Using deuterated H_3^+ and other molecular ions to probe the formation of stars and planets

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H_3^+ in star-forming regions: A twofold role

- In cold gas (<20 K): mostly deuterated
  - reaction HD + H_3^+ exothermic
  - rotational lines of H_2D^+ and D_2H^+ in far-IR/submm
- Great tracers of H_2 at low temperatures
  - CNO-bearing species mostly frozen out
  - ionization, kinematics
- Warm gas: direct study of H_3^+ possible
  - vibrational lines in mid-IR
  - limited to suitable lines of sight
- High density / mapping: use indirect probes
  - proton transfer to CO, N_2, ...
  - gas density, radiation field, magnetic field

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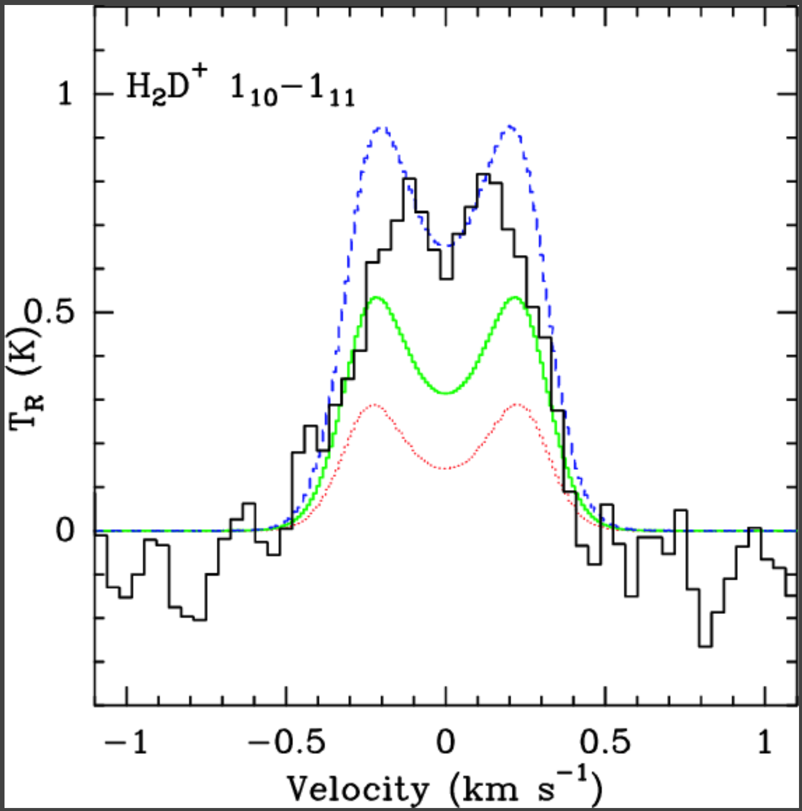
Outline

- **Deuterated H_3^+ in cold pre/protostellar cores**
  - abundance
  - spatial distribution
- Molecular ions in warm gas near young stars
  - the H_nO^+ puzzle
  - HF as a solution?
- Conclusions and outlook
  - deuterated H_3^+
  - other molecular ions

Caselli et al 2003: o/p ratio

Van der Tak et al 2005: V-field



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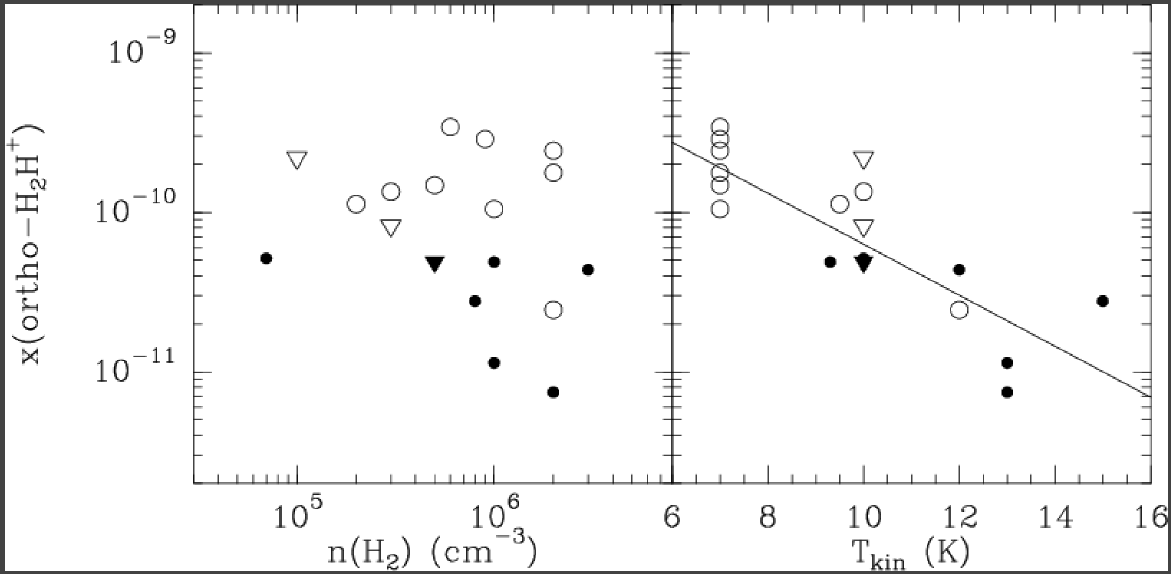
Survey of H_2D^+ in pre/protostellar cores

- Dense condensations of gas: 10 starless, 6 protostellar
  - o-H_2D^+ ground-state line 372 GHz
  - CSO 10.4-m, 20'' beam (2800 AU at 140 pc)
- Detect 7 starless, 4 protostellar cores
  - higher $N(H_2D^+)$ in starless cores
  - bright if centrally concentrated
- Clear trend with source temperature
  - CO depletion
  - N_2H^+ fractionation

Caselli et al 2008



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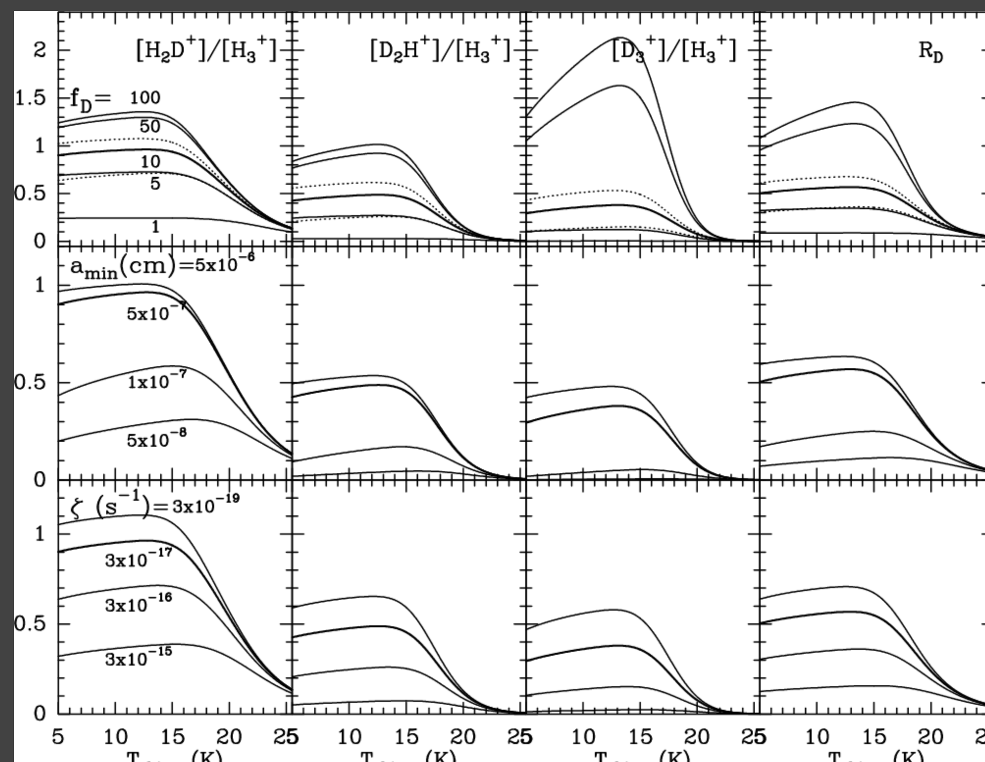
Survey of H_2D^+ in pre/protostellar cores (2)

- Compare survey results to chemical model
  - cosmic-ray ionization rate
  - depletion level of neutrals
  - volume density
  - grain size / PAH fraction
- All have an effect ...
  - need to observe p-H_2D^+
  - accurate *T,n* profiles

Caselli et al 2008



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Spatial distribution of H_2D^+

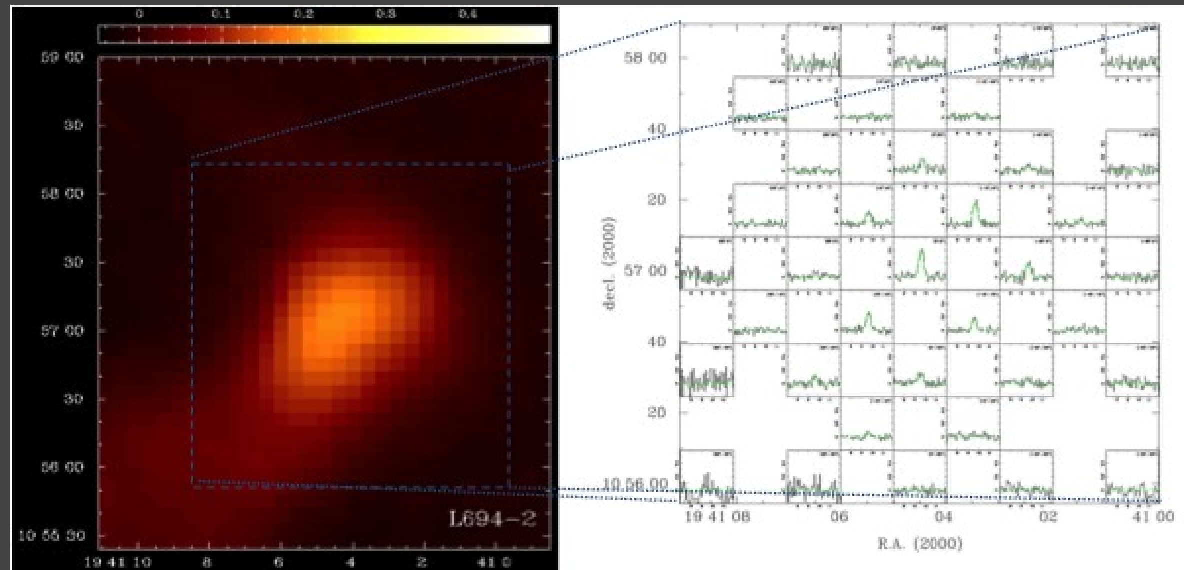
- Starless cores:
  - centrally peaked
- Protostellar cores:
  - H_2D^+ avoids heat
- Oph B2 core:
  - D-fractionation systematically decreases with distance to protostar

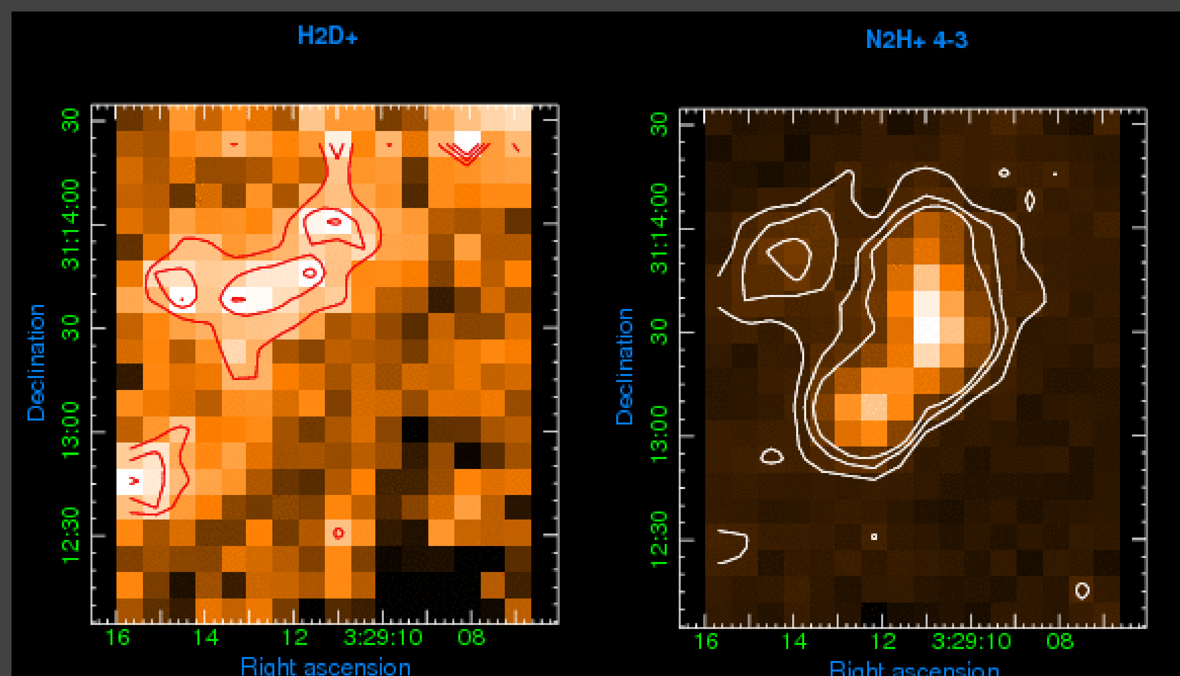
Vastel et al 2006;

Friesen et al 2010;

Di Francesco et al 201x;

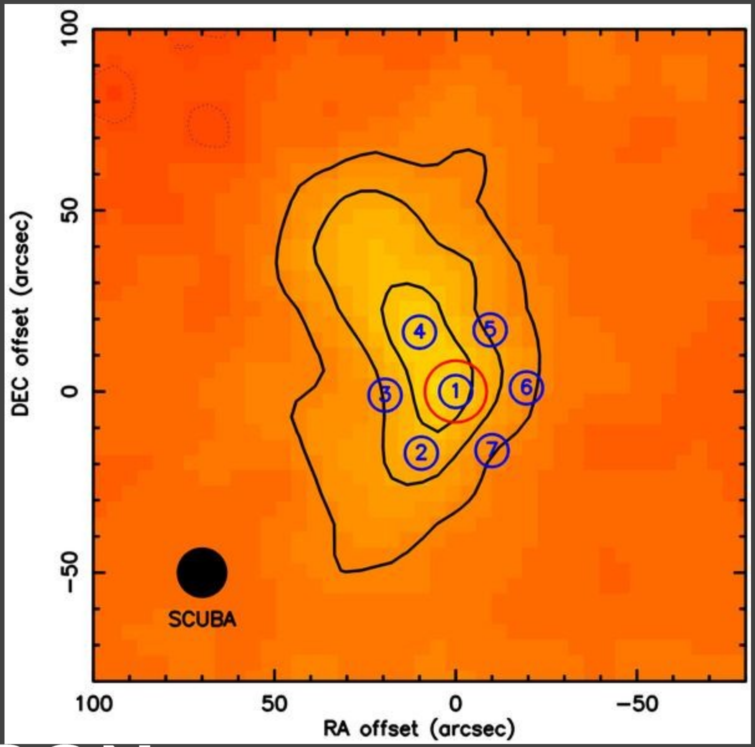
Koumpia et al 201x

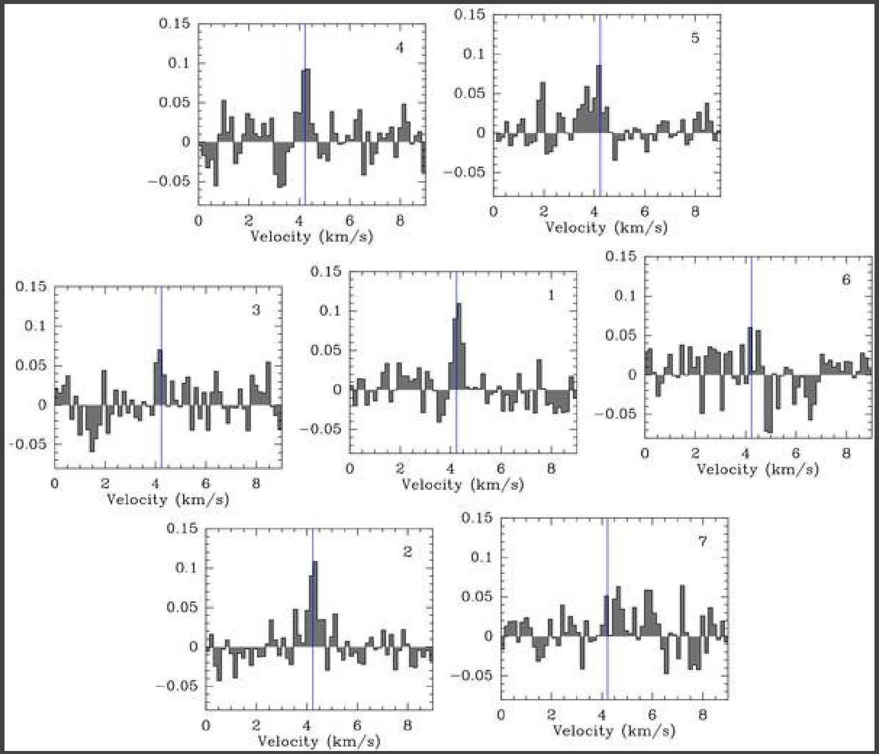




Confirmation and distribution of D_2H^+

- Detect 692 GHz line from H-MM1 core in LDN 1688
  - after tentative result in nearby 16293E core
- Emission seen on several pixels of CHAMP+ array
  - extended over >40'' (4800 AU)
- $N(H_2D^+) \sim N(D_2H^+)$
  - strong (90-99%) depletion of CO





Vastel et al 2004; Parise et al 2011

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Interstellar H_nO^+: Mixing atomic and molecular gas

Gas-phase formation of water:

- $O^+ + H_2 \rightarrow OH^+ + H$
- $OH^+ + H_2 \rightarrow H_2O^+ + H$
- $H_2O^+ + H_2 \rightarrow H_3O^+ + H$
- $H_3O^+ + e^- \rightarrow H_2O + H$

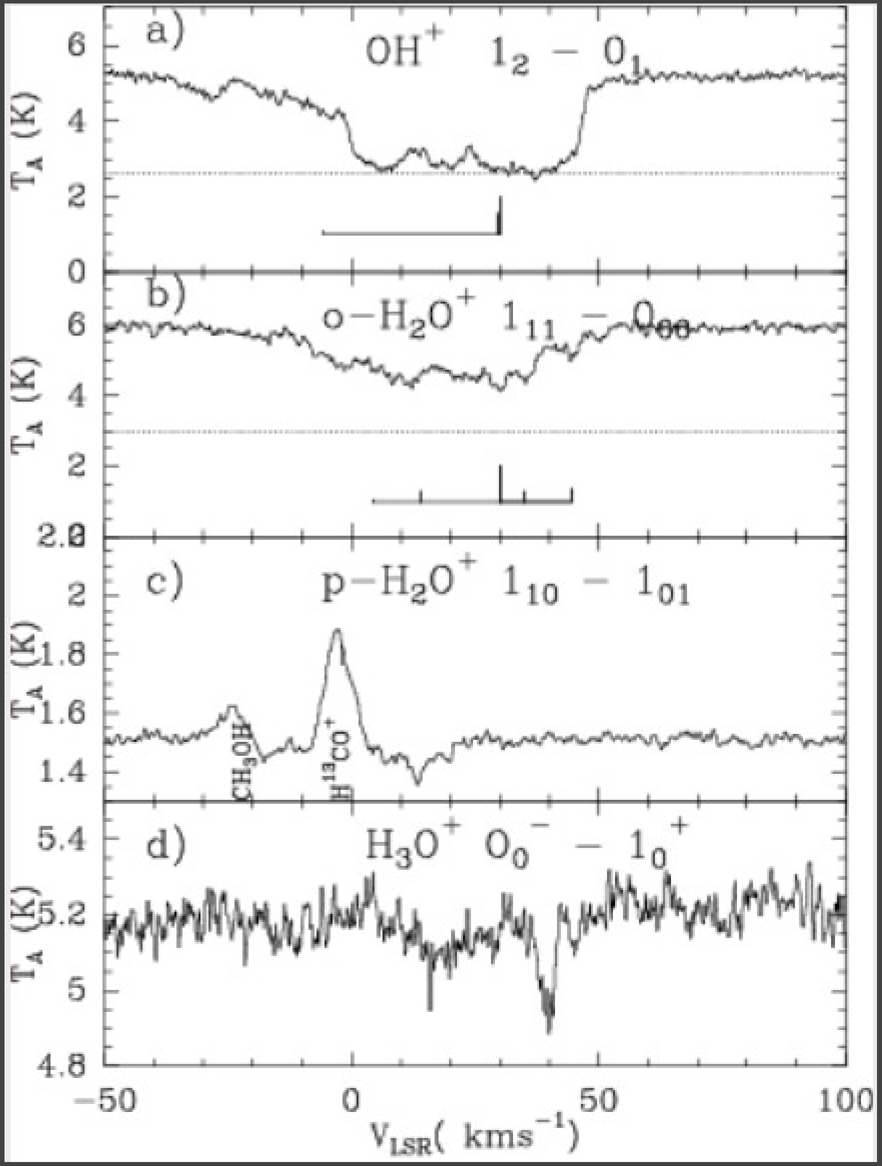
Fast reactions: do not expect intermediates

- dense clouds: all hydrogen in H_2

Herschel: lots of OH^+ & H_2O^+

- atomic and molecular clouds not separated but mixed

Ossenkopf / Gerin et al 2010



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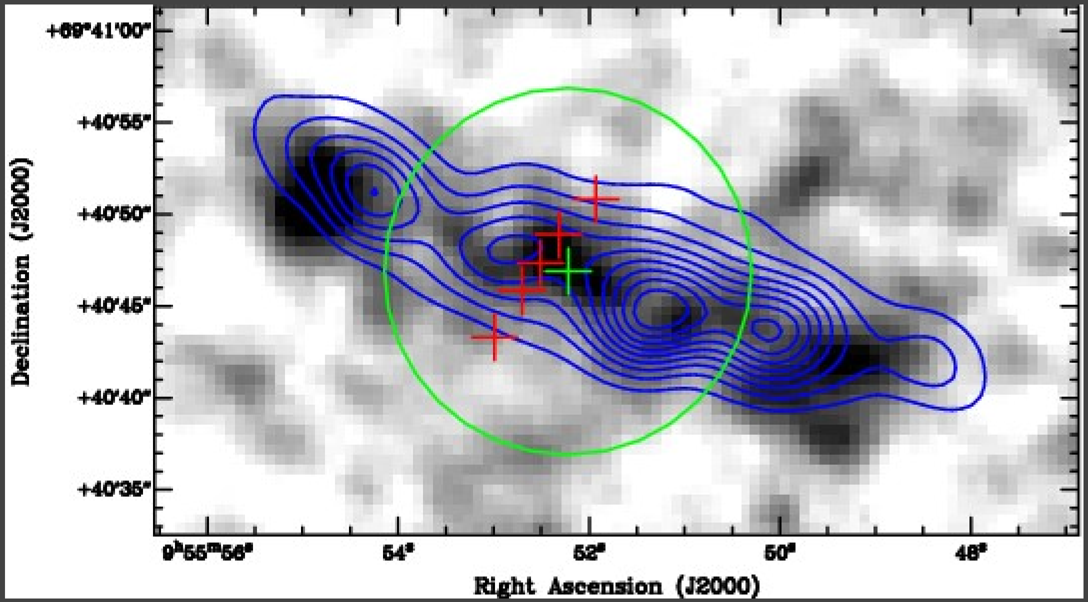
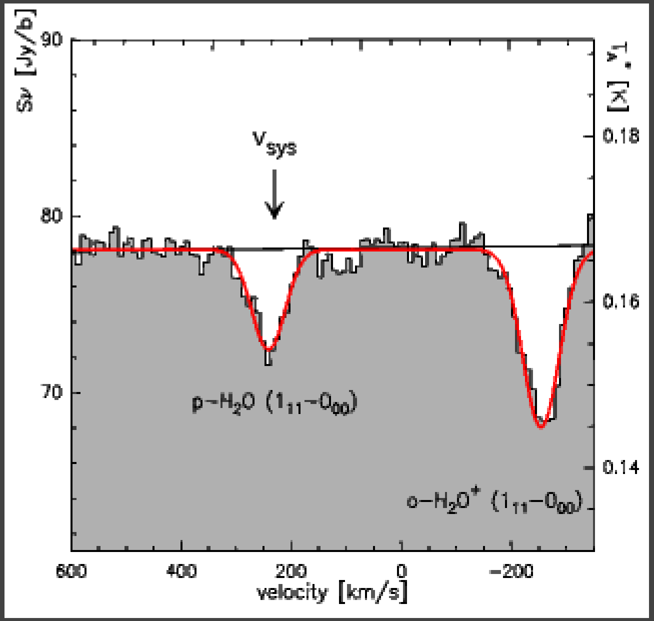
The M82 starburst

- Young stellar population: bright in UV
- Water searched and found..
- but H_2O^+ is almost as common!
- Much harder to dissociate





Weiss et al 2010

Even AGN show OH^+ & H_2O^+

Mrk 231

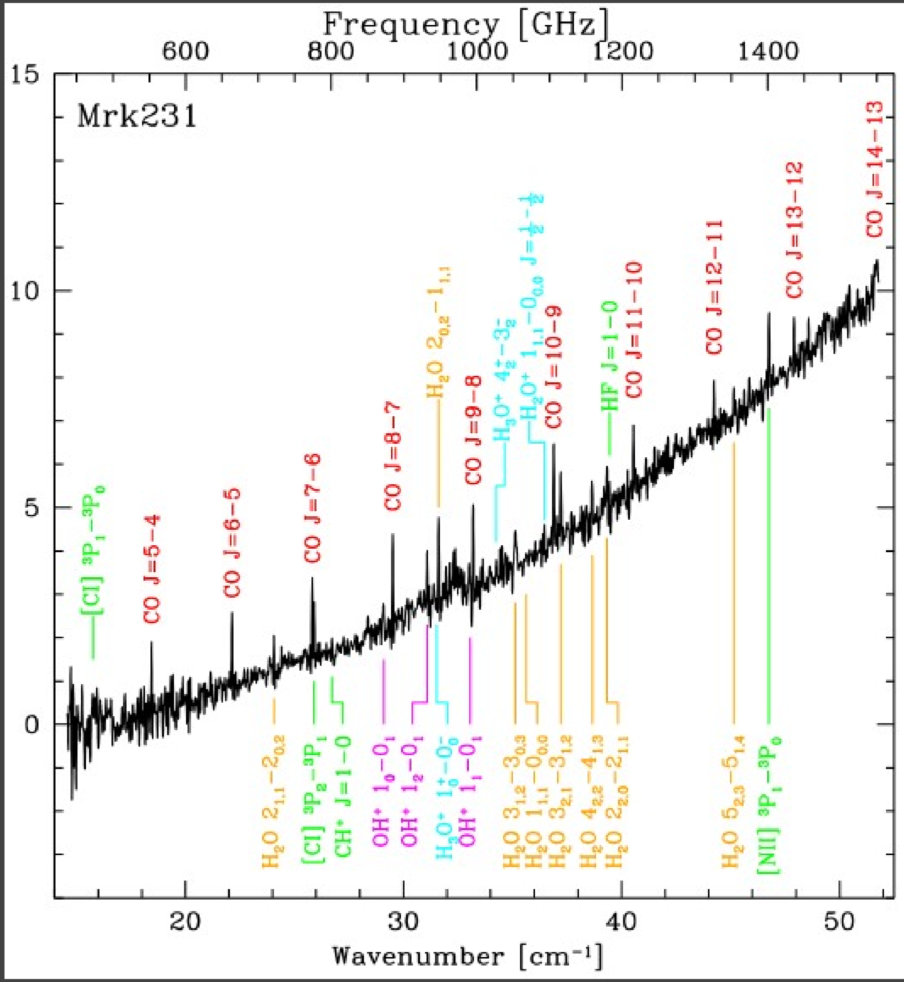
- Accretion onto 10^7 M_0 black hole
- Strong in X-rays
- Recent merger

Herschel-SPIRE spectrum:

- Hot molecular gas (CO)
- High ionisation (H_nO^+)

Puzzle: HF & H_nO^+ in emission

- rapid radiative decay
- chemistry or excitation?

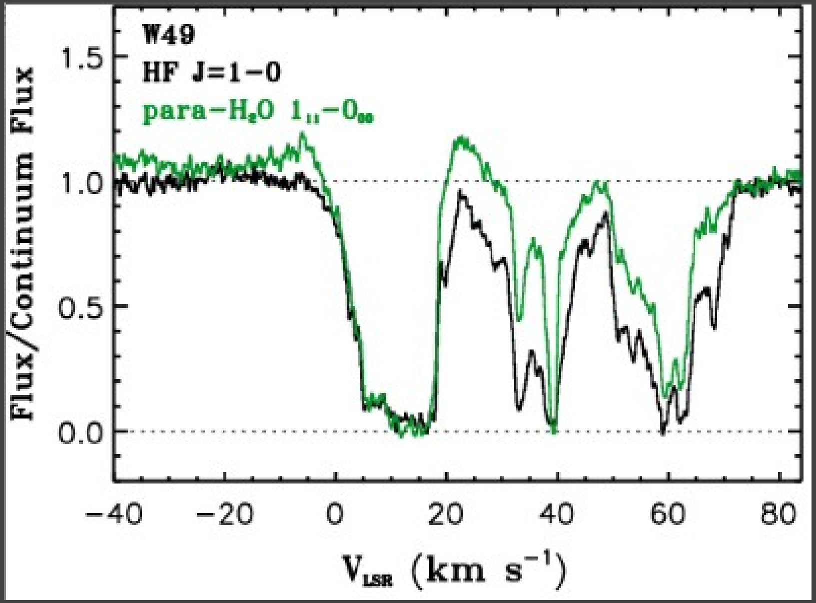


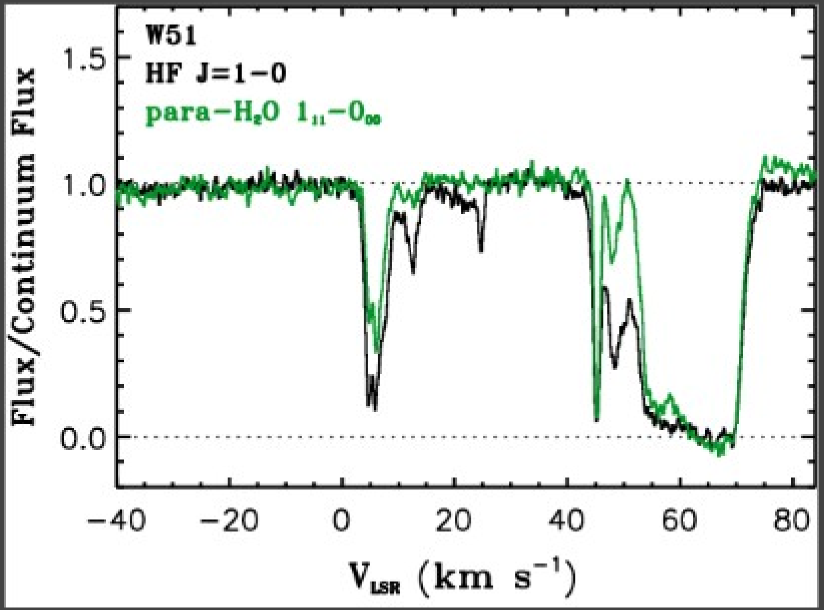
Van der Werf et al 2010

Observations of HF

- Ladder-type spectrum like CO
  - small reduced mass: high line frequencies
  - large dipole moment: rapid radiative decay
- Galactic ISM usually shows line in absorption

  Neufeld et al 1997; Sonnentrucker et al 2010





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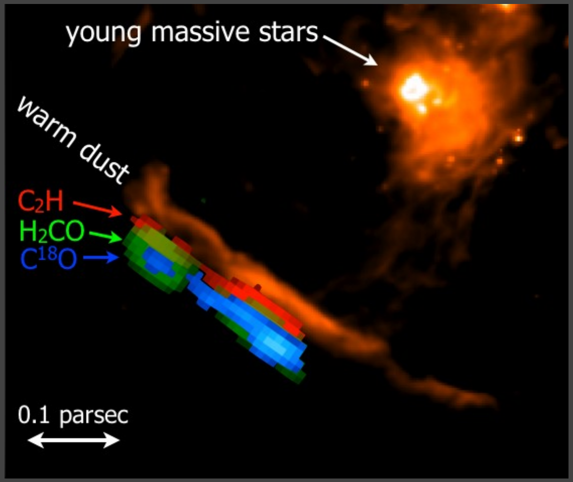
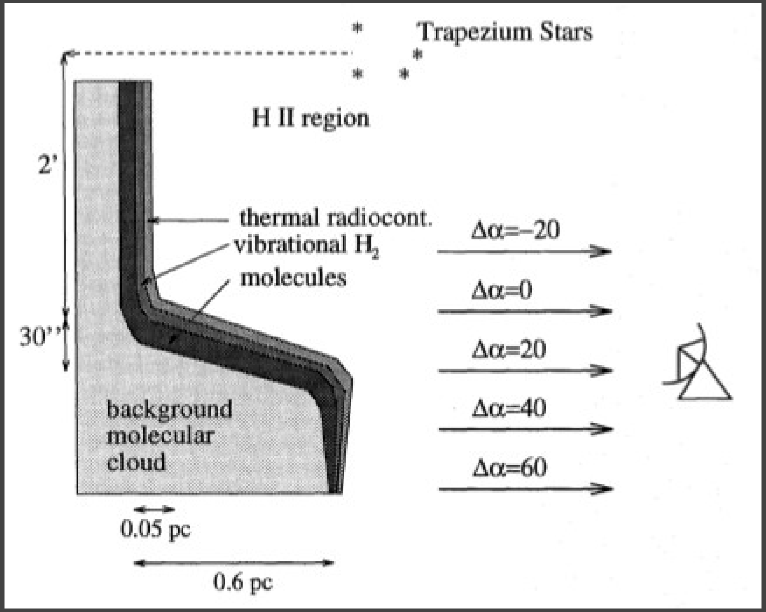
The Orion Bar

- PDR = UV-irradiated molecular cloud
  - temperature 80 – 150 K
  - seen edge-on; stratified
  - bright in infrared
- Clumpy density structure
  - clumps 1.5..6 x 10^6 cm^{-3}
  - interclump few..20 x 10^4 cm^{-3}
  - confirmed by interferometer
  - also other PDRs





Hogerheijde et al 1995; Van der Wiel et al 2009

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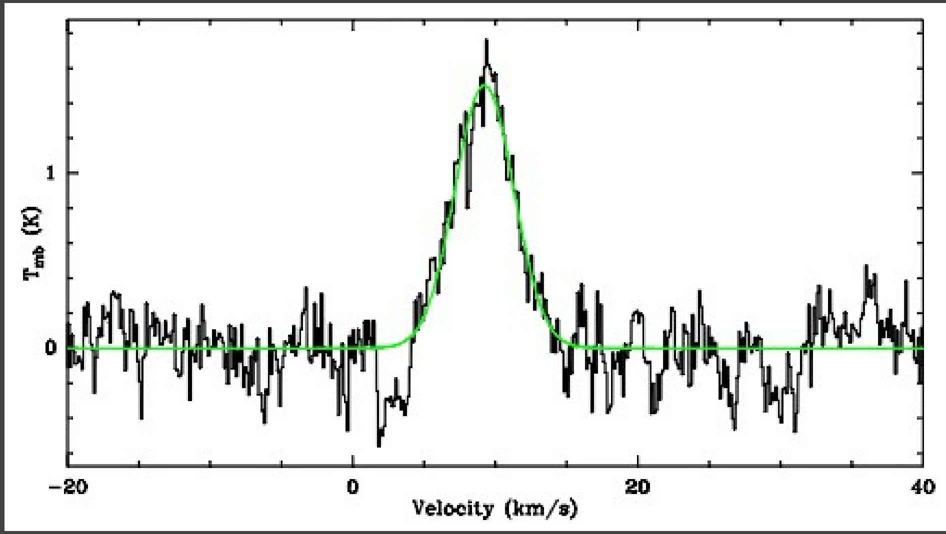
HIFI observations of HF

- Line appears in emission
  - V_{LSR} similar to H_2CO, CH_3OH etc
  - large ΔV more like C^+, CH^+
  - origin in interclump gas
- Absorption near +3 km/s
  - maybe from Orion Ridge
  - detect no continuum

Van der Tak et al 2012



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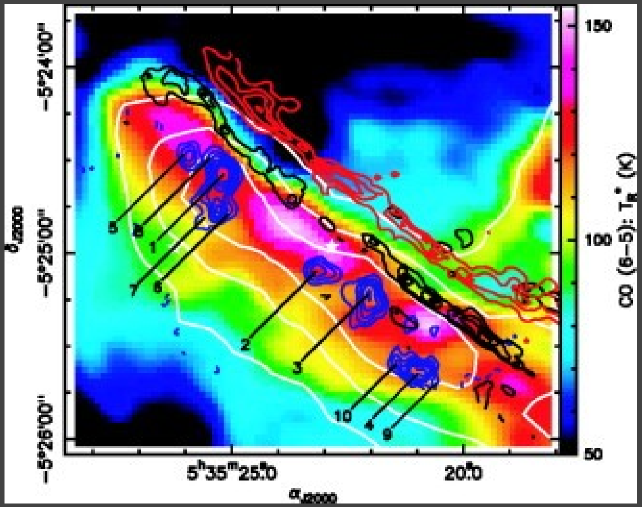
Excitation by H_2 collisions (Radex)

- Rate coefficients for HF-H_2: Guillon & Stoecklin 2011
  - ~10x larger than HF-He rates (Reese et al 2005)
  - due to large well depth of HF-H_2 interaction potential
- Case 1: Interclump gas
  - $n(H_2) = 10^5$ cm^{-3}
  - $T_{kin} = 100$ K
  - $N(H_2) = 10^{22}$ cm^{-2}
  - all fluorine in HF: N(HF) = 3.6 x 10^{14} cm^{-2}
- Calculate 0.5 K line = 3x below observation
  - warm atomic surface: not enough column density

Dense clumps in the Orion Bar

- Clumpy density structure well established
  - line ratios / abundances
  - direct imaging
- Case 2: Dense clumps
  - T_{kin} = 85 K
  - $N(H_2) = 10^{23}$ cm^{-2}
  - most fluorine in HF: $N(HF) < 3.6 \times 10^{14}$ cm^{-2}
- Require $n(H_2) = 10^{8-9}$ cm^{-3}
  - like for IRC 10216 (Agúndez et al 2010)
  - implies HF / H_2 ~ 10^{-10} like other dense clouds
- Unreasonably high for Orion Bar
  - especially as average over 7200 AU beam
  - also inconsistent with large line width



Lis & Schilke 2003

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Electron collisions

- Strong radiation field: high electron abundance
  - interclump gas: all carbon in C^+
  - $n(e) \sim 10\ cm^{-3}$
- e-HF collisional excitation rates: Born approximation
  - validated with R-matrix calculations (Thümmel et al 1992)
  - expected accuracy = factor of 2 = sufficient
  - reproduce observation with $N(HF) = 1 \times 10^{15}\ cm^{-2}$
- Estimate corresponding $N(H_2)$ from C^+ observations
  - implies HF / H_2 = few 10^{-8} consistent with Solar F/H

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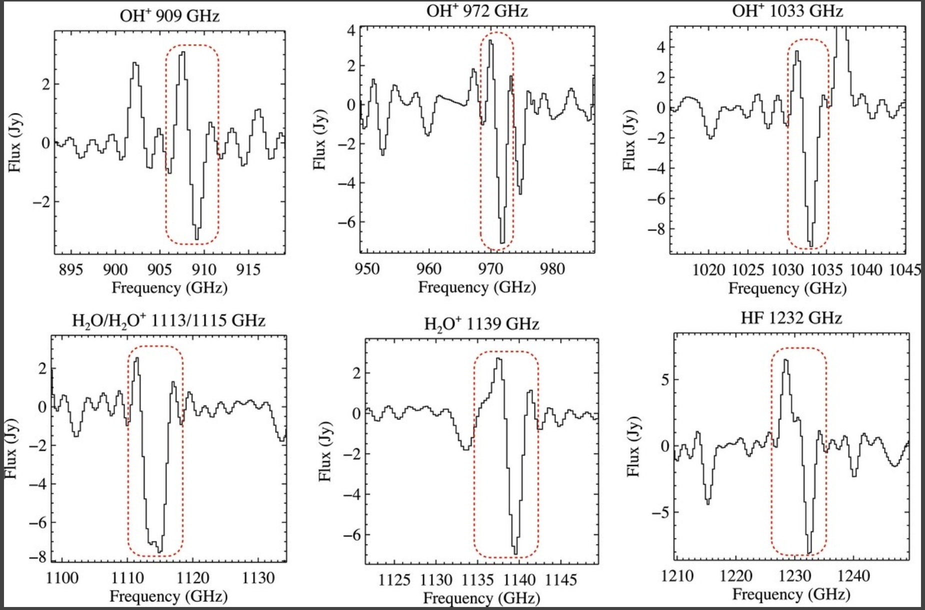
Similarity between HF and H_nO^+?

- Galactic ISM: both pure absorption
  - except Orion Bar (Nagy et al 201x)
- Mrk 231: both pure emission
  - coincidence?
- Arp 220: both wind-type profile
  - maybe a trend ...
  - more data needed
- Electron collisions important?
  - needs cross sections
  - A. Faure, in prep.



Arp 220: Rangwala et al 2011

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Deuterated H_3^+ in space: A story of success

- 88^{th} birthday (2000):
  - first detection of interstellar H_2D^+ (Stark et al 1999)
- 94^{th} birthday (2006):
  - abundant H_2D^+ in pre-stellar cores (Caselli et al 2003)
  - tentative D_2H^+ detection (Vastel et al 2004)
  - first H_2D^+ map (Vastel et al 2006)
- 100^{th} birthday (2012):
  - first H_2D^+ survey (Caselli et al 2008)
  - confirmation of interstellar D_2H^+ (Parise et al 2011)
  - H_2D^+ mapping surveys ongoing (JCMT / HARP)

- So what will we see in 6 years' time?

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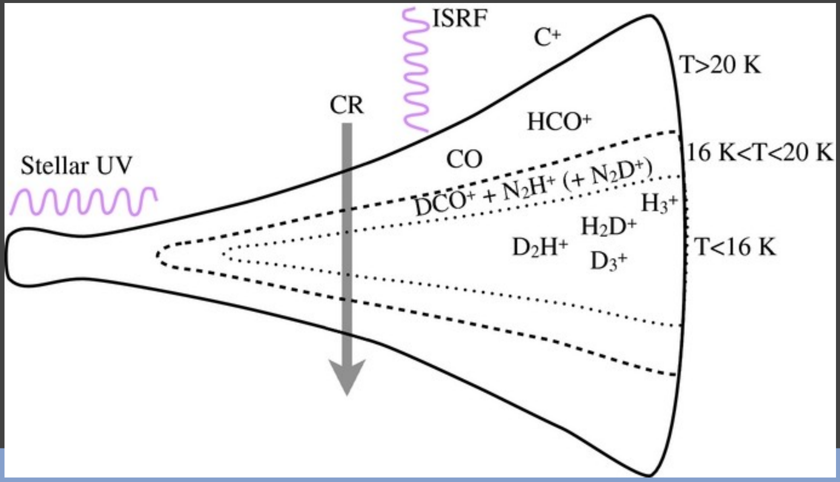
Future work: Cold gas

- Observe p-H_2D^+ & o-D_2H^+ ground states at 1370, 1477 GHz
  - with GREAT(+) on SOFIA (in absorption)
- High resolution maps of pre-stellar H_2D^+ with ALMA
  - tuning range extended after LDN 1544 discovery
- Survey of pre-stellar D_2H^+ at 692 GHz with ALMA
  - but probably weak in most cases
- Most important: ALMA detection of H_2D^+ in protoplanetary disk
  - unique probe of midplane ionization
  - efficiency of MRI in controlling accretion flow

Öberg et al 2011



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Conclusions & future work: Warm gas

- HF emission: A signpost of molecular gas with high n(e)
  - rare in Milky Way
  - more common in active nuclei
  - may help to solve H_nO^+ puzzle
- Herschel spectra of extragalactic H_nO^+
  - probe range of environments
  - after ~March 2013: ground-based OH^+, SH^+, CO^+, HOC^+
- Next step: observe spatial distribution
  - OT2 program approved at priority 1
- Higher-J lines: need heterodyne resolution
  - J=2-1 blended with N^+ line in PACS spectrum
  - Something for SOFIA ...

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