Probing Orion BN/KL energetics with HIFI maps of CH^+, CH, and C^+

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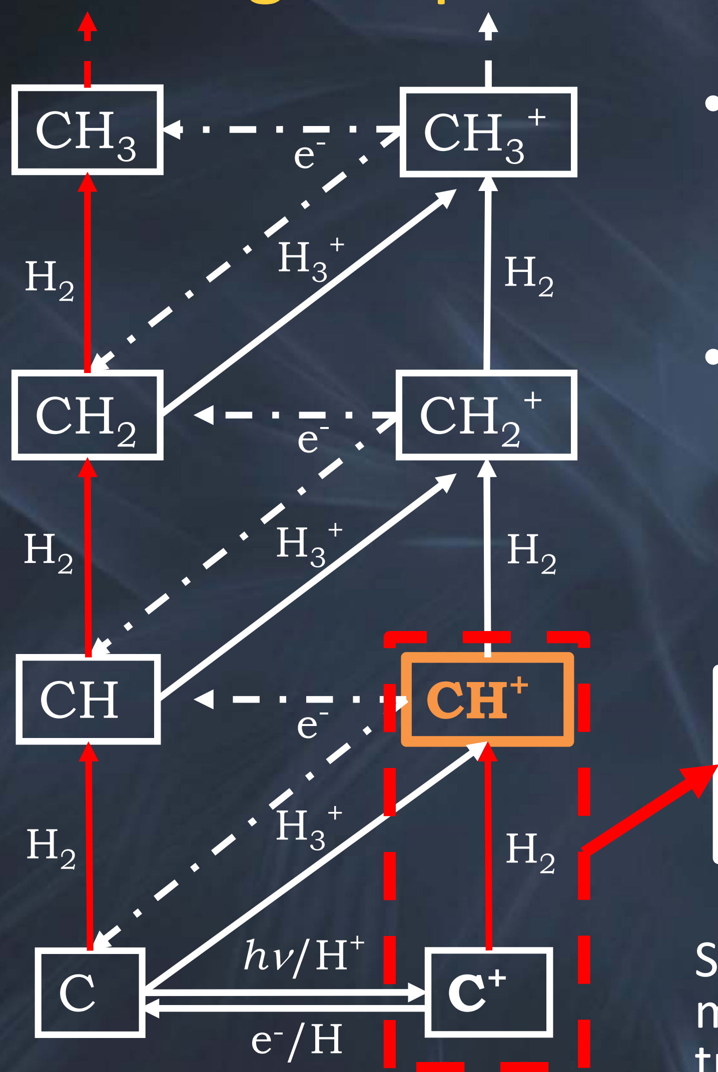
CH, C+ and esp. CH+ are excellent probes of energetic processes in diverse environments



- First observed molecules in the diffuse ISM ~75 years ago (Douglas & Herzberg 1941).

- CH^+ occurs 10^2 – 10^3 times more abundant than predicted by a UV driven steady-state chemistry (Dalgarno 1976; van Dishoek & Black 1986 and many since)

4640 K (0.41 eV)

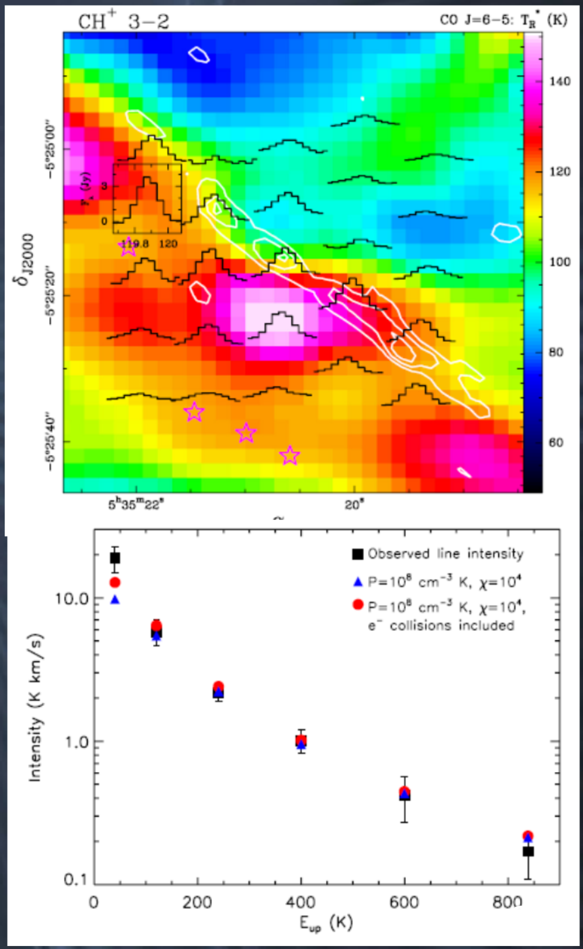
$$C^+ + H_2 \xrightarrow[\text{Shocks, TDRs, UV}]{} CH^+ + H$$

Shocks and UV fields in dense clouds contribute mechanical energy, radiative heating & cooling for triggering / regulating / inhibiting star formation, from collapse to the ZAMS

Breaking the 0.41 eV barrier

- **Shocks.** For example:
  - ❖ Stellar shock waves though HII regions – Elitzur & Watson (1978).
  - ❖ MHD shocks ~10 km/s in T ≲ 80 K diffuse ISM
    – Draine & Katz (1986);
    Pineau des Forêts et al. (1986a,b).
- **Dissipation of turbulence.**
  - ❖ Diffuse ISM
    (see Wed talk by B. Godard)
- **UV irradiation of H_2**
  - ❖ H2(v = 1): E/k = 5986 K.
  - ✓ Dense PDRs: e.g., Orion Bar

Orion KL hosts a wide range of conditions to explore these processes at friendly spatial scales for mapping observations.



Nagy et al. 2013, A&A 550 A96

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  - MHD sh… …M
    - – Draine & …
    - Pineau d… …et al. (1986a,b).

Chemical models for CH+ using shocks tend to overproduce some molecules, e.g. CH

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  - Diffuse ISM
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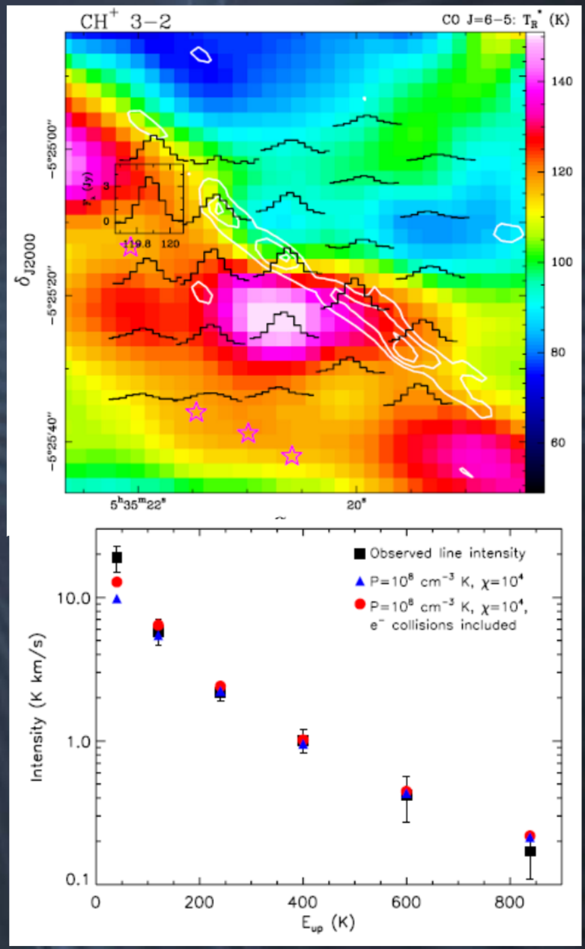

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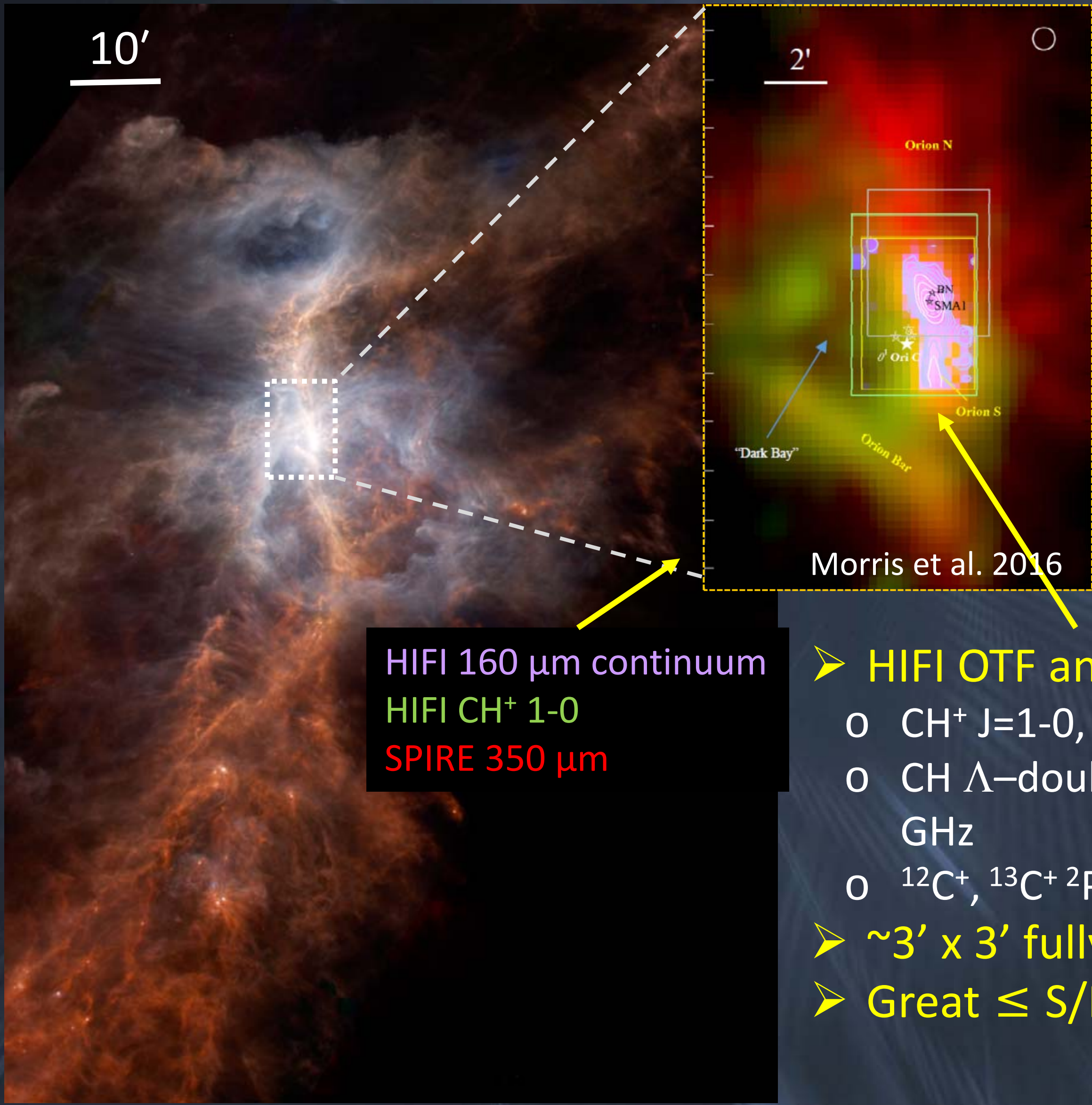
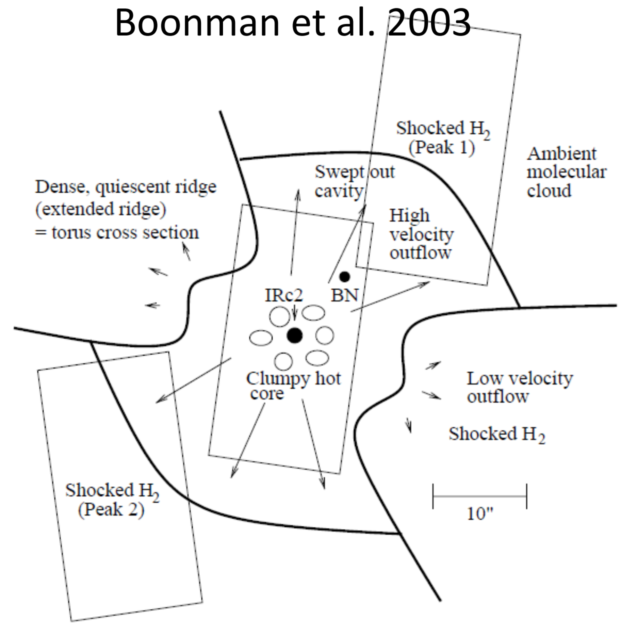
Orion BN/KL environment

Collection of young hot stars, shocks, strong continuum emission



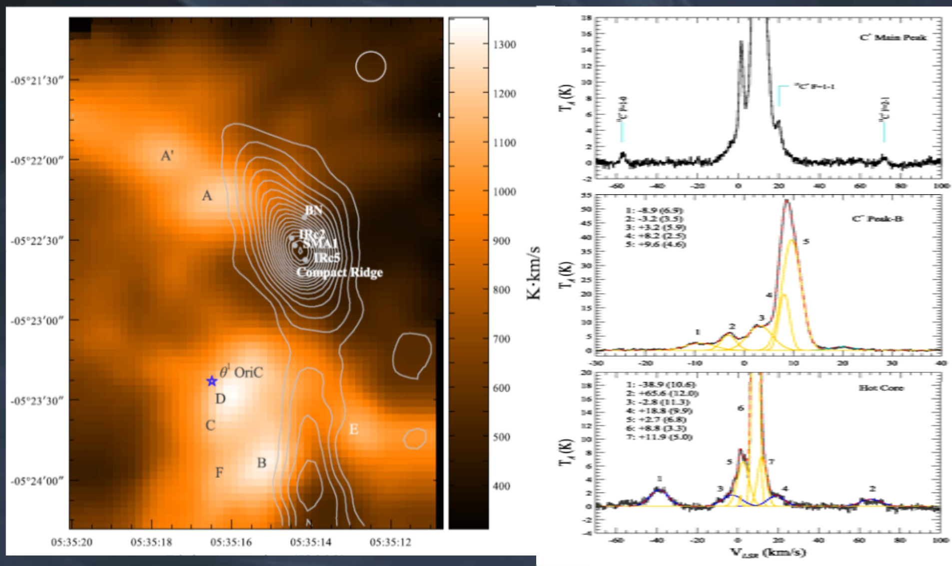


- HIFI OTF and DBS raster maps:
  - CH^+ J=1-0, 2-1
  - CH Λ–doubling $^2\Pi_{5/2,3/2}$ 1441/77, 1657/61 GHz
  - $^{12}C^+$, $^{13}C^+$ $^2P_{3/2,1/2}$
- ~3′ x 3′ fully sampled, ~centered on BN.
- Great ≤ S/N ≤ ∞ (some co-added maps)

C^+ and CH^+

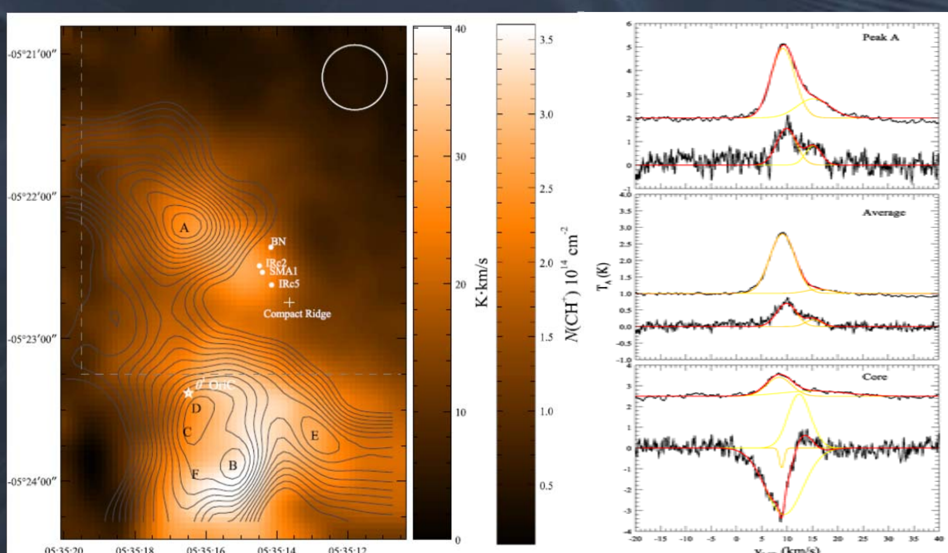
$^{12}C^+$ $^2P_{3/2} - ^2P_{1/2}$

1.9 THz continuum in white contours



CH^+ $J = 1 - 0$, $2 - 1$

CH+ 2-1 in gray contours



Optical depth of $^{12}C^+$

For a tested $^{12}C/^{13}C$ ratio of 67±10, $I(^{12}C^+)/I(^{13}C^+)$ yields:

- $1.4 \leq \tau(^{12}C^+) \leq 2.6$
- $200 \leq T_{ex}(C^+)$ 300 K
  - Hot Core: $\tau = 6.2$, $T_{ex} = 120$ K
  - Isotopic fractionation of C not indicated.

    $^{13}C^+ + CO \rightleftharpoons {}^{12}C^+ + {}^{13}CO + 34.8K$

$N(^{12}C^+) = (1 - 10) \times 10^{18}$ cm^{-2} for T_{ex} = 200 K, comparable to the Orion Bar PDR (Ossenkopf et al 2012).

Excitation of CH^+

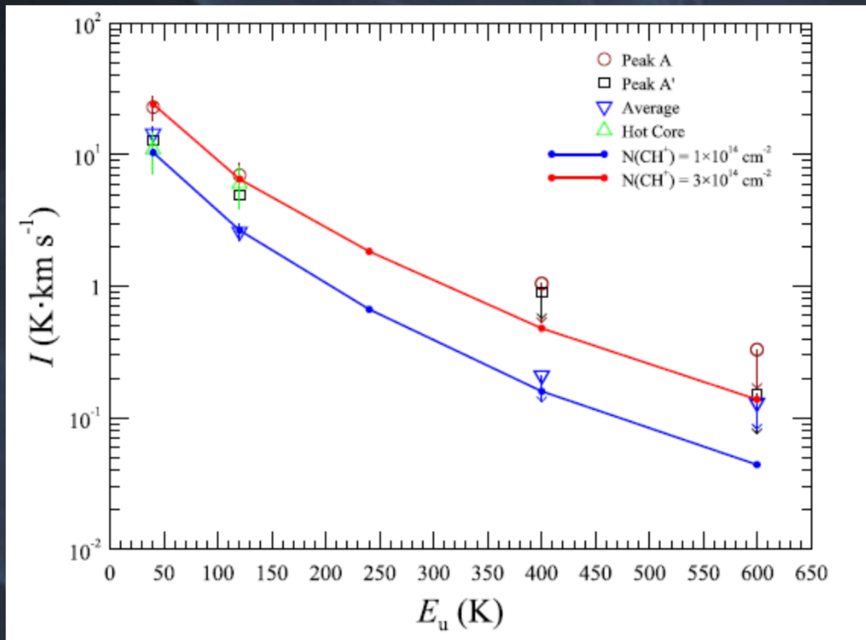
$J = 1 - 0$, $2 - 1$ in emission

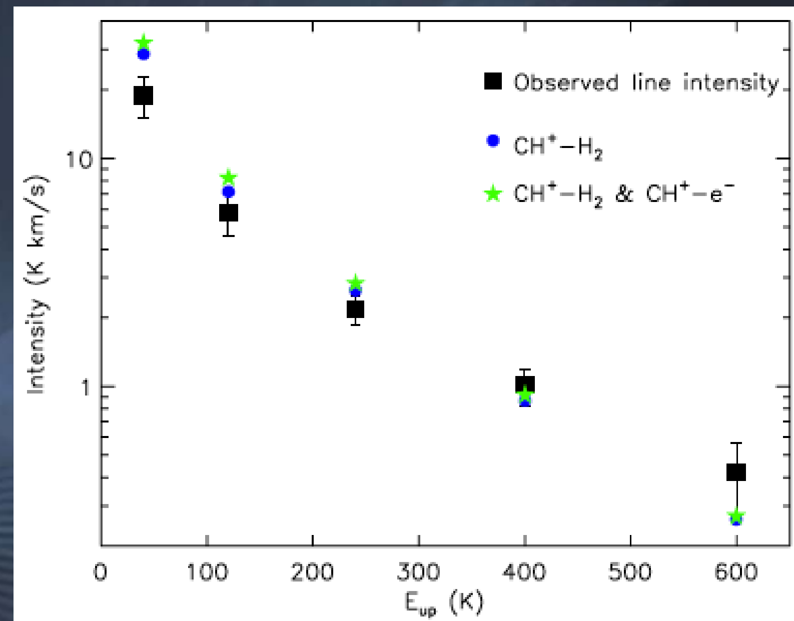
$J = 2 - 1$ absorbs against Hot Core

Non-LTE analysis incl. PACS lines through $J = 5 - 4$ yields

$N(CH^+) = (1 - 5) \times 10^{14}$ cm^{-2}

RADEX models of CH^+



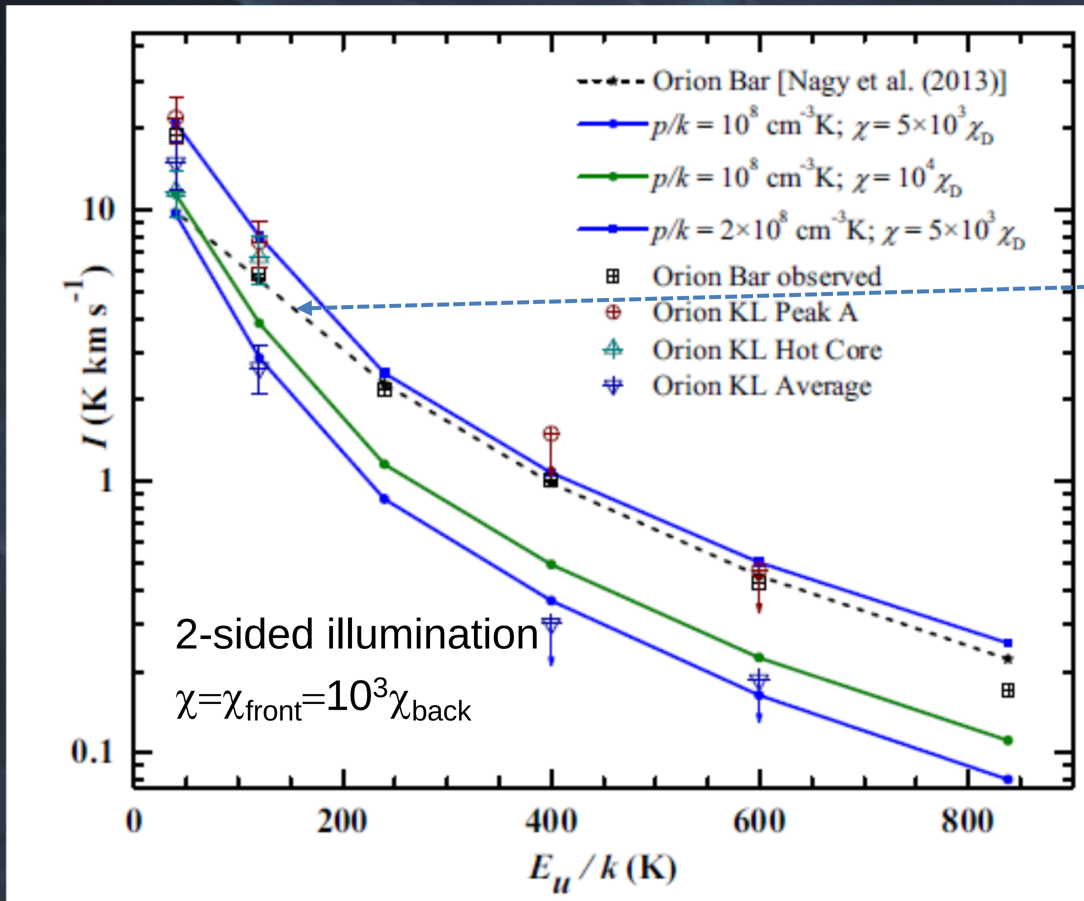


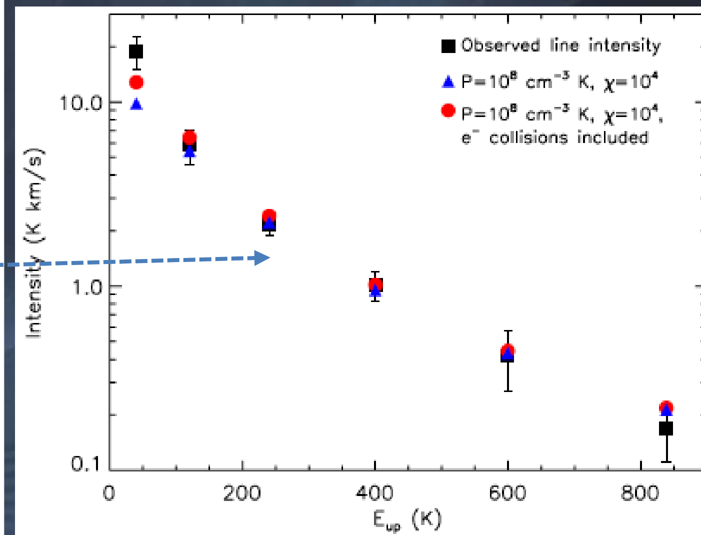
Orion KL:
$n(H_2)$ = 10^5 cm^{-3}; T = 500 K; $n(e^-)$ = 10 cm^{-3};
$N(CH^+)$ = 1.0 – 3.0 x 10^{14} cm^{-2}
(Morris et al. 2016)

Orion Bar:
$n(H_2)$ = 10^5 cm^{-3}; T = 500 K; $n(e^-)$ = 10 cm^{-3}; $N(CH^+)$ = 9 x 10^{14} cm^{-2}
(Nagy et al. 2013)

Background continuum emission increases I_J(CH+) of lowest 3 transitions by 1.1x – 1.5x

Isobaric PDR models of CH^+





Orion Bar

(Nagy et al. 2013)

Orion KL (Morris et al. 2016)

Meudon PDR code v 1.4.4 (Le Petit et al.).
CH^+ state-to-state formation rates from O. Roncero, A. Zanchet.

Similar parameters for Orion KL:

- *P/k* up to 2x higher
- χ is 2x lower
- *N*(CH+) ~ 5x lower (avg)

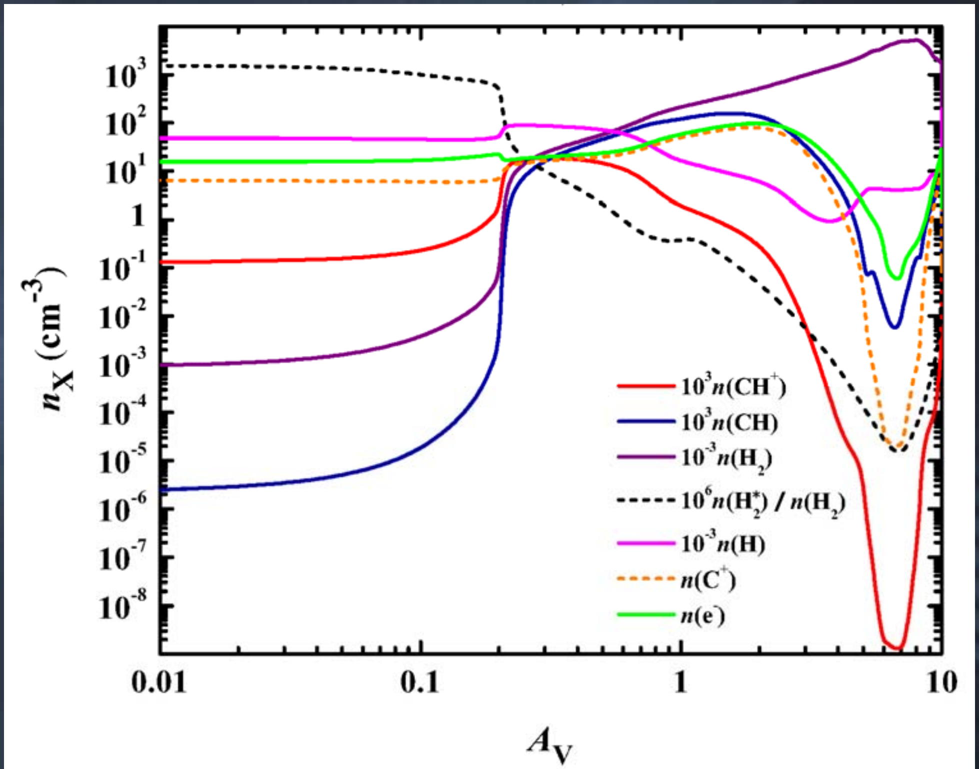
Abundance yields from PDR models

- C^+ (dashed orange) traces only the narrow cloud surface layers to A_V < 4 mag and not the full line of sight.
  - Broadly consistent with larger (lower-sampled) maps of OMC1 using more detailed treatment of the dust properties --- Goicoechea et al. (2015)

- CH (blue) peaks at comparable penetration depths.

- CH^+ (red) peaks at much lower depths, $0.2 \leq A_V \leq 0.6$ mag.
  - Consistent with increase of $n(e^-)$ (green) at depths similar to the C^+ peak abundance, where CH^+ will react to form neutral CH.

☞ UV-pumped CH^+ (and H_2*) trace outer cloud layers.



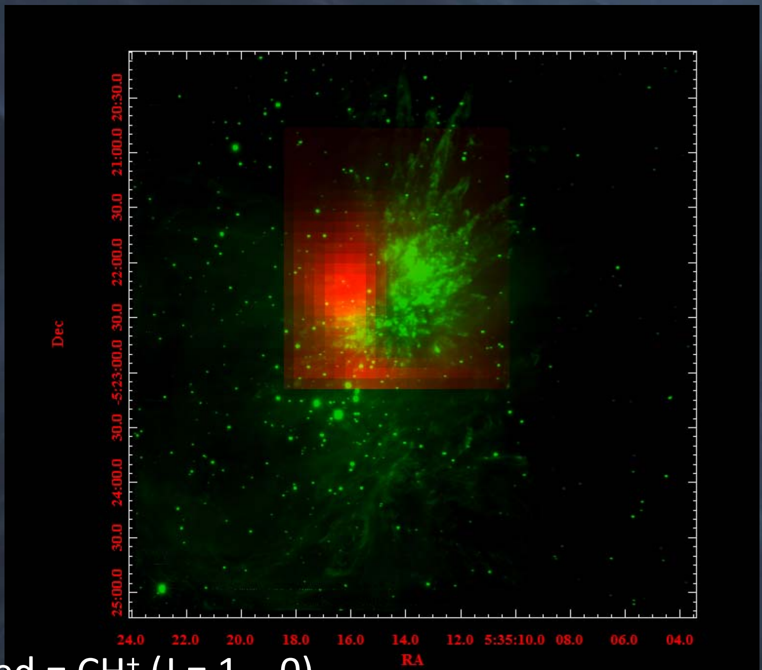
Orion KL

(Morris et al. 2016)

Results are similar with Orion Bar PDR (Nagy et al. 2013).

We can conclude that PDR conditions suited to the Orion KL region can be modeled to predict line intensities and excitation, abundances and cloud boundary conditions consistently with the observations.
Favors UV-irradiation for excitation of H_2 to $\nu \geq 1$.

A semi-boring result -- these conditions are similar for the Orion Bar PDR.
But there is something missing in this picture…



Red = CH^+ (J = 1 – 0)
Green = H_2 (ν = 1 – 0; S1) 2.12 μm (Bally et al. 2011; APO 3.5m)

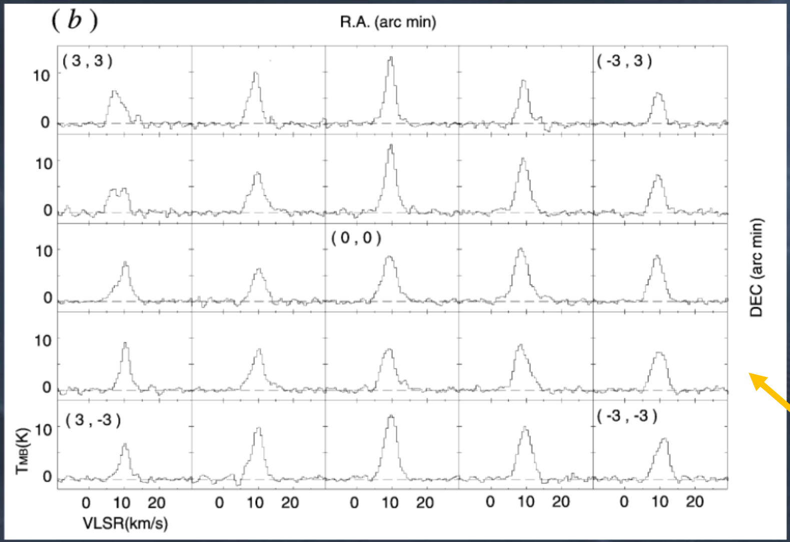
CH^+ distribution is not the same as the observed source of $H_2(\nu=1)$, namely the eruptive outflow from IRc2.

CH^+ is anti-correlated with the outflow. In fact so is CH and C^+ ! (strictly speaking the intensities are weakest there). No spatial *or* kinematic correspondences.

There seems no C^+ to react with H_2* in the shocked gas. *Why not?*

Non-ionizing Shocks?

- Unlikely: OH^+, CO^+, H_2O^+ etc. observed --- IPs of the neutrals > IP(C I) = 11.3 eV.



C I is indicated to arise in the PDR (Yamamoto et al. 2001).

Low T_{ex}(C I) suggested at the Hot Core.

C I $^3P_1 - {}^3P_0$, 1.5 arcmin spacings (Yamamoto et al. 2001)

- Spatial resolution of ions & neutrals observed around the Hot Core not always conclusive… e.g. whether in the outflow or lower velocity shocks impacting the central source (the Hot Core's external heating mechanism; Zapata et al. 2011).

- [O II] observations with SOFIA/GREAT (K. Menten et al.) should yield improved characterization of the eruption's shock properties.

Alternative Carbon Chemistry Depleting C^+?

- Radiative association with H_2 → CH, through rapid reactions involving intermediate CH^{+2} and CH^{+3} ?

  Probably not. This process is suited to low-density (diffuse ISM) conditions, and is inconsistent with the observed distribution and kinematics of CH in relation to the outflow.

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- CO production?

$C^+ + OH \rightarrow CO^+ + H$, followed by

$CO^+ + H \rightarrow CO + H$, ***or*** (1)

$CO^+ + H_2 \rightarrow HCO^+ + H$ then $HCO^+ + e \rightarrow CO + H$. (2)

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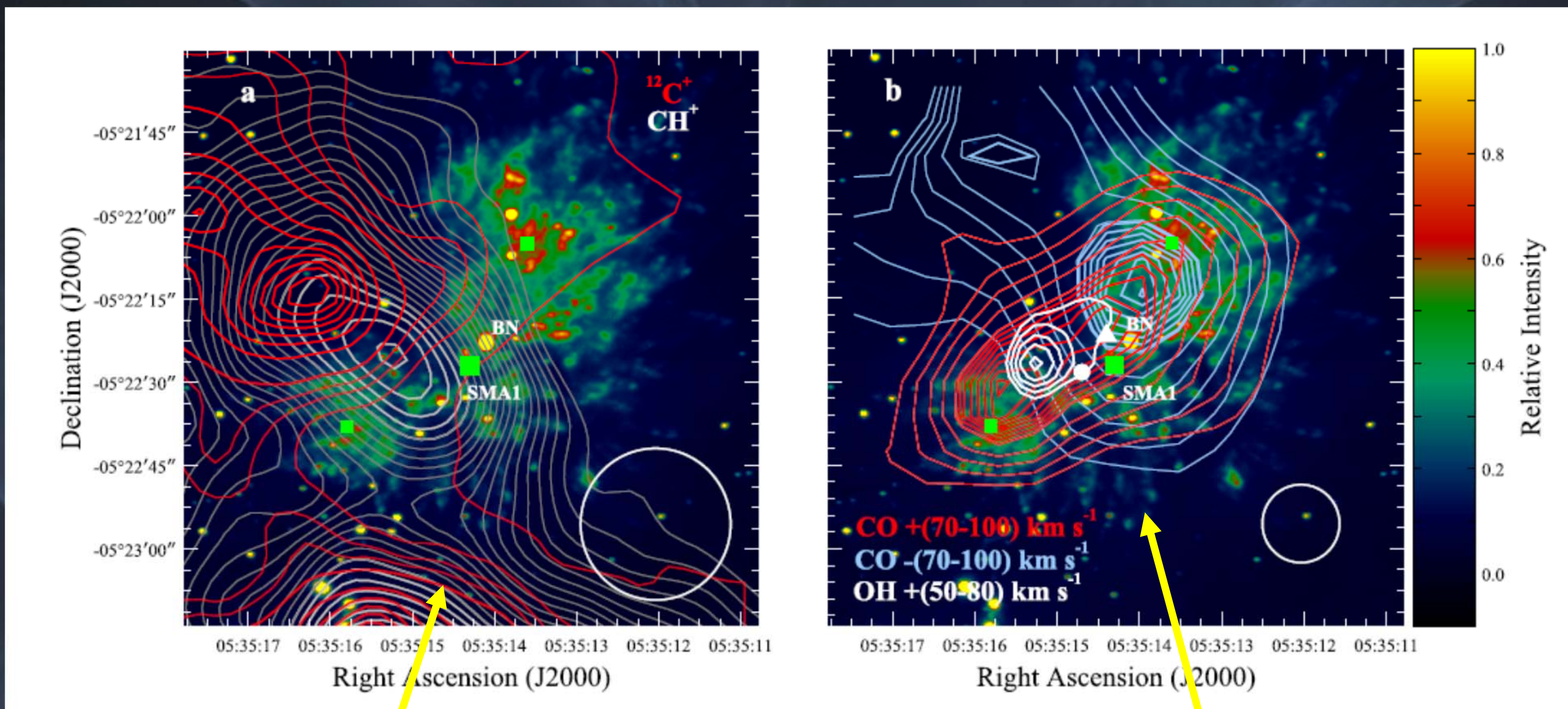
Good evidence for reaction (2) taking place: CO and OH are observed with broad, high-velocity wings (to |vLSR| ≈ 100 and 80 km/s, respectively), distributed in a geometry consistent the outflow's NW-SE orientation; see next slide.

C^+ depletion in CO production?



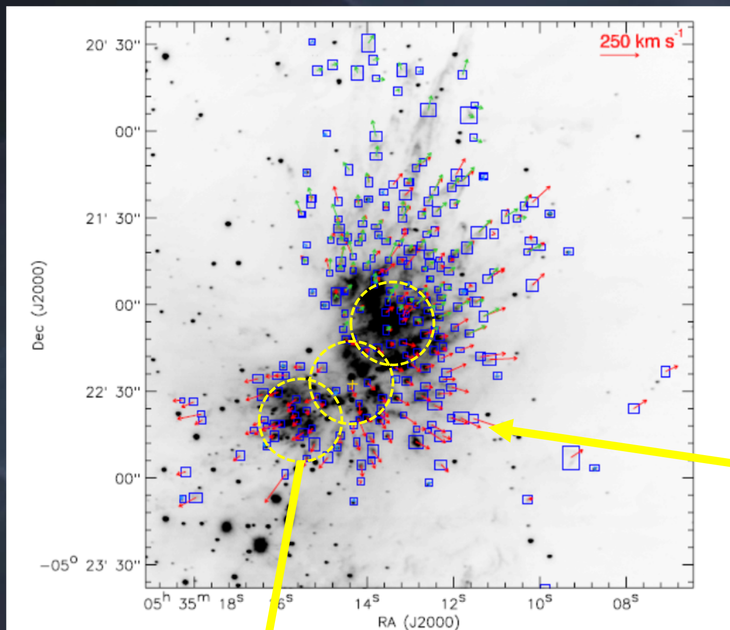
Morris et al. 2016

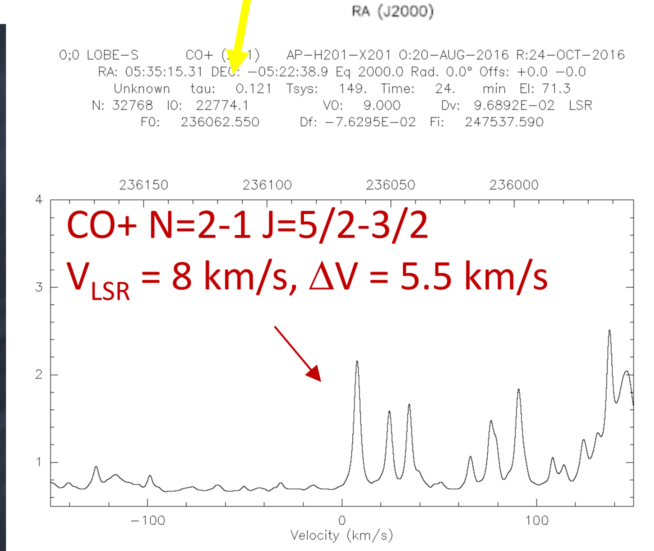
View of eruption in H_2 vs C^+ (red) and CH^+ (white) emission peaks.

The correlation of the fast CO (red and blue) with the H_2 lobes has been pointed out by, e.g., Zapata et al. (2009) and Peng et al. (2012).

Red-shifted OH (white) and CO peaks are similar. Blue-shifted OH not observed.

Following the CO production path





For the involved species we have good HIFI and ground-based data on the eruption for C^+, H_2, OH, CO, HCO^+.

APEX/FLASH and APEX-1 observations of CO^+ N=2-1 and 3-2 are freshly taken, 3 positions on the outflow, 2 in the PDR. We are combining these with earlier APEX CO^+ N=3-2 and 4-3 maps by K. Menten.

The data + detailed calculations for the reactions needed to remove C+ from the shocked gas may answer why no detectable C^+ or CH^+ there.

Summary

- For all of the BN/KL region's complexity, the observed properties of C^+, CH^+, and CH around Orion BN/KL can be well reproduced in a UV chemistry that is driven by the Trapezium stars.
  - Most accurate T_{ex}, abundance estimates to date.
  - Some small differences with Orion Bar PDR results, mainly from χ_{UV}, *p/k*.

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- Total lack of C^+ and CH^+ in the eruptive H_2 outflow is unexpected.
  - Most likely a result of C^+ being involved in more rapid production of CO.
  - H_2 is vibrationally excited $\nu > 1$ in the PDR ☞ no CH^+ - $H_2(\nu=1)$ correlation.
  - Work in progress.

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The prevailing conditions driving CH^+ formation and excitation deduced from our Orion maps (i.e., UV irradiation) warrants care with future integrated (e.g. galaxies) or pointed observations --- each of PDRs, shocks, and sightline TDRs are different paths to formation + excitation with distinct signatures, one or more may contribute!