the submm.
- Deuterium addition breaks the symmetry and creates two(!) dipole moments, giving NH_2D many rotation-inversion lines which might be observed, many in the centimeter spectral range
- Unfortunately,
  - D has an abundance 10^{-5} times that of H,
  - the molecule is light and lines are widely spaced,
  - The spectrum is complicated--NH_2D has two forms, ortho and para, and two dipole moments, creating two types of transitions for each form!
- This talk:
  - Demonstrate its usefulness: ***good probe of the chemistry and physics of grain evaporation regions***

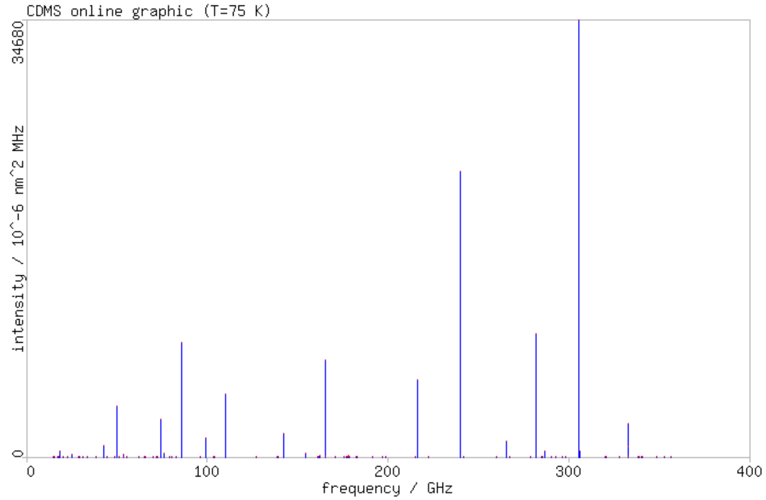
The NH_2D Spectrum

- Light molecule, widely spaced levels, sparse lines
- Weak 'a-type' transitions associated with the lesser dipole moment
- Strong 'c-type' transitions associated with the stronger dipole moment
- Fortunately, c-type transitions cross K-ladders, and provide cm, mm wave transitions.

Ammonia 75K

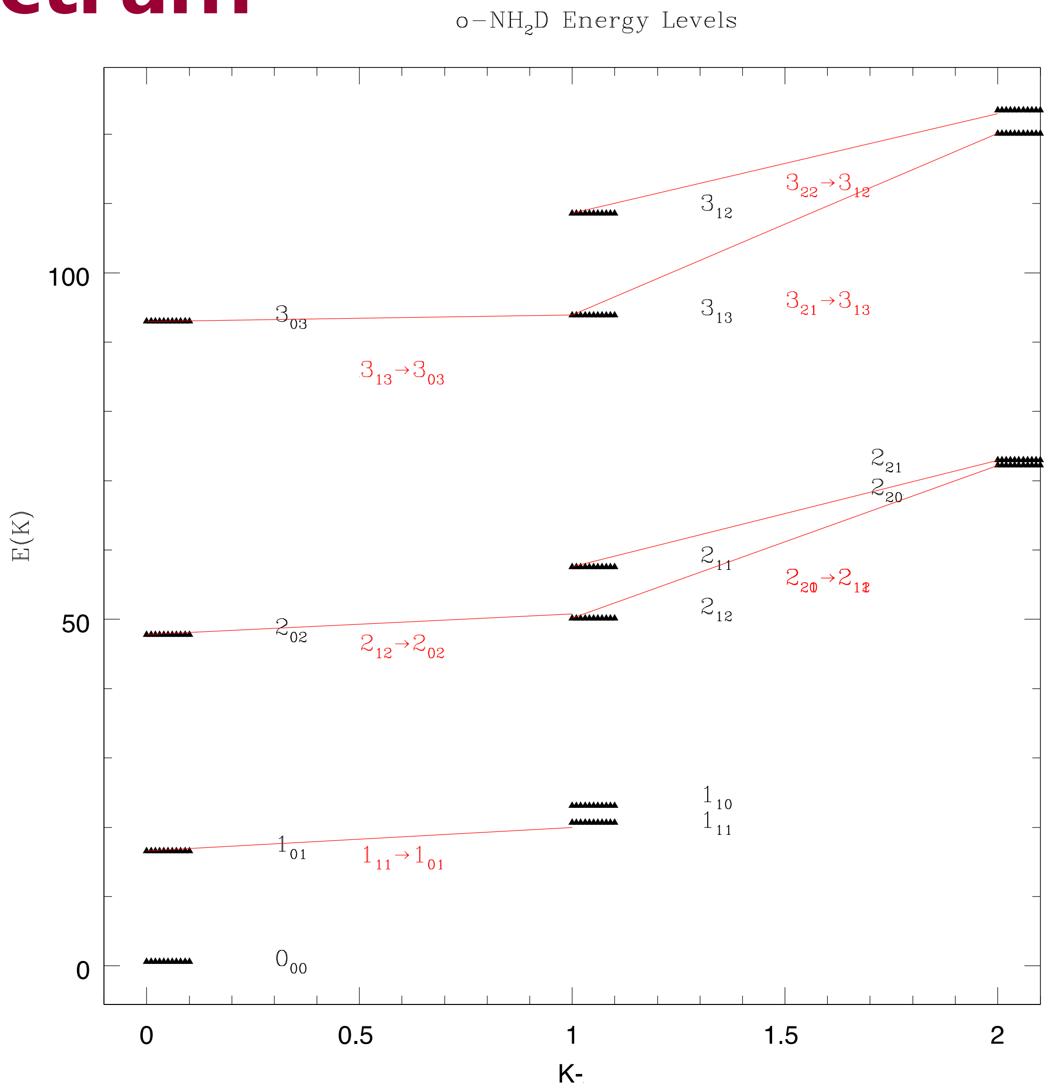


NH_2D 75K



The NH_2D Spectrum

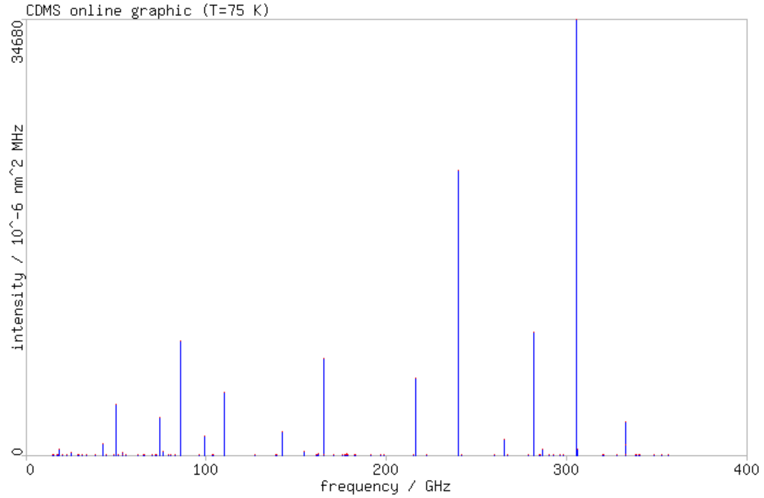
- The c-type transitions are the stronger, ΔK=1
- Owing to the proximity of the K=0 and K=1 ladders in energy, there are a number of transitions in the 1cm-3mm range
    - 86, 50, 18 GHz for ortho-ammonia
    - 110, 74, 43, 25 GHz for para-ammonia



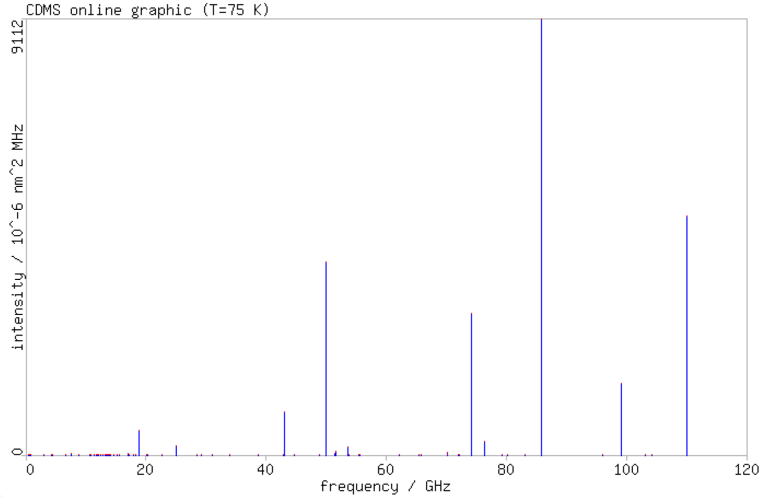
Warm Temperature NH_2D Spectrum

- For warm dense cores, the low-lying lines at 86 and 110 GHz dominate but several other lines join the spectrum.
  - GBT receiver stops at 49.8 GHz but third strongest line at 49.9!
  - EVLA performance poor at 50 GHz
  - Somewhat higher excitation lines at 18, 25, 43 GHz
  - MM, submm lines observable with several interferometers
- Opportunities quite good, but are there sources???

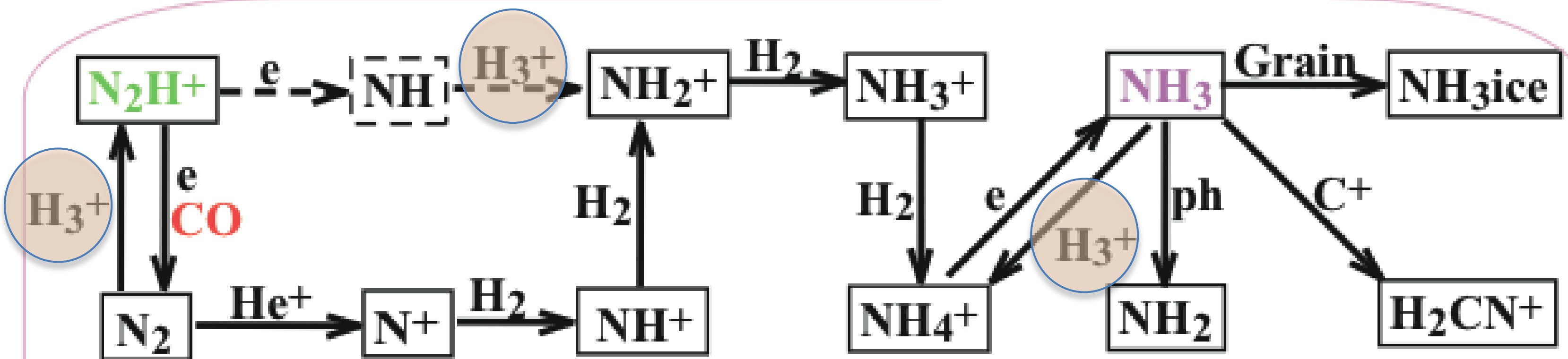
Spectrum 75K to submm



<3mm 75 K spectrum



Ammonia Chemistry



$N_2H^+ + CO \rightarrow HCO^+ + N_2$ k=1.5E-9

$N_2H^+ + e \rightarrow NH + H$ k=2.4E-6 (Geppert et al. 2004)

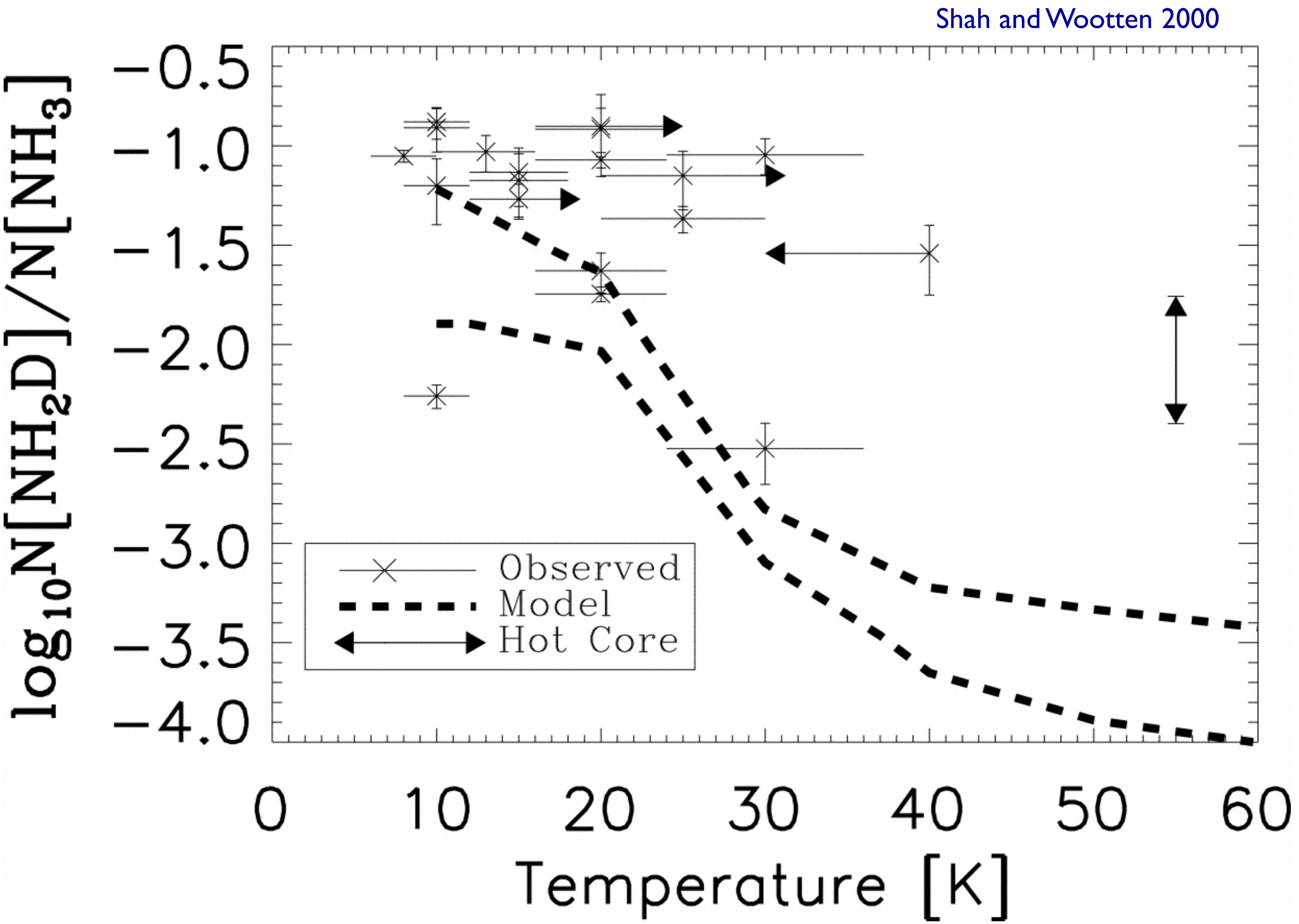
$\therefore NH_3 / N_2H^+$ is enhanced when $n(CO)/n(e) < 10^3$

Aikawa et al

Temperature Dependence of NH_2D

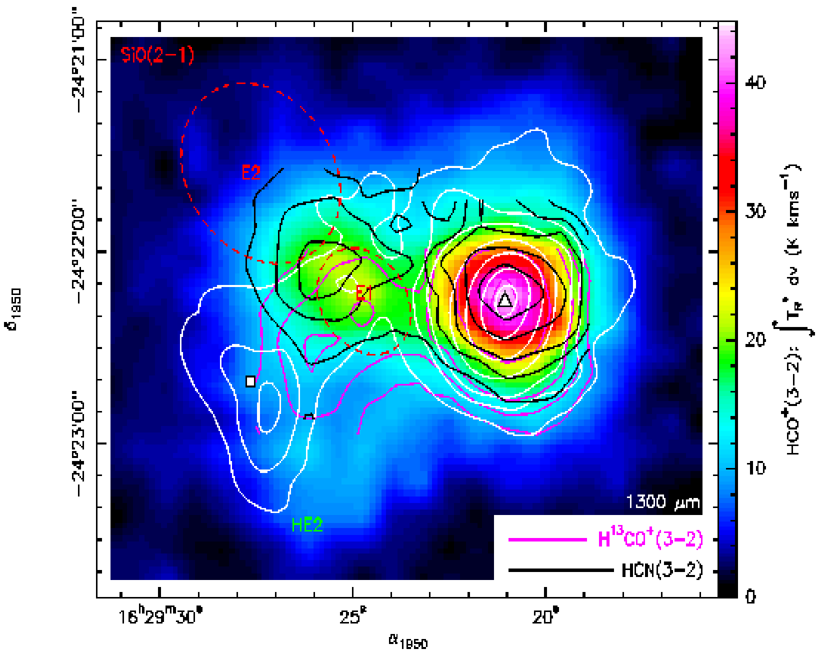
A cold cloud molecule, in general

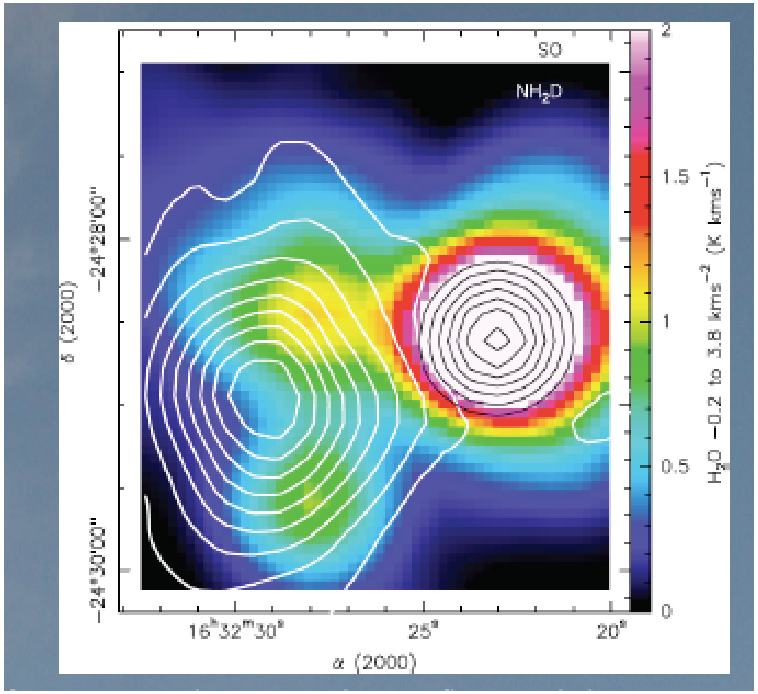
But note that it is overabundant in Hot Core, suggesting a grain source



Example: Cold Starless Core L1689N

Lis et al 2013





- HCO^+ 3-2, $H^{13}CO^+$ 3-2, HCN 3-2, SiO 2-1, and 1.3mm continuum emission from L1689N (Lis etal. 2002). The square locates the position of the DCO^+ 3-2 peak, while the triangle locates the position of the IRAS source.

NH_2D 1-0 integrated intensity from L1689N. The observations are from Herschel. Deuterium enhancement of NH_2D/NH_3=.07 does not change over scales from 1000 to 10,000 AU in this frigid core (left); no embedded protostellar object detected. The color scale shows water emission, thought to arise from interaction of the core with the outflow from IRAS16293.

Deutero-ammonia in OMC1

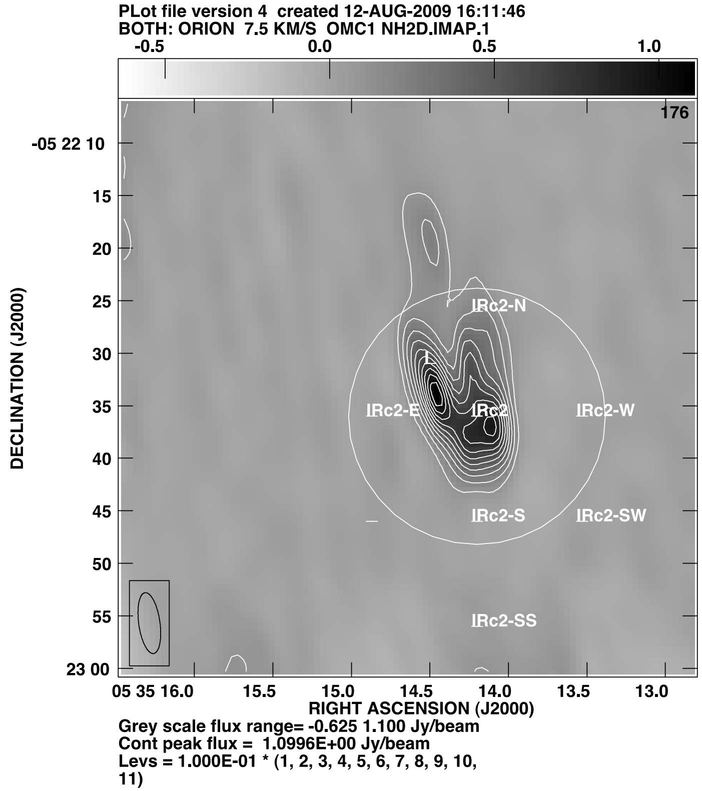
Higher energy lines also

- Walmsley et al. 1987 4_{14}-4_{04} (para) and 3_{13}-3_{03} (ortho) lines
- Groddi et al 2009, Favre et al. GBT Qband 3_{13}-3_{03} (para) line at 43 GHz
- High energy (261K) 5_{24}-5_{14} line in Friedel data originates in Hot Core alone
- Deuterium enhancement of NH_2D/NH_3=.003 (Walmsley et al)

- Mixed message—certainly a grain component, possibly no ion-molecule source (at least in the hot gas)?
- Ion-molecule timescale for destruction of released NH_2D~1000yr

IRAM PdBI Observations from T. Jacq, Favre, Brouillet, 110 GHz low energy line

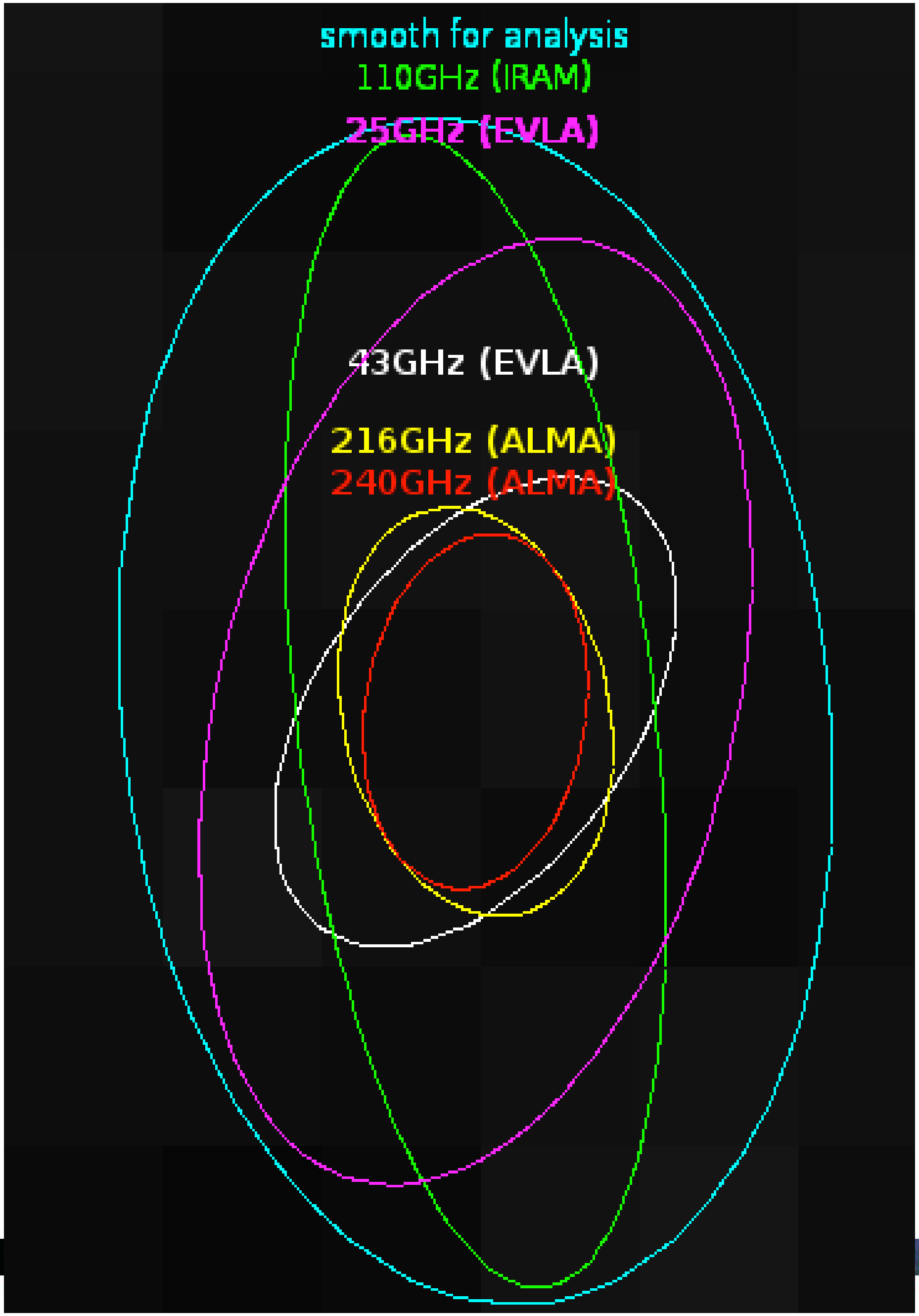
- Compact ridge source confused by juxtaposed HCOOCH3 line (Brouillet)
- Some hot core emission



Complexity: OMC1

- Tale of three Molecules
  - Methyl Formate (blue)
  - Acetone (green)
  - Ethyl cyanide (peach)
- Note that the N-bearing molecule show a distinctive pattern, with a distribution much different from MetFor (HCOOCH3) but similar acetone (CH3COCH3)

NH_2D Data
Work with REU A. Lucy



-240 and 216 GHz
ALMA, 2012
Science Verification, Band 6
High res. spectral survey of Orion KL
(other frequencies also used to search for contaminants)

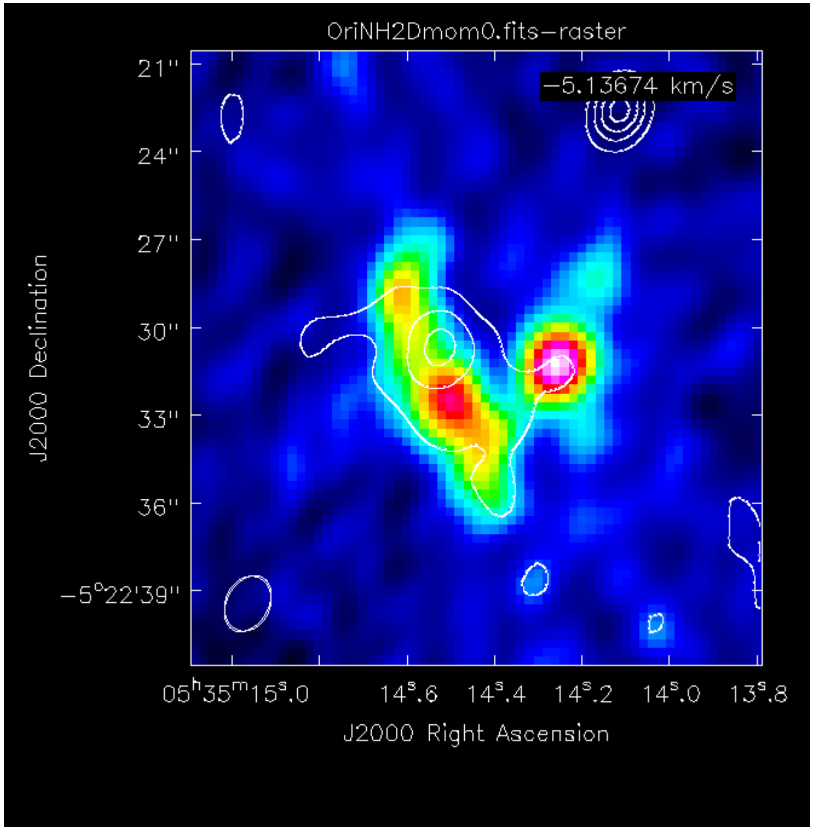
-43 GHz
EVLA, 2010.

-25 GHz (archival)
EVLA, 2009

-110 GHz (archival)
IRAM, 1990

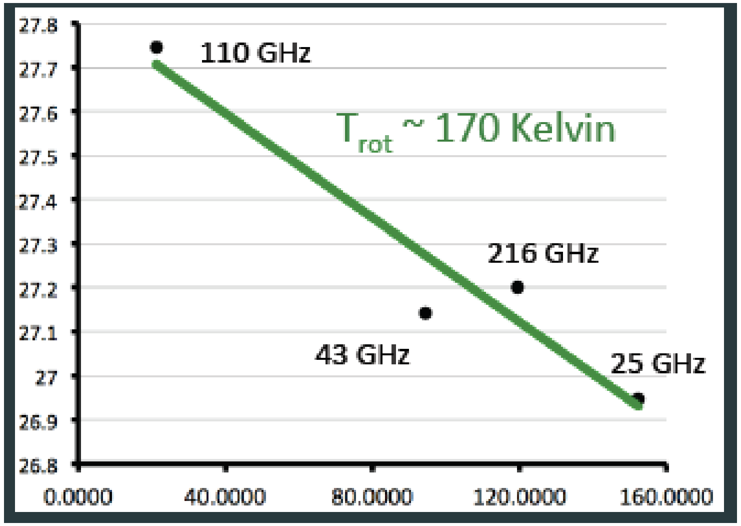
EVLA: 3_{13}-3_{03} (para) line

- At 43 GHz, the EVLA offers a primary beam well-suited to OMC1 imaging, as well as an excellent synthesized beam (1".5).
- Components include the elongated structure east of source 'I' and the 'IRc7' cloud prominent in EtCN.
- Neither methyl formate nor formaldehyde are strong in the 'IRc7' core
- As it is relatively isolated in space and velocity, examine NH_2D exctiation there.



Temperature of NH_2D in IRc7

- Using beams as closely matched as practicable in this archival data, we estimate a kinetic temperature of 170K.
- These molecules almost certainly formed on the grains during a colder phase of dense core evolution.
- With more refined modeling and higher resolution observations, the temperature profile within the core should be accessible.



Lucy et al 2014

Prognosis

- Although we are unaware of surveys of NH_2D excitation outside the cores shown here, surveys have shown the 86/110 GHz resonance lines to be easily detected in both cold and warm cloud cores.
- One problem in interpretation of emission from cold cores is the lack of collisional cross-sections for NH_2D.
- In warmer cores this may not be so important, as resonances tend to be less critical.
- NH_2D is one of a number of molecules which will provide a useful probe of physical conditions using large telescopes in the mm/cm wavelength range.
- Provides a direct probe of the chemistry in the icy grains, thought to be the very place where planets or stars may form.

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