Herschel Observations of Molecular Oxygen in Orion

Herschel Oxygen Project "HOP"

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for the HOP Team

with special thanks to Tom Bell, John Black, Jo-Hsin Chen, David Hollenbach, Michael Kaufman, Di Li, and Darek Lis

IAU Symposium 280 "The Molecular Universe", May 31, 2011

Herschel Oxygen Project

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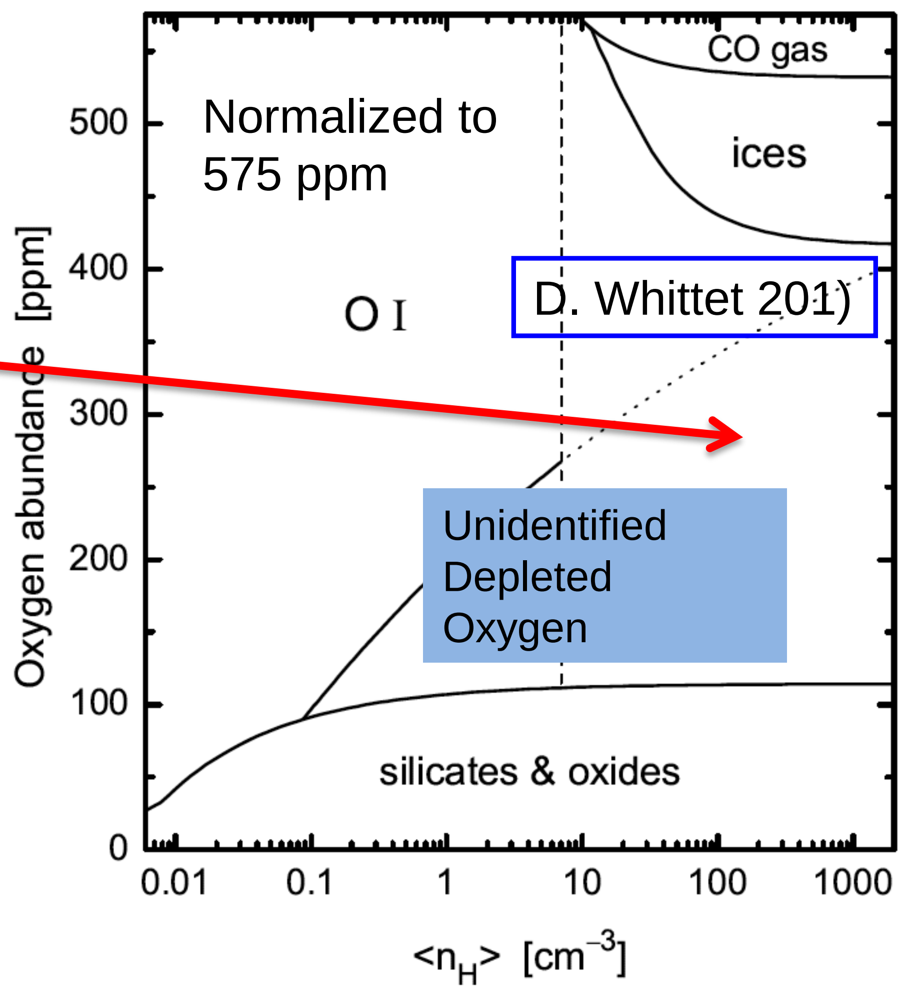
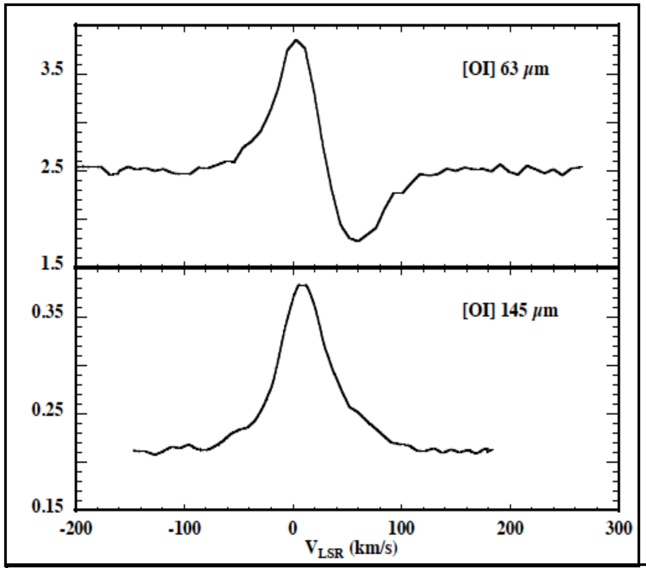
Part of a Bigger Question: Oxygen is 3rd Most Abundant Element. Where is it in the Dense ISM?

- Its form in the Dense ISM is very unclear – OI ??
- Should O_2 be in this figure??





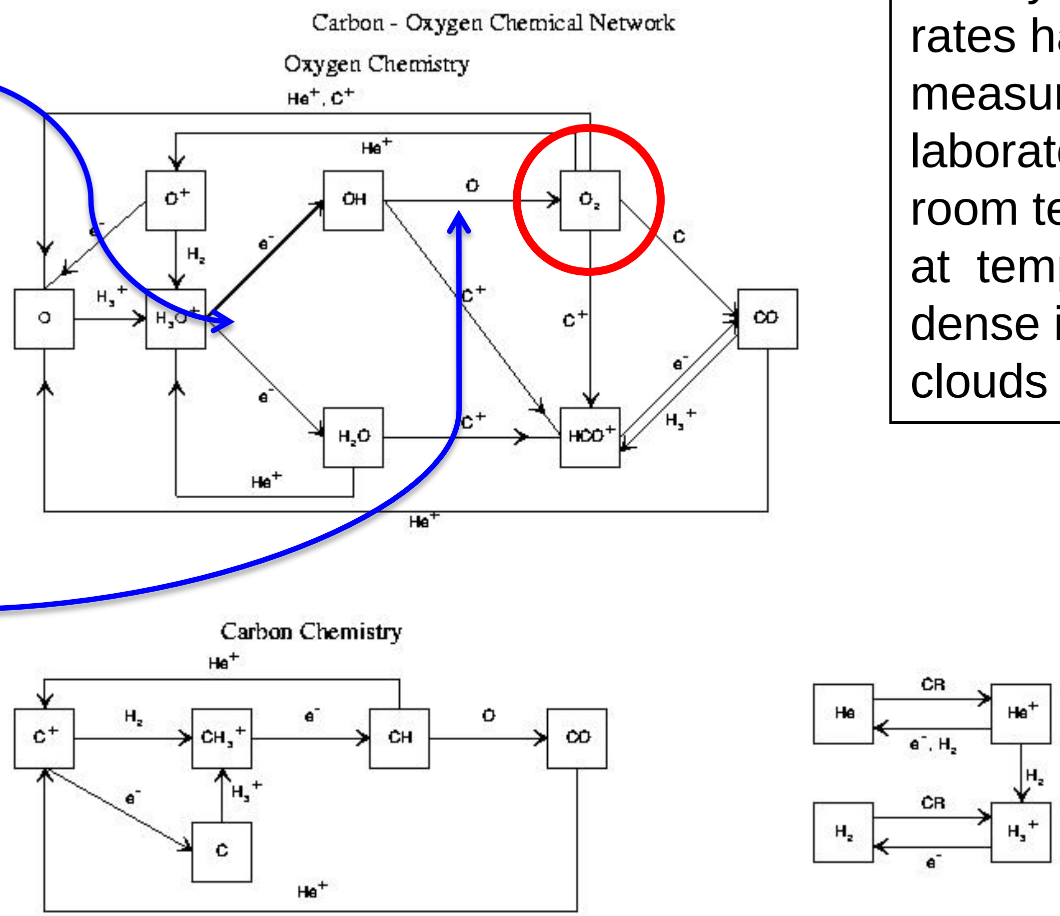
Caux et al. 1999; Vastel et al. 2000: OI/CO = 10 – 50 !!

Gas Phase Chemistry for O, H_2O, O_2 and CO is Relatively Simple

Branching ratio measured by ASTRID and CRYRING experiments (Jensen et al. 2000; Neau et al. 2000) $f(H_2O):f(OH) = 0.25:0.75$

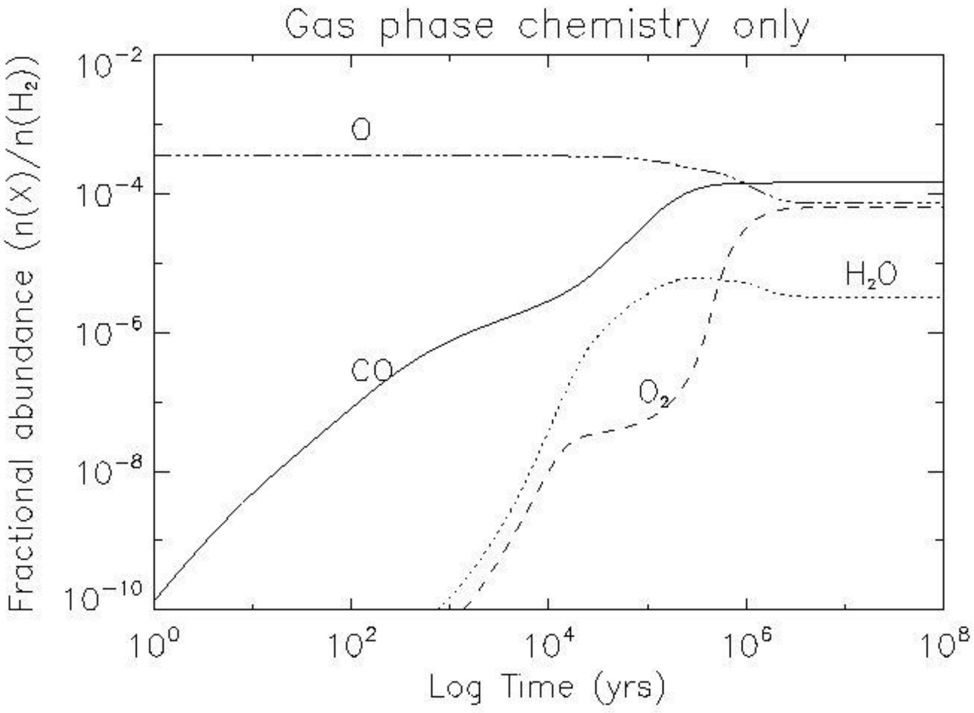
OH + O −> O_2 is an endothermic neutral-neutral reaction

Measurements (Carty et al. (2006) and full quantum calculations (Lique 2010) indicate ~ temp-indep. rate from 300 K to very low temperatures ≅ 4×10^{-11} $cm^3 s^{-1}$



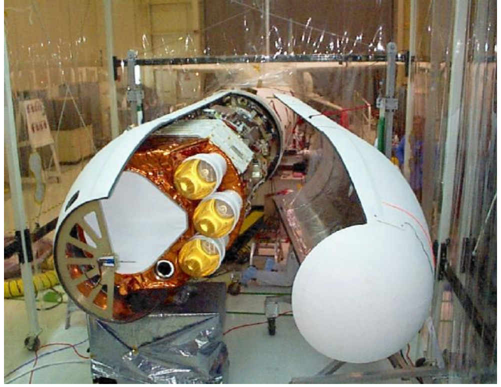
All key reaction rates have been measured in laboratory, both at room temperature & at temperatures of dense interstellar clouds

Standard Gas-Phase Chemistry Models Predict Lots of O_2

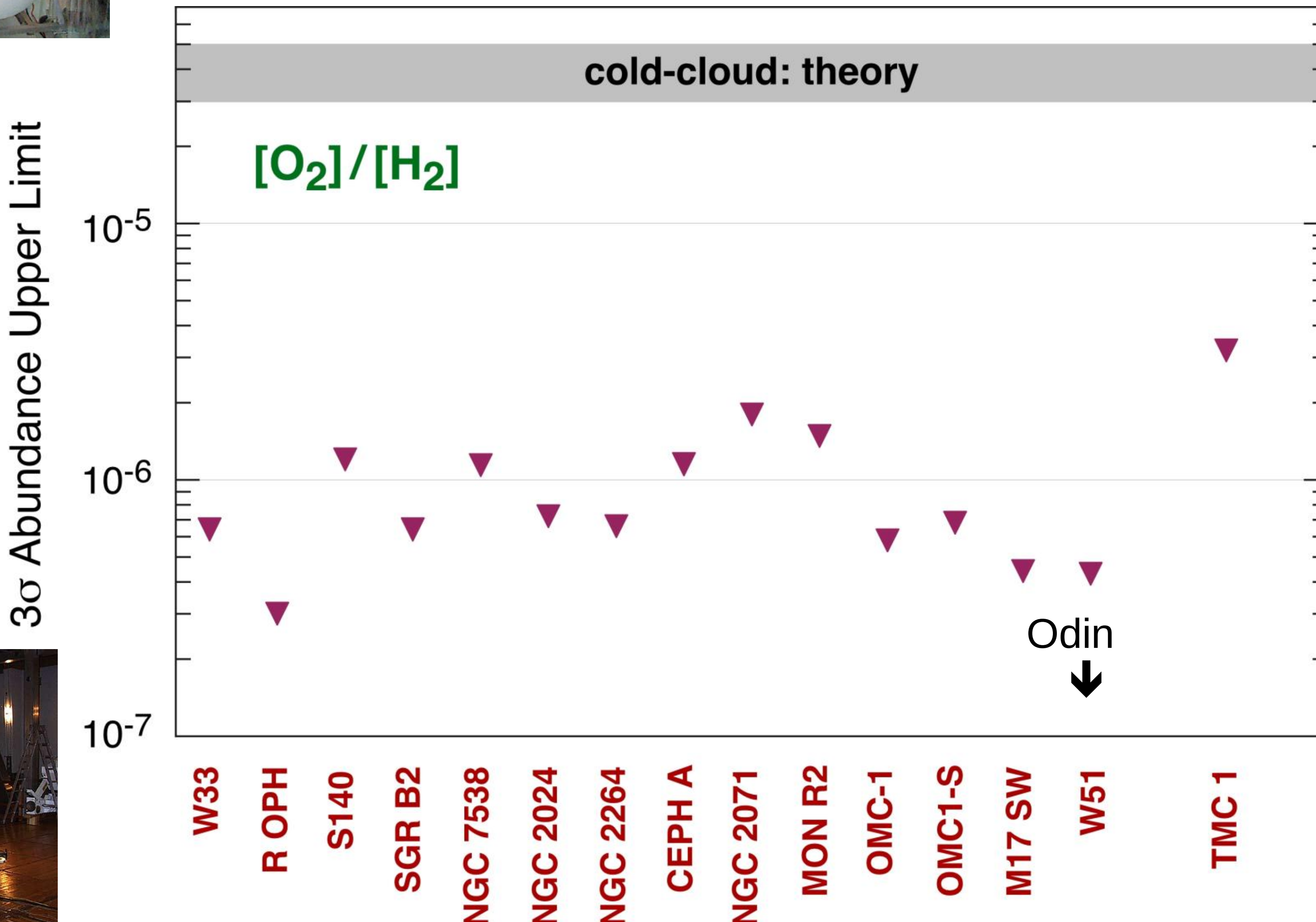


The time dependent evolution of a gas phase chemistry model. The physical conditions are $n(H_2)$ = 10^4 cm^{-3}, T = 10 K, and A_v = 10 mag. The oxygen is initially atomic (K. Willacy).

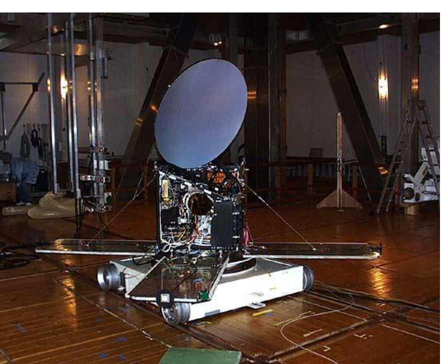
$X(O_2)$ in IS Clouds from SWAS & Odin is ≥ 100X Below Prediction of Gas-phase Chemistry



SWAS

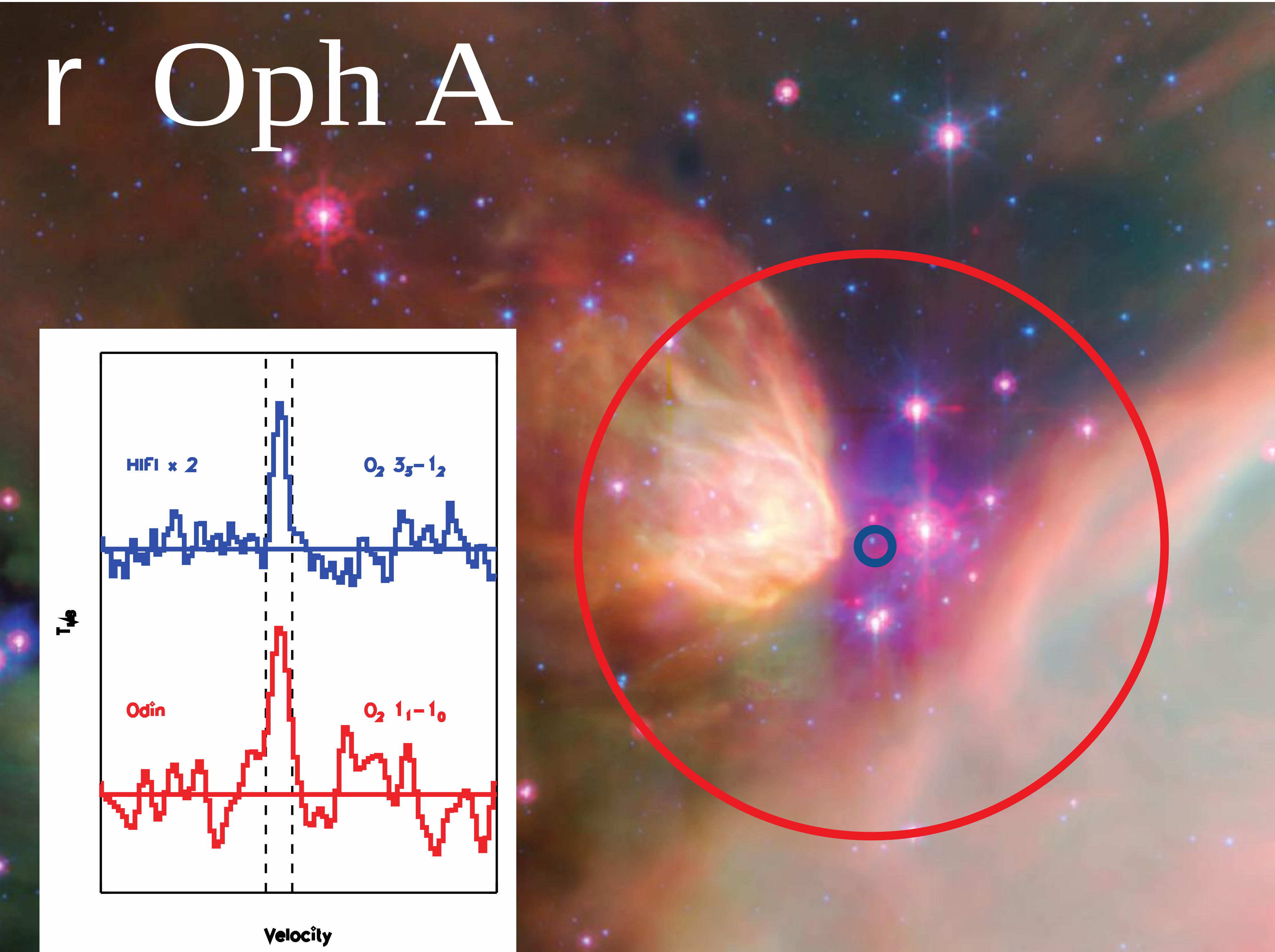


Odin



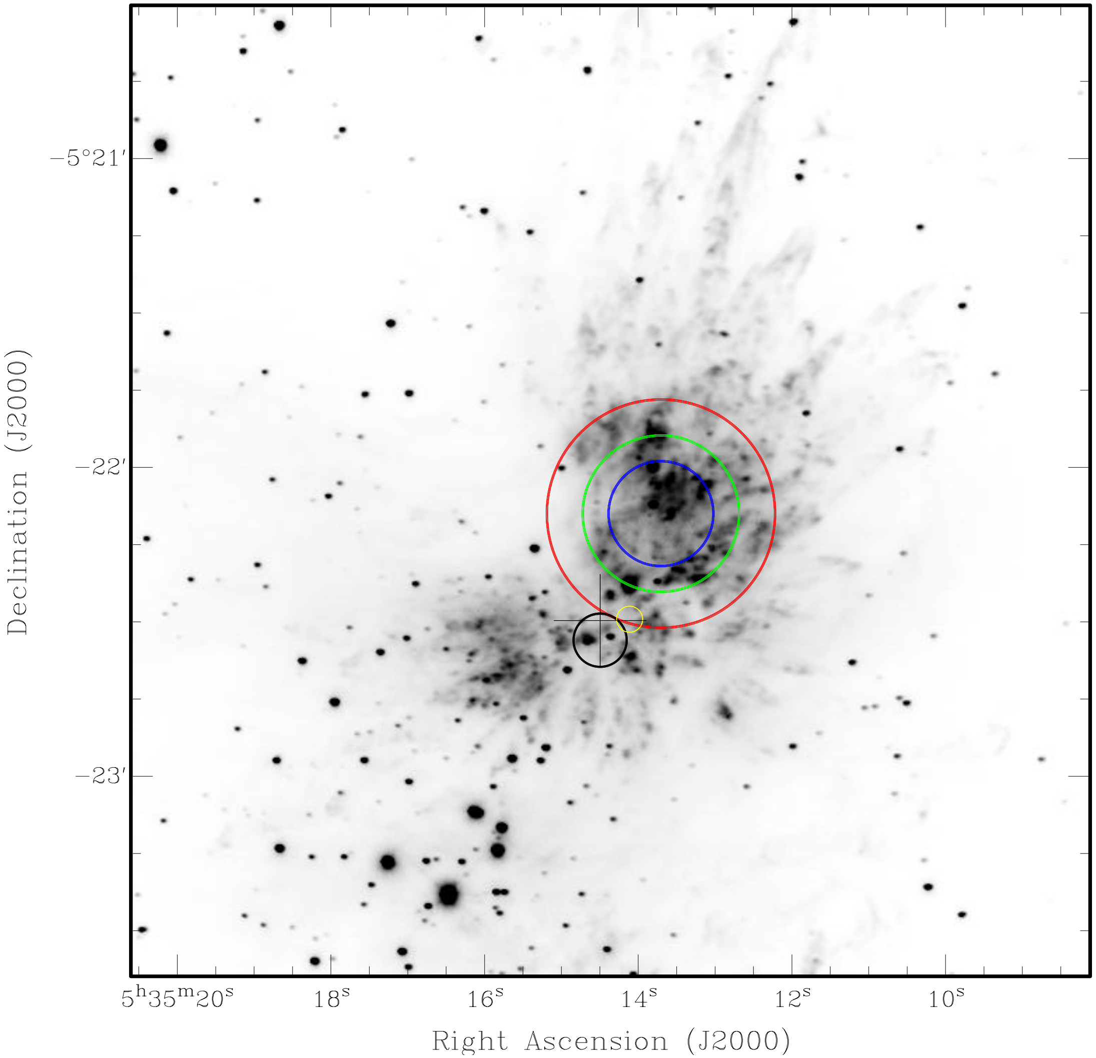
HOP Initial Results

- **Orion Bar** – classic PDR G ~ 10^5 [Melnick, Tolls]
  - 487 and 774 GHz O_2 transitions observed. Based on parameters for CS J = 10-9 line, upper limits for O_2 correspond to $X(O_2) \leq 5x10^{-8}$ if O_2 traces full H_2 column
- **ρ Oph** – intermediate mass YSO region possibly PDR [Liseau, Larsson]
  - Detection at 487 GHz ; analysis in progress
- **Orion(S)** – embedded protostar L ~10^4 L_{sun} [Nagy, van der Tak]
  - 3 O_2 transitions observed; $N(O_2) < 1x10^{16}$ cm^{-2}; total $N(H_2)$ ~ $5x10^{24}$ cm^{-2} (McMullin et al. 1993]. If this is relevant #, $X(O_2) < 2x10^{-9}$
- **AFGL2591** - XDR [Benz, Bruderer]
  - No detections at few mK level; X-ray dominated region severely beam diluted; overall $X(O_2) < 5x10^{-8}$
- **NGC1333 IRAS4A –** low-mass YSO region [van Dishoeck, Yildiz]
  - $X(O_2) <$ few x 10^{-9}; further data analysis and source modeling in progress
- **Sgr A 50 km s^{-1}** - Galactic Center foreground cloud
  - Detection of 487 GHz line in very recent observations, but not 774 GHz line -> low temperature
- **NGC6334** – cluster of luminous protostars; analysis in progress [Lis]



r Oph A
HIFI x 2
O_2 3_3-1_2
Odin
O_2 1_1-1_0
T_{mb}
Velocity

O_2 Observations of H_2 Peak 1 Position in Orion



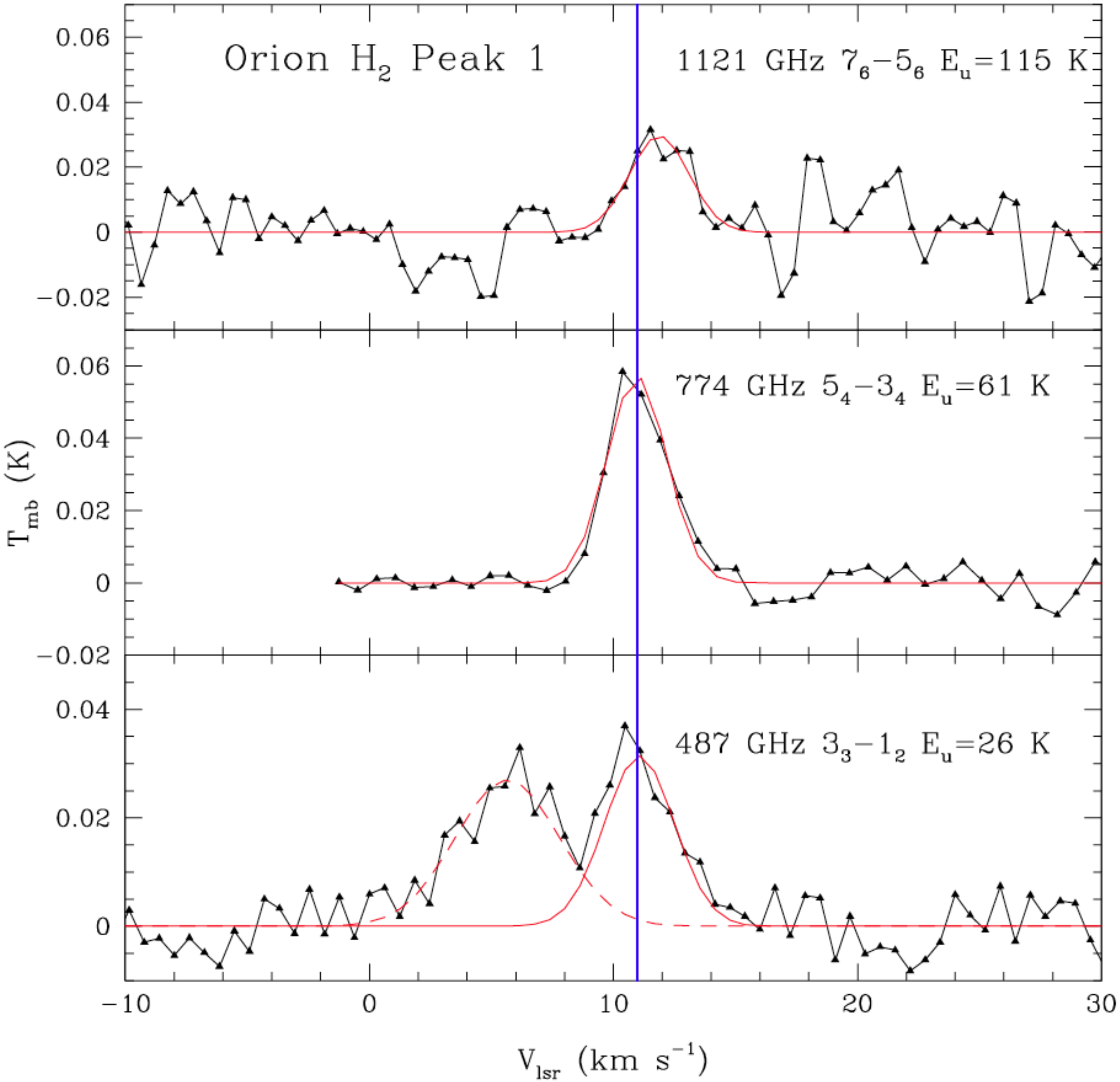
H_2 v=1-0 2 μm Emission from Bally et al. (2011)

Herschel HIFI beams at 487 GHz, 774 GHz, and 1121 GHz indicated by red, green, and blue circles

Hot core is 10" black circle

Peak A / Western Clump / Cnt D is 5" yellow circle

IRc2 is the black cross

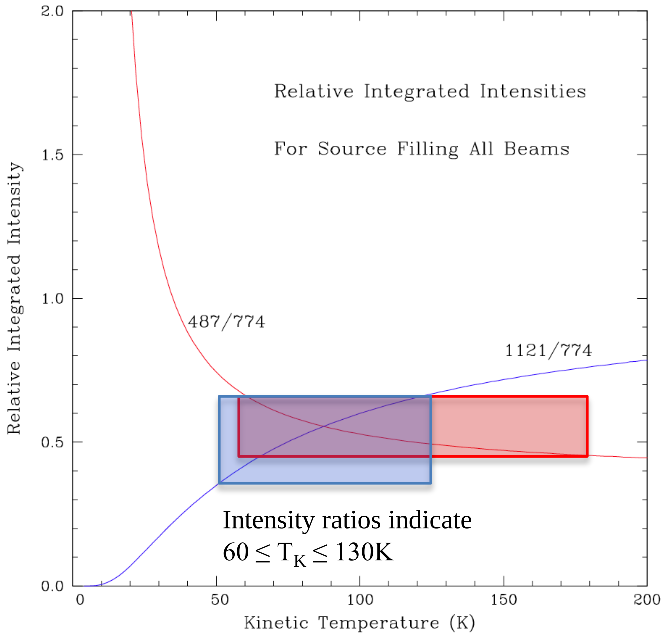


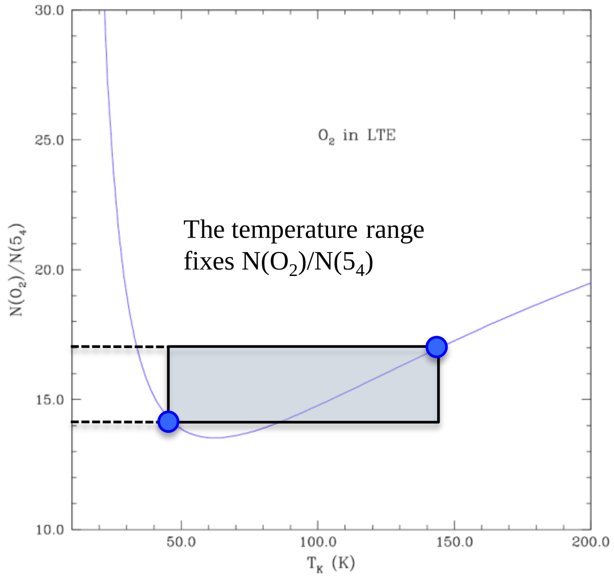
Herschel HIFI Data on O_2

- Beam Sizes:
  487 GHz 44”
  774 GHz 30”
  1121 GHz 20”
- Integration times up to 8 hr
- 3 transitions observed consistent with v_{lsr} = 11 km s^{-1}
  δv = 2.9 km s^{-1}

First multitransition detection of molecular oxygen in the ISM

Line Intensity Ratios Determine Kinetic Temperature and Total O_2 Column Density





Assuming that the source fills all three Herschel beams:

$N(O_2)$ = 6.8(+0.7 -1.0) x 10^{16} cm^{-2} (statistical + kinetic temperature uncertainties)

Possible Explanations for O_2 Seen in Orion H_2 Peak 1

- **Heated Dust:**

desorb water ice mantles -> regain “standard” gas-phase large $X(O_2)$

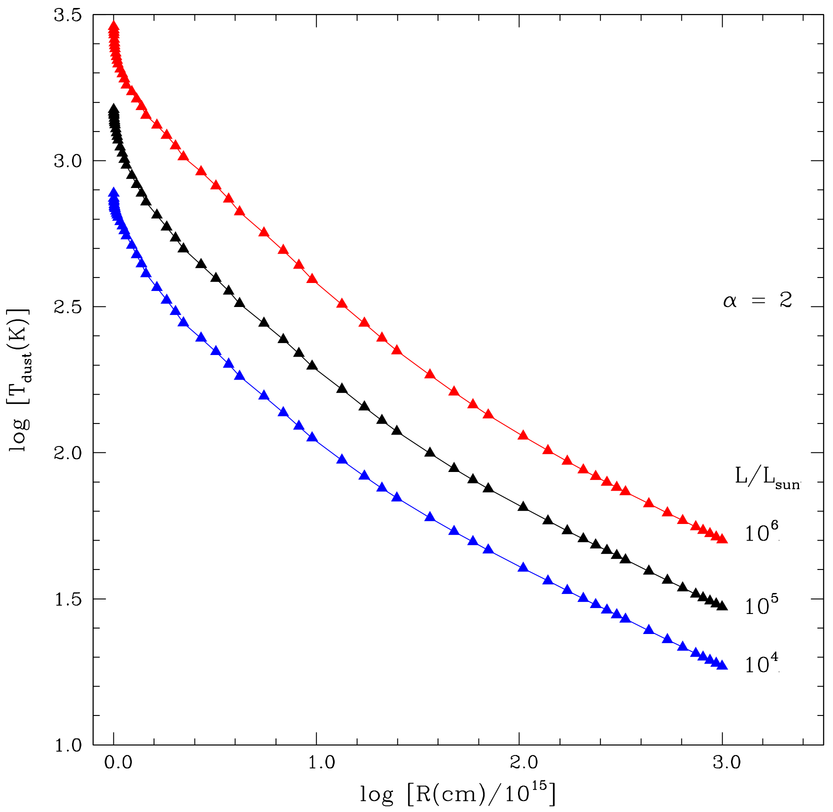
- **Shocks:**

enhance reaction rate of $OH + O \rightarrow O_2 + H$

(see poster by M. Kaufman)

Warm Dust Surrounding Embedded Source ⇒ Large Gas Phase $X(O_2)$

- O_2 binding weak compared to that of H_2O (Acharyya et al. 2007) O_2 on grains likely to be converted to H_2O (Ioppolo et al. 2008; Miyauchi et al. 2008)
- Atomic O will start desorbing for $T_d > 25$ K (Hasegawa & Herbst 1993)
- When $T_d \geq 100$ K, H_2O will start desorbing (Fraser et al. 2001)
- With gas phase H_2O present, "normal" gas-phase chemistry will reassert itself in few x 10^5 yr

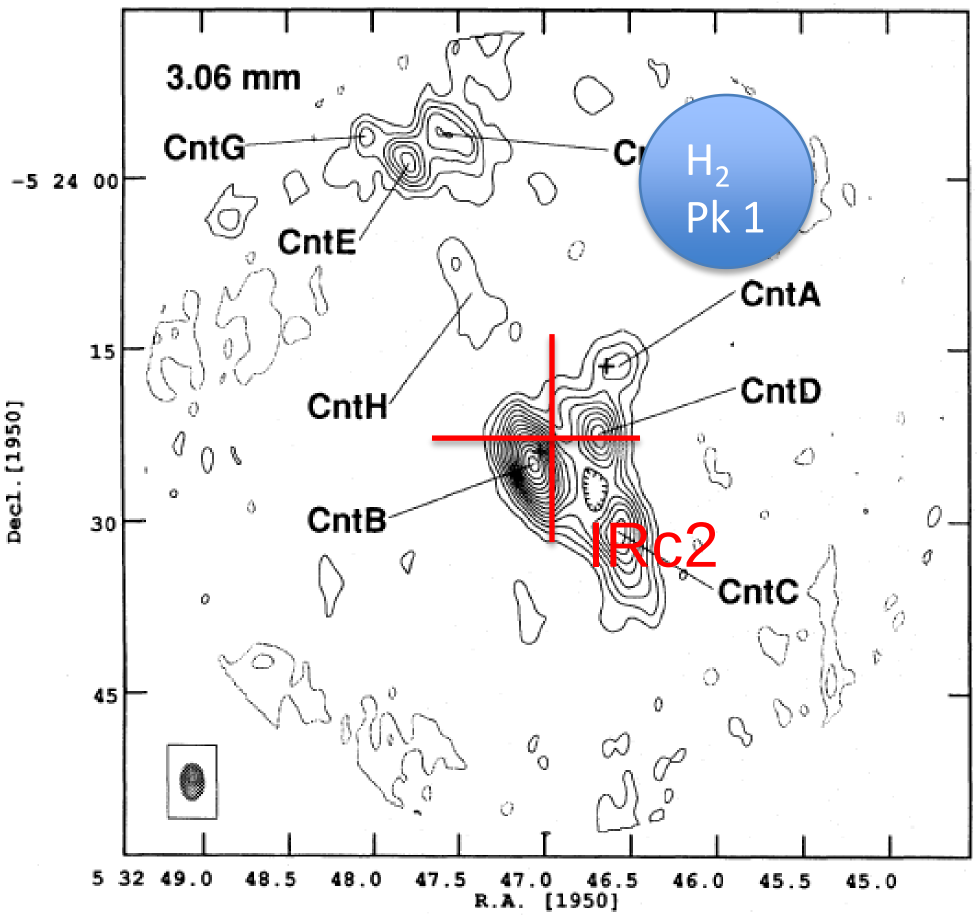


DUSTY code(Nenkova, Elitzur)

Where is the Source?

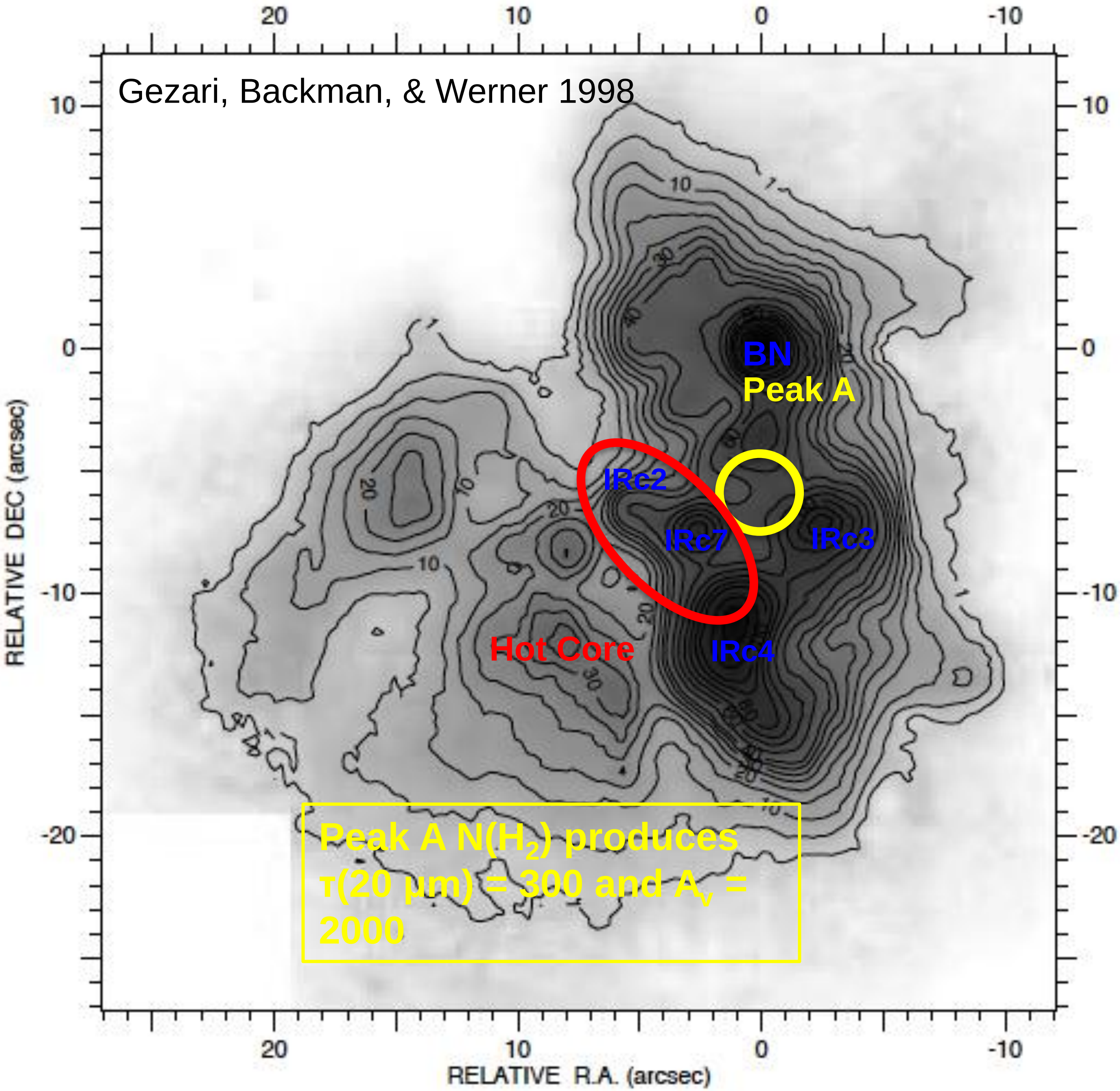
Dust Emission from 3mm Continuum (Murata et al. 1992)

IRc2 (1950)
α = 5h32m47s
δ = -5°24’23’’



Cnt D source is coincident with Peak A, Western Clump, and MF4

This is only source with narrow lines & molecular emission in range 10 < v < 12 km/s



20 μm image
(0,0) = BN

BN (1950)
α = $5^h32^m46.6^s$
δ = - $5^o24'16.5''$

IRc2 has only ~ 1000 L_{sun}

Total region has ~ 10^5 L_{sun}

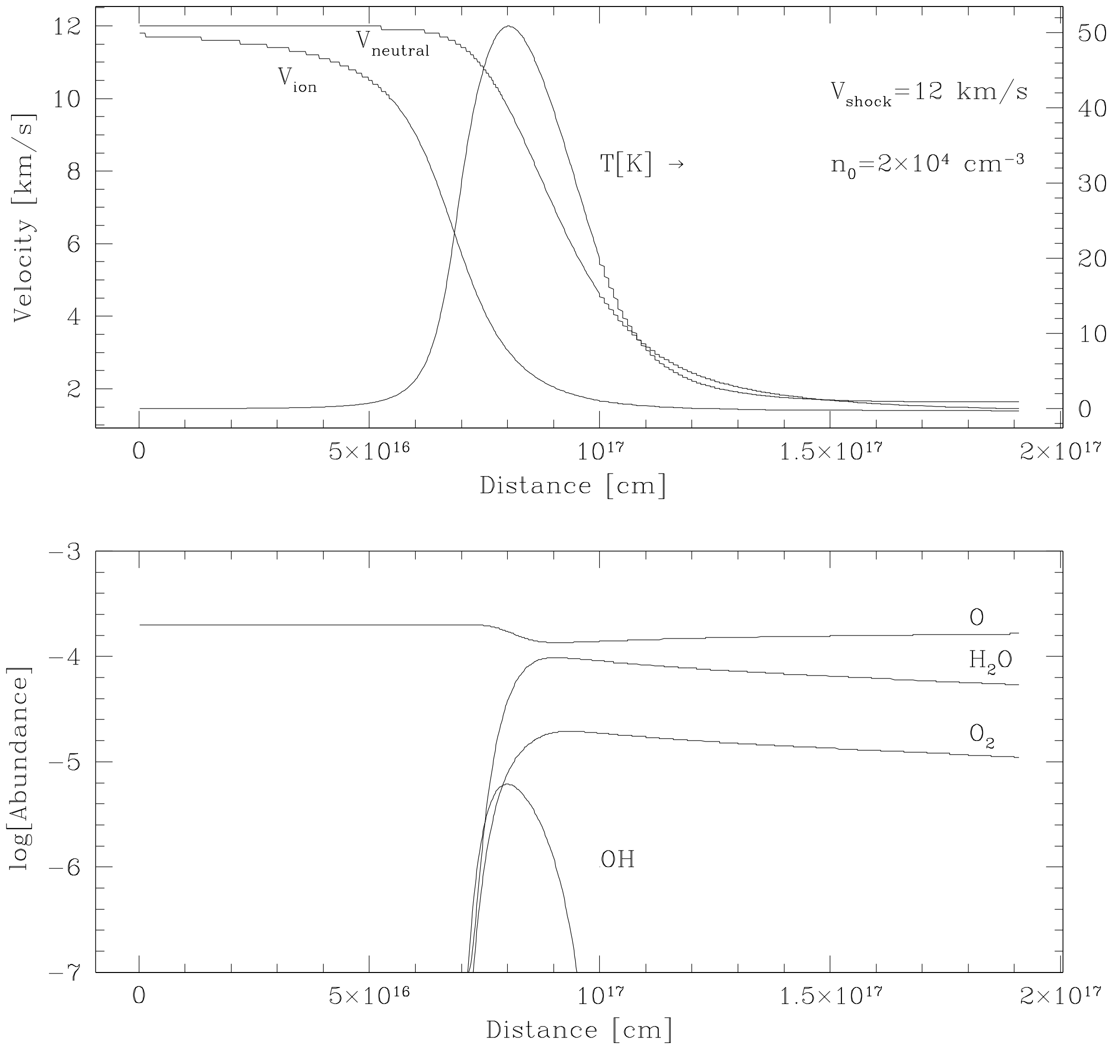
Compact Source with Warmed Gains Restoring Pure Gas-Phase O_2 Chemistry

- Almost all species having emission in 10 - 12 km s^{-1} range have local maximum at Peak A/Western Clump/MF4/Cnt D location
- Semi-detailed modeling of effects of source dilution and offset suggest that relative intensities of O_2 lines can be fit, but now with $T_{kin} \geq 150$ K.
- Column Density of O_2 is 1.3×10^{19} cm^{-2} assuming ~5" source size. H_2 column density is tricky to determine, but scaling from $C^{17}O$ we find $N(H_2) = 2.3 \times 10^{24}$ cm^{-2}. This agrees very well with the column density obtained from dust emission by Murata et al. (1992), $N(H_2) = 5 \times 10^{24}$ cm^{-2}.
- Resulting fractional abundance of molecular oxygen is $X(O_2) = 6.6 \times 10^{-6}$, which is straightforward to produce in warmed grain model.

Predictions and Tests

- Observe Ori KL (OT-1 observations pending)
- There should be large column density of OI as well, which should be detectable, but very difficult to disentangle e.g. from PDR emission.

Low-velocity Shocks are Effective at Producing O_2



V > 10 km/s gives sufficient heating to allow rapid

$O + H_2$ -> $OH + O$

Followed by

$OH + O$ -> $O_2 + H$

V > 15 km/s produces high enough T to allow back reaction $O_2 + H$ -> $OH + H$ ~exp-(8750/T)

$N(O_2)$ can be as high as 10^{17} cm^{-2}

(from M. Kaufman)

Pros and Cons of Shock Model for O_2 Abundance Enhancement

- Shock model can produce up to 10^{17} cm^{-2} of O_2 with V_{shock} = 10 – 15 km s^{-1}.
- O_2 velocity agrees with that of H_2O masers in the vicinity
- Need to get substantial O in gas BEFORE the shock. This could come from higher-velocity J-type shocks in vicinity as indicated by H_2 emission, by sputtering, or by UV from PDR surface
- Line profile is a question, as one would expect velocity shifts (could be avoided if shock in plane of the sky) and line broadening.

Conclusions

- With limited data available, mostly in lowest frequency transition, most sources show no detectable O_2 emission with Herschel HIFI.
- The broad-brush interpretation is that in regions of modest temperature, the O_2 abundance is extremely low, with limits between few x10^{-9} and few x10^{-8}.
- O_2 in ρ Oph has been confirmed and in Sgr A (50 km/s) detected.
- These results confirm and extend SWAS and Odin results: O_2 is not a significant coolant or major contributor to Unidentified Depleted Oxygen (UDO).
- We have statistically significant detections of three O_2 transitions in Orion. Modeling in terms of of shocks and warm dust chemistry is encouraging, but not yet fully satisfactory. HOP team inclined to favor warmed dust model with O_2 emission concentrated in Peak A - Western Clump – MF4 - Cnt D condensation
- Complete HOP data set will provide important tests of various aspects of astrochemistry and models of cloud and protostar evolution.

Now we know where all the oxygen has been hidden!

Thanks to B. Larsson