High-Mass Star-Forming Clumps with Unusual N_2H^+/HCO^+ Line Ratios

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Boston University

March 19, 2015

Outline/Advertisements

- MALT90 overview (Two talks tomorrow!!)
  - **James Jackson** : The MALT90 Molecular Line Survey
  - **Yanett Contreras** : MALT90: Unveiling Its Treasures
- N_2H^+ Anomalies
  - N_2H^+ Poor Sources (Low N_2H^+/HCO^+ ratios)
  - N_2H^+ Rich Sources (High N_2H^+/HCO^+ ratios)
- Source with two of the most massive protostellar sources: G333.234–00.061

Come by and see my poster:
Hubble Observations of Isolated YSOs in the Large Magellanic Cloud

MALT90 Collaborators (partial list)

James Jackson	Boston University
Scott Whitaker	Boston University
Patricio Sanhueza	Boston University/NAOJ
Sadia Hoq	Boston University
Jill Rathborne	CSIRO
Yanett Contreras	CSIRO
Jonathan Foster	Yale
Andres Guzman	CfA
Steve Longmore	Liverpool John Moores U.

Over 50 collaborators and in many more countries: Germany, France, Austria, Chile, and Japan

MALT90

The Millimetre Astronomy Legacy Team 90 GHz (MALT 90) Survey

Observing Parameters:

- 16 lines simultaneously
  - High critical densities
  - High-mass star formation tracers
- $3' \times 3'$ maps around $\sim$2000 high-mass sources
- $38''$ resolution
  - Clump scale ($\sim$1 pc)
- 0.1 km s^{-1} spectral resolution
- 0.25 K typical noise (T_A^*) per channel

ATNF Mopra 22 m

MALT90

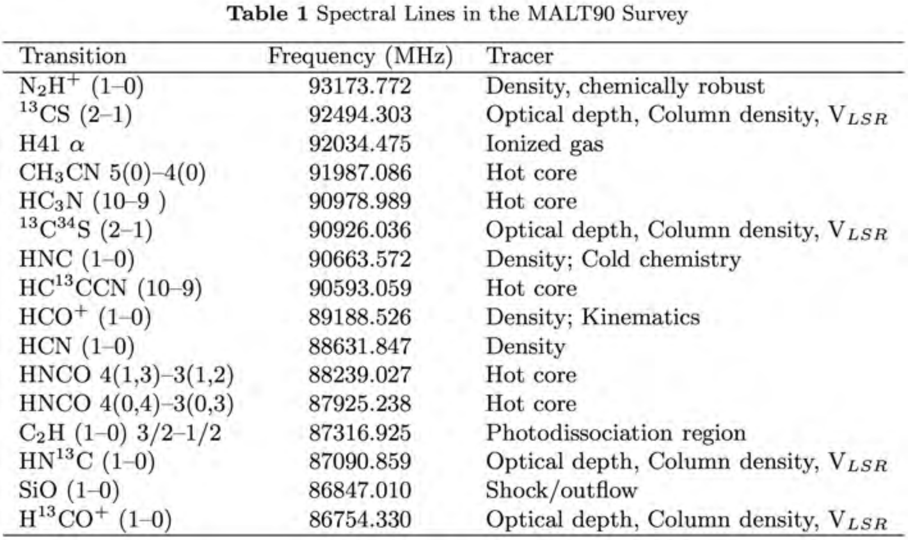
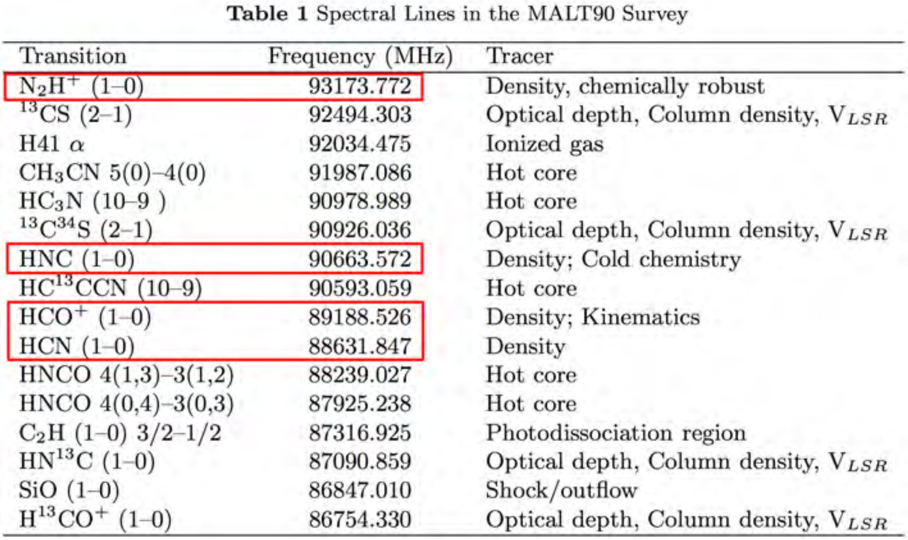


Table 1 Spectral Lines in the MALT90 Survey

Transition	Frequency (MHz)	Tracer
N_2H^+ (1–0)	93173.772	Density, chemically robust
^{13}CS (2–1)	92494.303	Optical depth, Column density, V_{LSR}
H41 α	92034.475	Ionized gas
CH_3CN 5(0)–4(0)	91987.086	Hot core
HC_3N (10–9)	90978.989	Hot core
$^{13}C^{34}S$ (2–1)	90926.036	Optical depth, Column density, V_{LSR}
HNC (1–0)	90663.572	Density; Cold chemistry
$HC^{13}CCN$ (10–9)	90593.059	Hot core
HCO^+ (1–0)	89188.526	Density; Kinematics
HCN (1–0)	88631.847	Density
HNCO 4(1,3)–3(1,2)	88239.027	Hot core
HNCO 4(0,4)–3(0,3)	87925.238	Hot core
C_2H (1–0) 3/2–1/2	87316.925	Photodissociation region
$HN^{13}C$ (1–0)	87090.859	Optical depth, Column density, V_{LSR}
SiO (1–0)	86847.010	Shock/outflow
$H^{13}CO^+$ (1–0)	86754.330	Optical depth, Column density, V_{LSR}

Jackson et al. (2013)

MALT90



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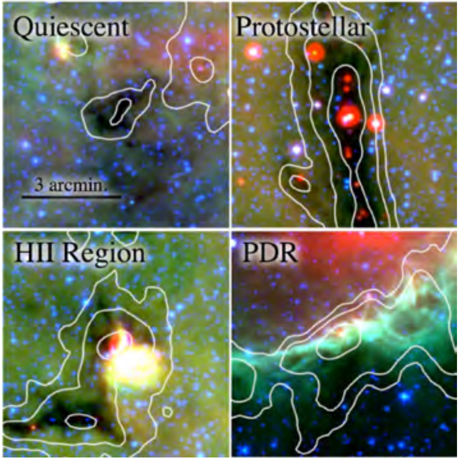
Jackson et al. (2013)

MALT90

Span a large range of evolutionary stages



Spitzer 3.6 μm (blue), 8.0 μm (green), and 24 μm (red)
Contours: ATLASGAL

MALT90

Over 2000 $3' \times 3'$ maps toward high-mass ATLASGAL (870 μm) sources
Multiple ATLASGAL sources and velocities per map: 3566 sources

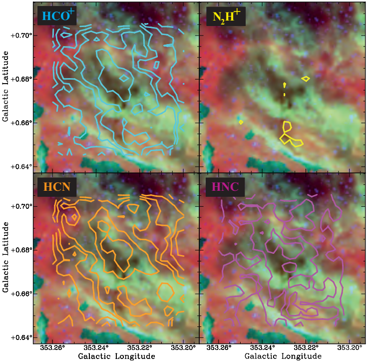
- PDR: 10%
- H II Region: 26%
- Protostellar: 22%
- Quisecent: 19%
- Unknown: 22%

Finding Chart for Interferometers

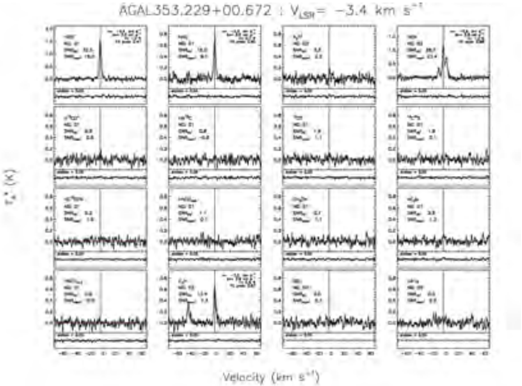
- The Atacama Large Millimeter Array (ALMA)
  - The Brick (Cycle 0 & 1) : Tuesday's talk, **Jill Rathborne**
  - Initial gas structure in a cold, massive clump (Cycle 2)
- The Australian Telescope Compact Array (ATCA)
  - N_2H^+ Anomalies (follow-up of Hoq et al. 2013)
    - N_2H^+ Poor Sources
    - N_2H^+ Rich Sources

N_2H^+ Anomalies

N_2H^+ Poor Source: G353.229+00.672

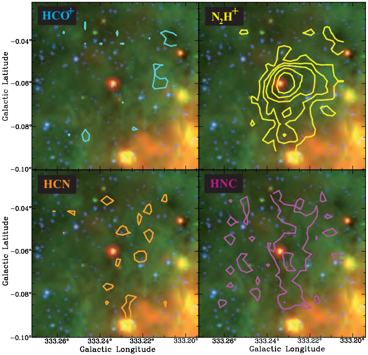


Spitzer 3.6 μm (blue), 8.0 μm (green), and 24 μm (red)
MALT90: Contours

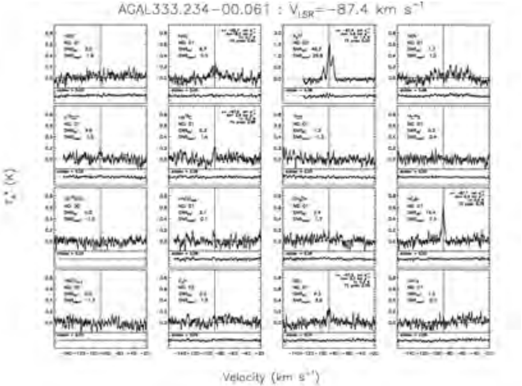


N_2H^+ Anomalies

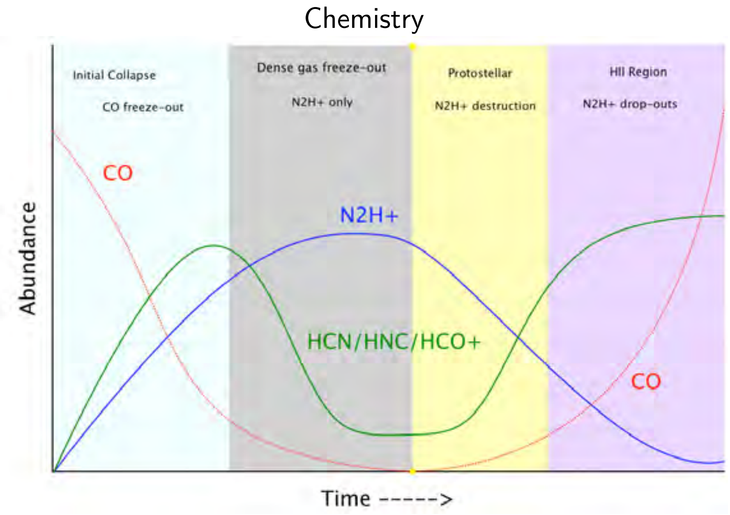
N_2H^+ Rich Source: G333.234–00.061



Spitzer 3.6 μm (blue), 8.0 μm (green), and 24 μm (red)
MALT90: Contours



N_2H^+ Anomalies



Based on chemical models of Lee et al. (2004); see also Bergin (2007)

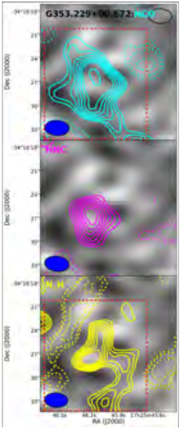
N_2H^+ Anomalies

Follow-up ATCA 3 mm Observations, August 2013

- Four sources: two N_2H^+ poor, two N_2H^+ rich
- 2.2″ resolution
- Velocity resolution 0.1 km s^{-1} over ∼200 km s^{-1}
- HCO^+(1–0), HNC(1–0), N_2H^+(1–0), ^{13}CS(2–1)
- 90 and 93 GHz continuum

N_2H^+ Anomalies

N_2H^+ Poor Source: G353.229+00.672



ATCA 3-mm observations

N_2H^+ Anomalies

N_2H^+ Poor Sources

- Not anomalous on small scales
- Must use large-scale (MALT90) observations to assess this anomaly
  - Pick the most reliable N_2H^+ poor sources (e.g., significantly detected, strongly anomalous, no huge linewidths, not in CMZ, etc.)
  - Compare to large-scale *Spitzer* images to see global star formation properties

N_2H^+ Anomalies

124 Extreme MALT90 N_2H^+ Poor Sources, $I(N_2H^+)/I(HCO^+) < 0.2$

- 41 PDRs (11% of all MALT90 PDRs are N_2H^+ Poor Sources)
- 36 H II regions (4%)
- 5 Protostellar (0.6%)
- 8 Quiescent (1%)
- 34 Unknown (4%)

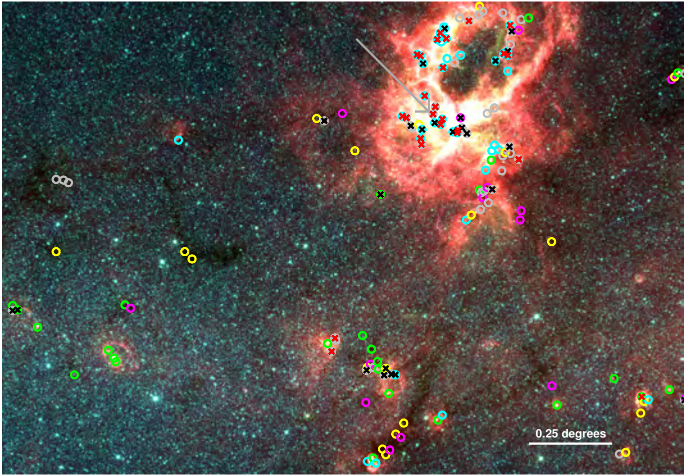
Generally associated with ionized regions

N_2H^+ Anomalies

NGC 6357 star formation complex (1.9 kpc).

○ Quiescent ○ Protostellar ○ H II ○ PDR ○ Unknown

× Anomalies (Hoq et al. 2013 criteria) × Extreme Anomalies $I(N_2H^+)/I(HCO^+) < 0.2$



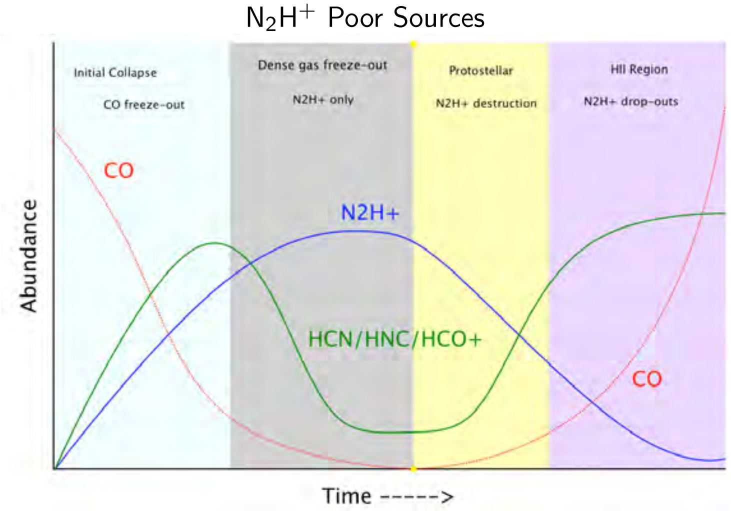
Spitzer 3.6 μm (blue), 4.5 μm (green), and 8.0 μm (red)

N_2H^+ Anomalies

N_2H^+ Poor Sources

- Associated with PDRs and H II regions
- Particularly prevalent around shells, indicative of PDRs

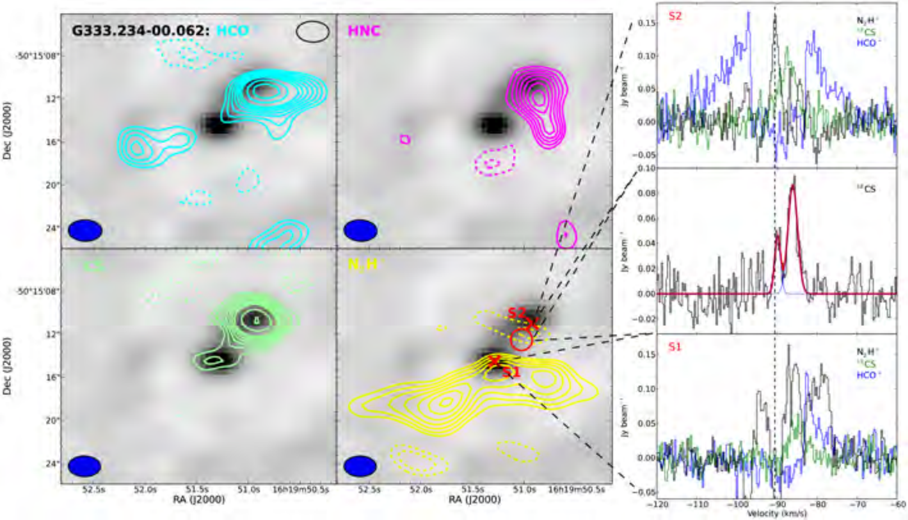
N_2H^+ Anomalies



High-mass N_2H^+ destruction confirmed with the largest dataset to date!

N_2H^+ Anomalies

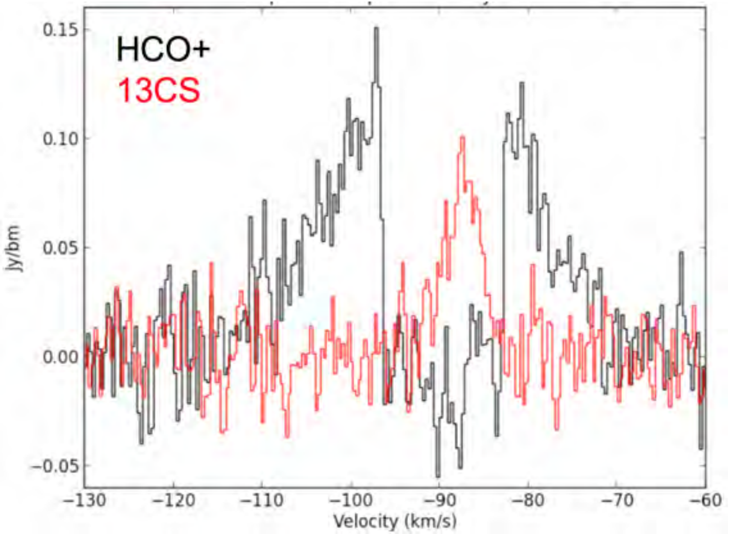
N_2H^+ Rich Source: G333.234–00.061



ATCA 3-mm observations

N_2H^+ Anomalies

N_2H^+ Rich Source: G333.234–00.061



N_2H^+ Anomalies

N_2H^+ Rich Sources

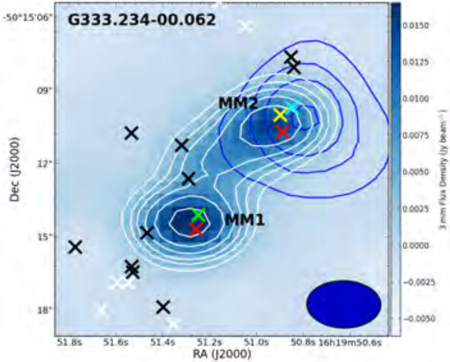
- These are sources with **extreme** HCO^+ self-absorption at large-scales.

G333.234–00.061 : Unique N_2H^+ "Rich" Source

Two protostellar sources located 4.7 kpc from the sun

No obvious free-free emission

White contours: 3 mm continuum Blue contours: 8 μm IRAC



MM1 has ∼25% more flux than MM2

G333.234–00.061 : Unique N_2H^+ "Rich" Source

$$M = \frac{F_\nu^i D^2}{\kappa_\nu B_\nu(T_D)}$$

F_ν^i integrated flux, D distance, κ_ν dust opacity, $B_\nu(T_D)$ Planck function, T_D temperature

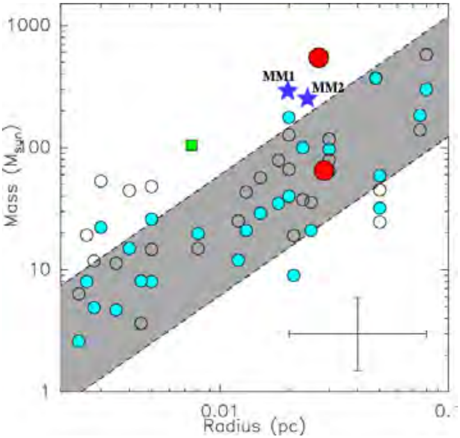
$T_D = 100$ K, GDR=100

$\kappa_{1.3\,\mathrm{mm}} = 0.90$ cm^2 g^{-1} (Ossenkopf), $\beta = 1.5$

$\rightarrow \kappa_{3.3\,\mathrm{mm}} = 0.22$ cm^2 g^{-1}

MM1: $>36\ M_\odot$ MM2: $>29\ M_\odot$

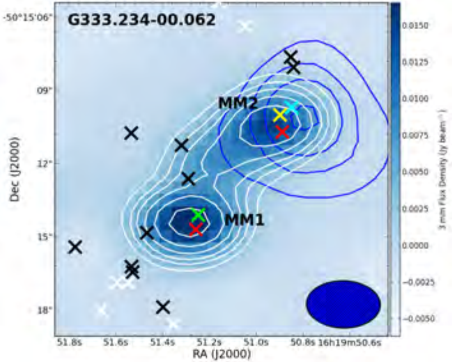
Adopting κ_ν for all protostellar sources and using $T_D = 50$ K (Peretto et al. 2013), two of some of the most massive *protostellar* cores known, separated by a projected distance of only 0.12 pc



Peretto et al. (2013)

G333.234–00.061 : Unique N_2H^+ "Rich" Source

MM2 has **IRAC** emission, and MM1 does not. MM2 is likely hotter.

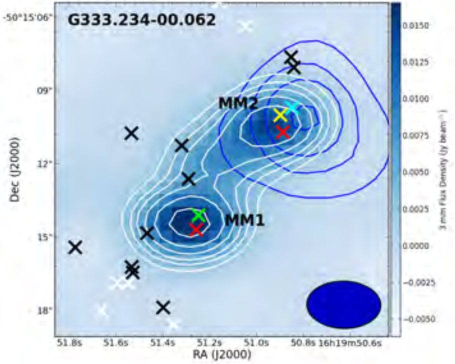


MM1 is at an earlier evolutionary stage than MM2

G333.234–00.061 : Unique N_2H^+ "Rich" Source

Collisionally Pumped Masers: × 36 GHz class I methanol × 44 GHz class I methanol × 95.1 GHz class I methanol × 22 GHz water

Radiatively Pumped Masers: × 6.7 GHz class II methanol × 1.7 GHz OH

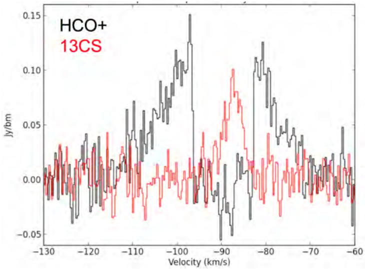


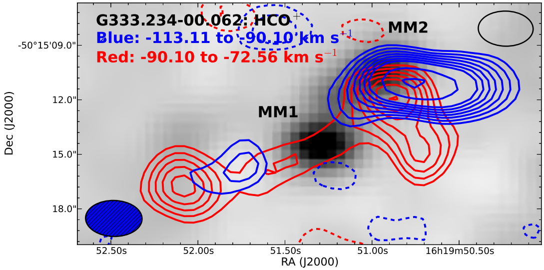
Evolutionary sequence (some overlap):
Class I Methanol→Class II Methanol→Water→OH (Forster & Caswell 1989, Ellingsen 2006, Breen et al. 2007):

MM1 is at an earlier evolutionary stage than MM2

G333.234–00.061 : Unique N_2H^+ "Rich" Source

MM2 Spectra





MM2 has a much more developed outflow

MM1 is at an earlier evolutionary stage than MM2

G333.234–00.061 : Unique N_2H^+ "Rich" Source

MM1 is at an earlier evolutionary stage than MM2:

(1) MM2 has *Spitzer* IRAC emission while MM1 does not, suggesting much warmer temperatures for MM2.
(2) MM2 has a large outflow, while MM1 does not have a definitive outflow.
(3) ^{13}CS has a stronger peak on MM2 even though MM1 is brighter in the continuum, suggesting MM1 could be colder.
(4) The detected maser species for MM1 and MM2 indicate that MM2 is likely at a later evolutionary stage.

MM1 is at an earlier evolutionary stage than MM2 **but is more massive.** This is **unexpected** for two sources at a projected distance of only 0.12 pc!!!

G333.234–00.061 : Unique N_2H^+ “Rich” Source

Explanation?

- Multiple epochs of massive star formation
- Changes in accretion rates
- MM2 had faster free-fall time
- Unaccounted multiplicity
- Feedback: prestellar cores more massive than star’s final mass (e.g., Tan et al. 2014)

G333.234–00.061 : Unique N_2H^+ "Rich" Source

Do N_2H^+ "rich" sources (i.e., sources with extreme HCO^+ self-absorption) show the location of the most massive young stellar objects?

- Indicate locations of extremely high column density
- Line observations advantages over *Herschel* column density maps in finding the most massive sources
  - Separate multiple velocity components
  - Kinematic distances
  - Integrated intensity ratio of N_2H^+ and HCO^+ is immune to the beam dilution
- A new method of finding the highest mass protostars?

Summary

- N_2H^+ Anomalies
  - N_2H^+ Poor Anomalies arise in ionized regions
  - N_2H^+ Rich Anomalies arise from strong self-absorption in HCO^+ lines
- G333.234–00.061
  - Two of some of some of the most massive cores forming in close proximity (projected distance ∼0.12 pc)
  - More massive core is at an earlier evolutionary state!
- Stephens et al. (2015), ApJ, 802, 6