The Herschel Oxygen Project

Jo-Hsin Chen (Jet Propulsion Laboratory)
for the HOP team

Nealfest/ April 26 2013

The HOP Team:

Paul Goldsmith (NASA JPL), U.S. PI; René Liseau (Chalmers Univ.), European PI

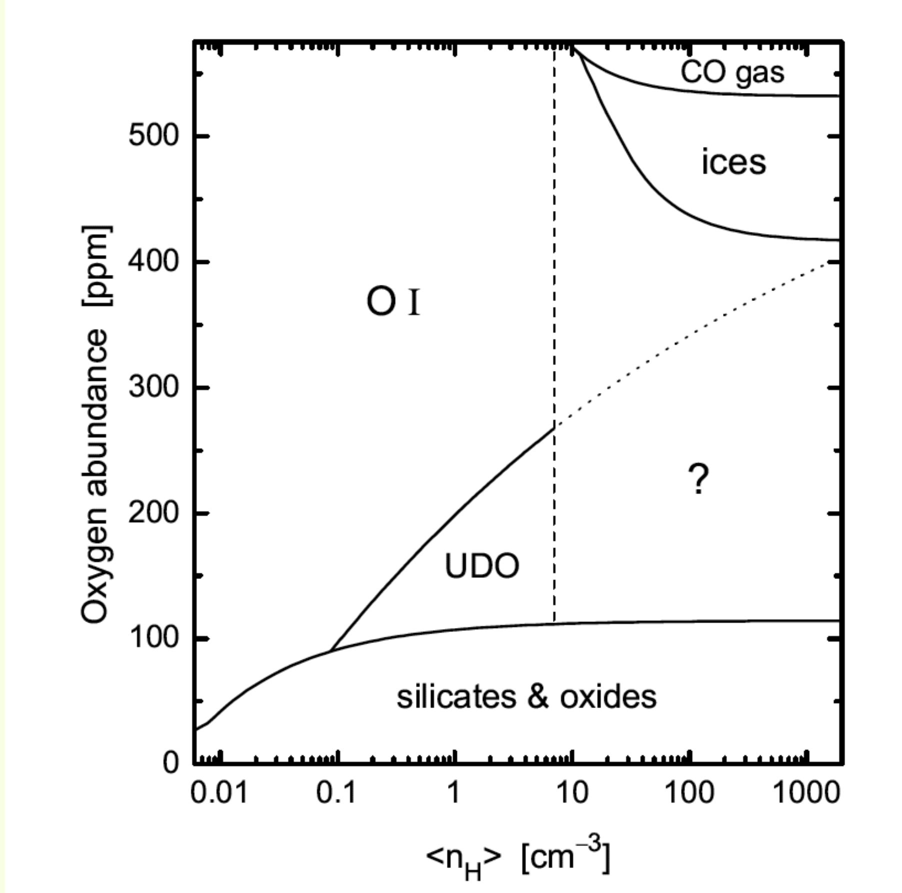
Tom Bell	*Astrobiology Inst. Madrid*
Arnold Benz	*ETH, Zurich*
Edwin Bergin	*Univ. Michigan*
John Black	*Chalmers Univ.*
Simon Bruderer	*ETH, Zurich*
Paola Caselli	*Univ. Leeds*
Emmanuel Caux	*CESR Toulouse*
Jo-Hsin Chen	*NASA JPL*
Pierre Encrenaz	*Univ. Paris*
Edith Falgarone	*CNRS, Paris*
Maryvonne Gerin	*CNRS, Paris*
Javier Goicoechea	*Obs. Paris*
Ake Hjalmarson	*Onsala Space Obs.*
David Hollenbach	*NASA Ames*
Michael Kaufman	*San Jose State Univ.*
Bengt Larsson	*Stockholm Obs.*
Jacques Le Bourlot	*Univ. Paris*
Franck Le Petit	*Obs. Paris*
Di Li	*Caltech*
Darek Lis	*Caltech*
Gary Melnick	*Center for Astrophys.*
Zsofia Nagy	*SRON, Groningen*
David Neufeld	*Johns Hopkins Univ.*
Henrik Olofsson	*Obs. Paris*
Laurent Pagani	*CNRS, Paris*
Evelyne Roueff	*Obs. Paris*
Aage Sandqvist	*Stockholm Univ.*
Ronald Snell	*Univ. Massachusetts*
Floris van der Tak	*SRON, Groningen*
Ewine van Dishoeck	*Leiden Univ.*
Charlotte Vastel	*CESR, Toulouse*
Serena Viti	*Univ. College London*
Umit Yildiz	*Leiden Observatory*

HOP: A Herschel Open Time Key Program

- Deep observations of O_2 in molecular clouds
- HIFI spectroscopy at 487, 774, and 1121 GHz
- 140 hrs + follow up

Where is oxygen in the dense ISM?

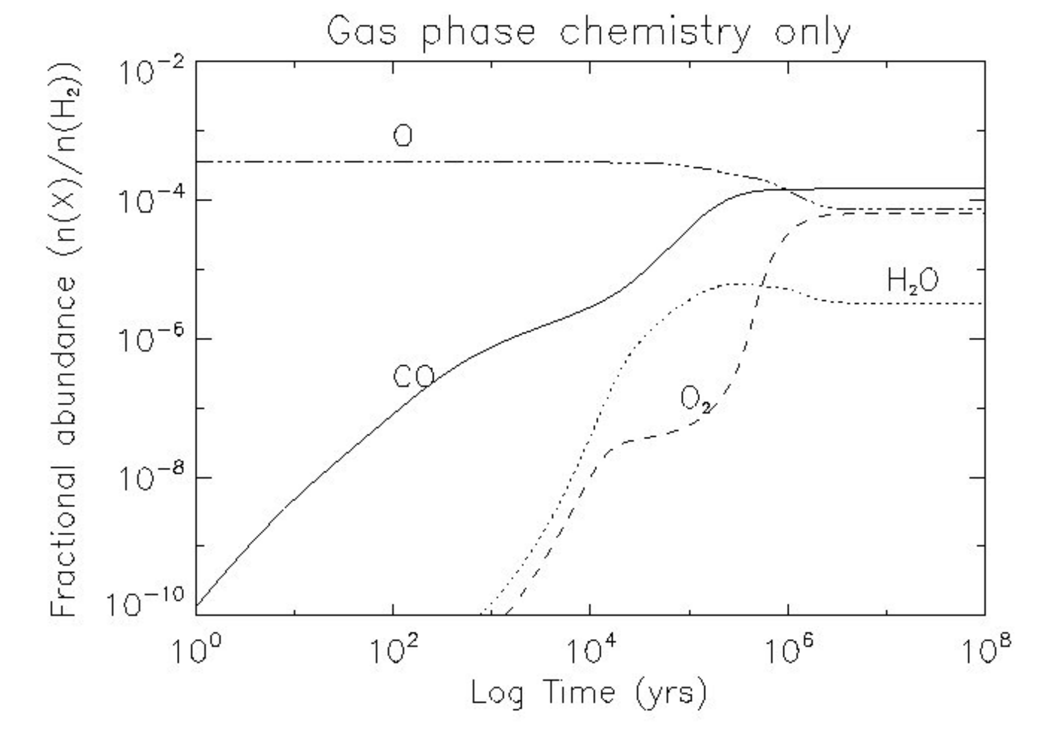
- The 3rd most abundant element
- In dense clouds, the observed values and limits of O-bearing species appear to be insufficient
  - Could O_2 contribute to the Unidentified Depleted Oxygen (UDO)?



Whittet 2010
The total range is set to the adopted reference abundance of 575 ppm for interstellar oxygen (Przybilla et al. 2008)

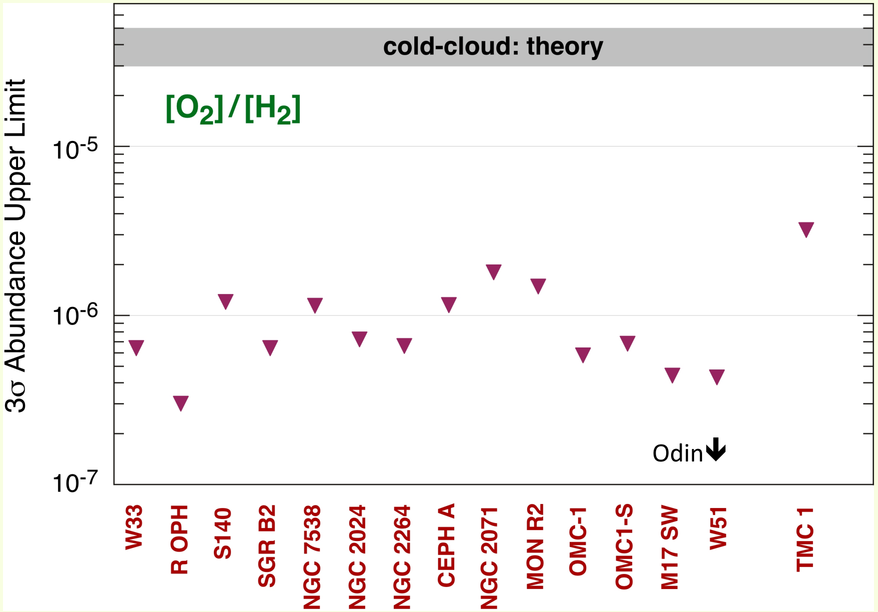
O_2 as a probe of oxygen

- O_2 is a simple molecule, and the gas-phase chemistry is thought to be well-known
- Standard gas-phase chemistry models predict high abundance $\geq 10^{-5}$ (e.g. Graedel et al 1982)



Time dependent evolution of a gas phase chemistry model: $n(H_2) = 10^4$ cm^{-3}, T = 10 K, and A_v = 10 mag (K. Willacy)

X(O_2) from SWAS & Odin observations is ≥ 100x below prediction



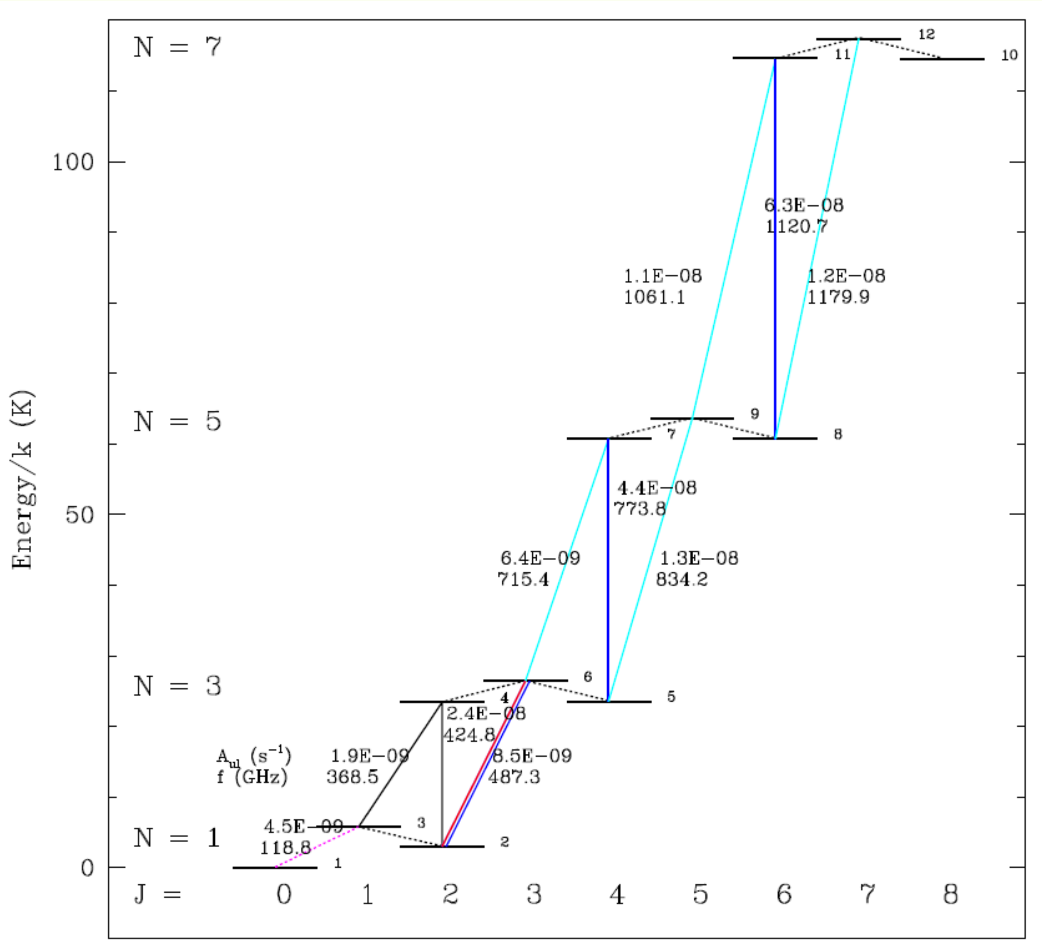
- SWAS
  - 3.'5 x 5' beam at 487 GHz
  - Upper limits of X(O_2) ~ 10^{-7} (Goldsmith et al. 2000)
- Odin
  - 9' beam at 119 GHz
  - Upper limits of X(O_2) ≤ 10^{-7} for half of the sources (Pagani et al. 2003)
  - Detection towards ρ Oph A with X(O_2) ~ 5 x 10^{-8} (Larsson et al. 2007)

- Favored explanation: O atoms stick onto grains followed by the formation of H_2O ice (e.g. Bergin et al. 2001)
  - The ice would not evaporate unless T > 110-120 K (Fraser et al. 2001)

HOP source selection

- Embedded sources
  - Central heating from the protostar
  - Low mass: ρ Oph A, NGC 1333 IRAS 4A
  - High mass: NGC 6334I, Sgr A (50 km/s), Sgr B2 (S)
- PDRs
  - Photodesorption and photodissociation of H_2O (Hollenbach et al. 2008)
  - Orion Bar
- XDRs
  - OH + O from photo-dissociated CO (e.g. Stauber et al. 2005)
  - AFGL 2891
- Shock heated sources
  - O_2 produced from H_2O desorption in shocks
  - Orion H_2 Peak 1
- Good tests of our understanding chemical processes in different environments

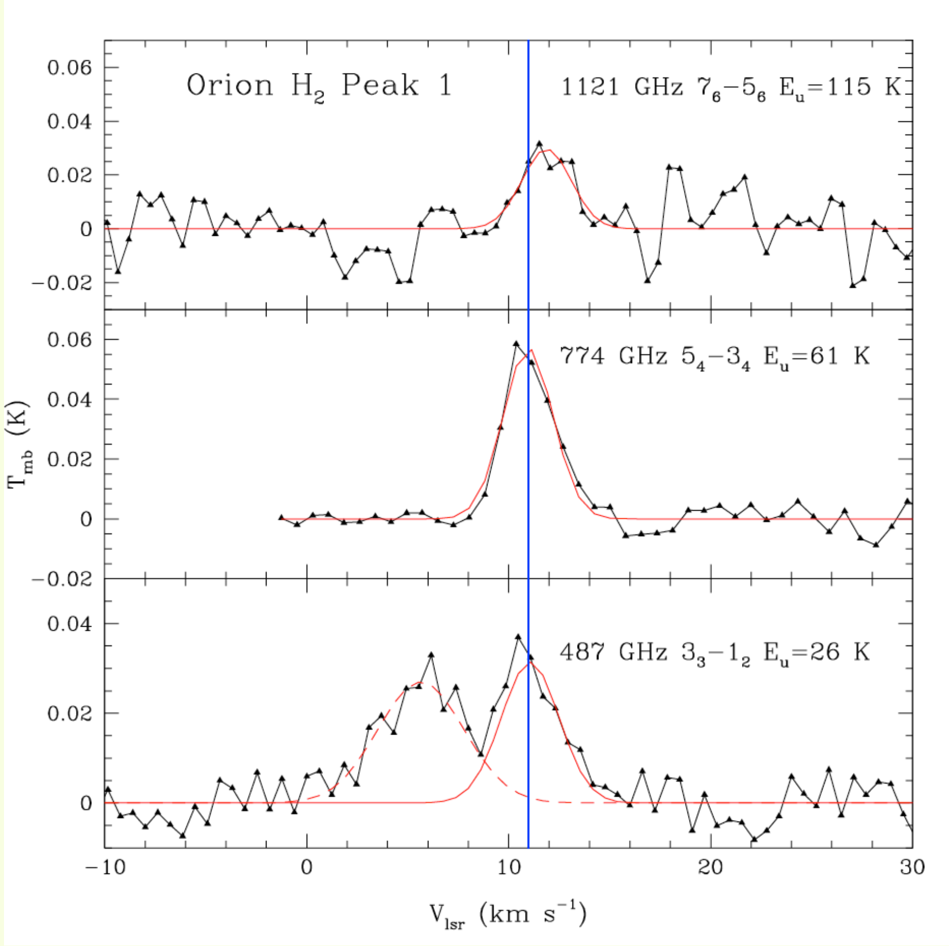
Lower Rotational Levels and Transitions of O_2

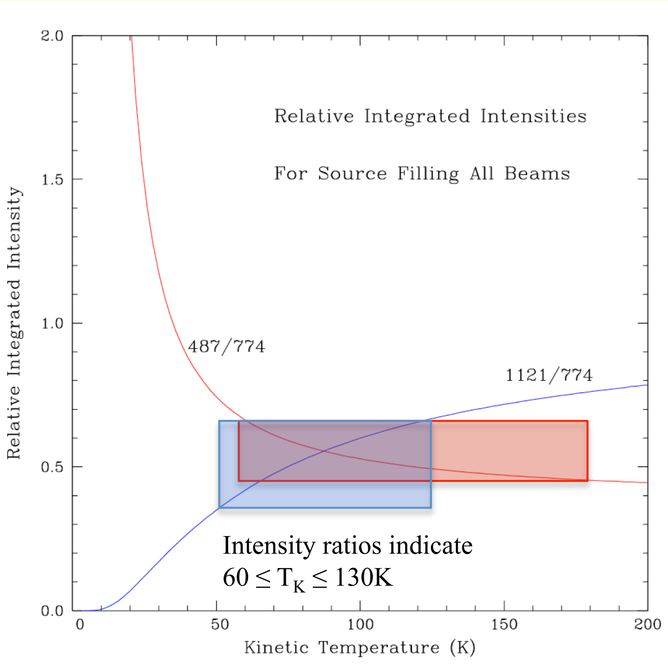


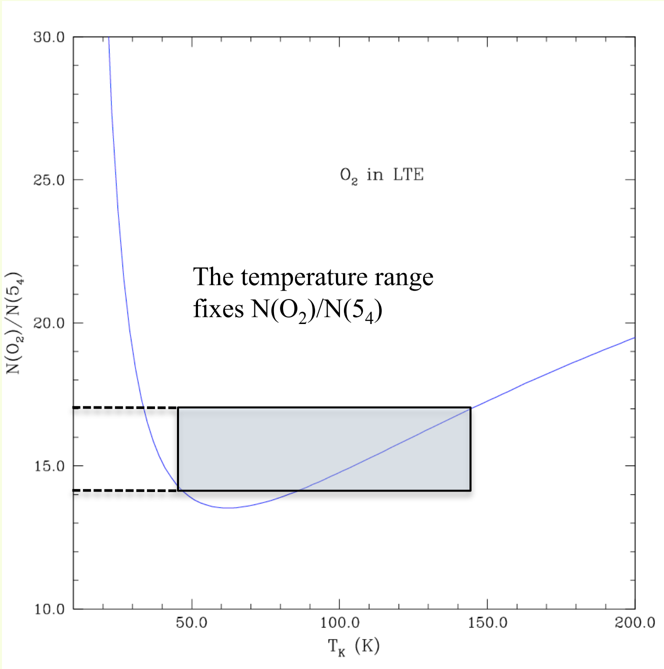
- The rotational levels are connected by weak magnetic dipole transitions
- Observed by SWAS ______
- Observed by Odin ……….
- Observable with Herschel ______
- Most favorable transitions for Herschel ______
- Herschel
  - 44” beam at 487 GHz
  - Great sensitivity

Detection: Orion H_2 Peak 1 (Goldsmith et al. 2011)

- First multi-transition detection of O_2 in the ISM!
- Chemically poor comparing with the hot core
- 8 hrs integration
- 3 transitions observed consistent with v_{lsr} = 11 km s^{-1} and δv = 2.9 km s^{-1}
  - Orion Hot Core: 5-6 km s^{-1}
  - The Compact Ridge (including KL): 8-10 km s^{-1}







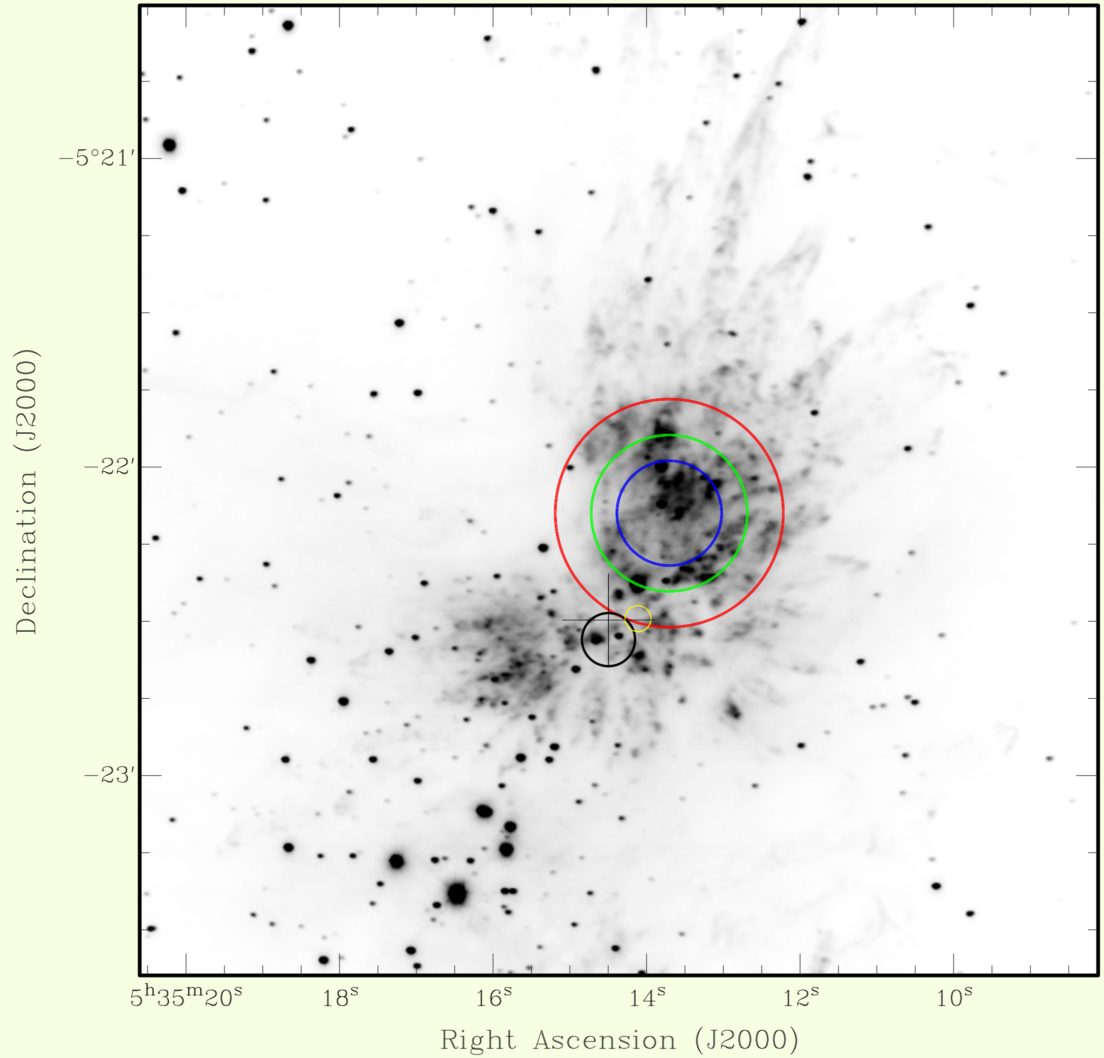
- Assuming the emission fills the beam, the lines are opt thin and produced in LTE, the beam averaged column density is $N(O_2) = 6.5 \times 10^{16}\ cm^{-2}$, $X(O_2) = (0.3\text{-}7.3) \times 10^{-6}$

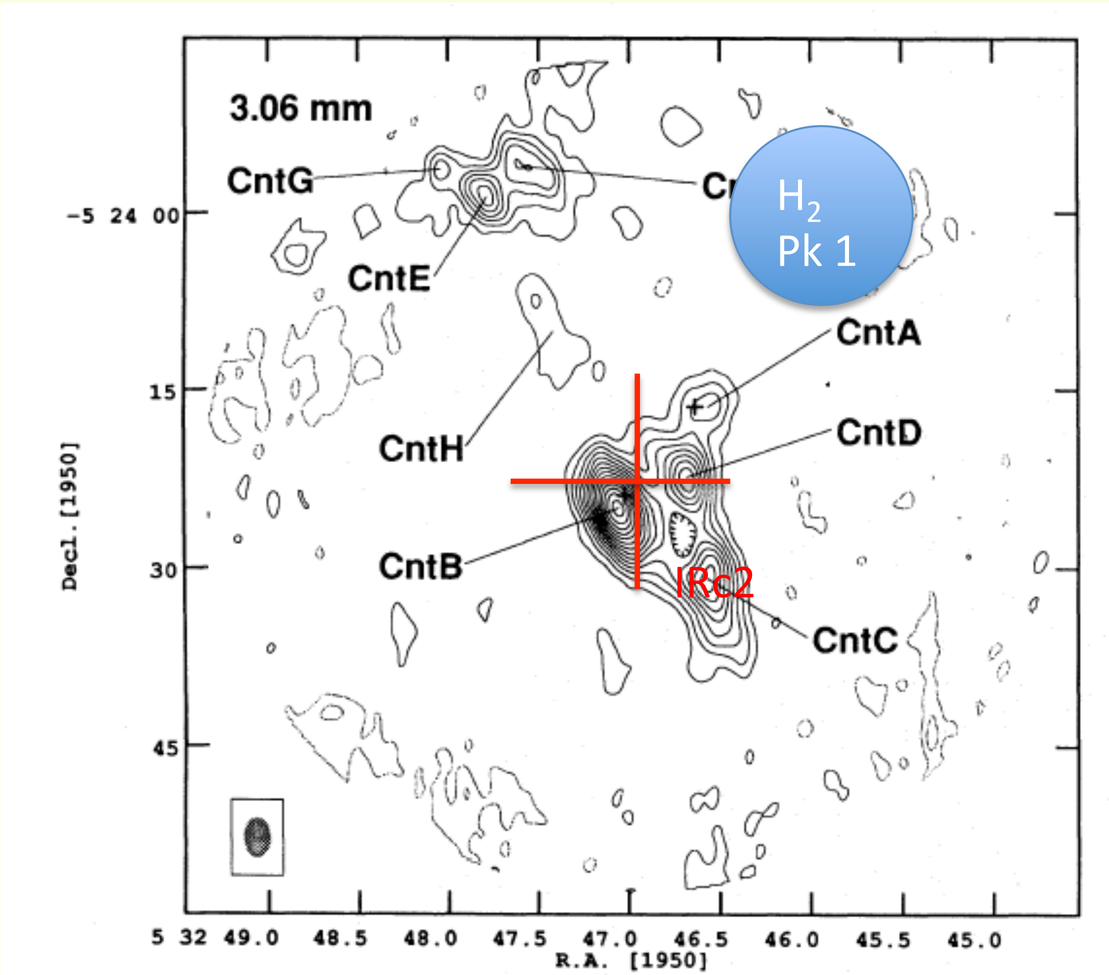
Possible explanations:

- Heated Dust- desorb water ice mantles; initially, there is spike in gas-phase $X(H_2O)$, but after ~10^4 years we regain “standard” gas-phase chemistry with large $X(O_2)$
- Shocks- enhance reaction rate of $OH + O \rightarrow O_2 + H$

Where is the emitting source?

- H_2 v=1-0 2 μm Emission from Bally et al. (2011)
- Herschel Beam size: 487 GHz 44", 774 GHz 30", and 1121 GHz 20"
- Black circle: hot core (5-6 km/s)
- Yellow circle: Peak A/ Western clump
  - NH_3, HDO, HC3N, NO
  - 10-11.4 km/s
- Black cross: IRc2

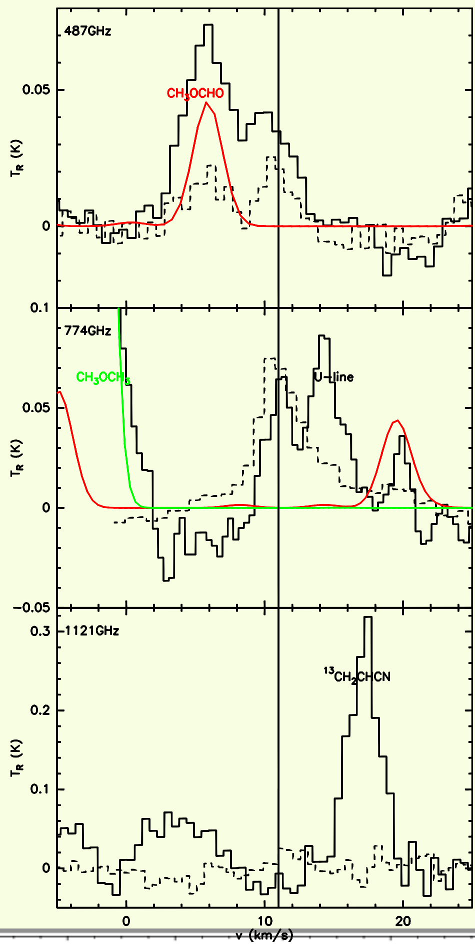




- 3mm Continuum (Murata et al. 1992)
- Cnt D source is coincident with Peak A, Western Clump, and MF4

- **Where and how is the O_2 produced?**
  - ✧ **OT1 and CARMA follow up toward Peak A**
  - ✧ **Could help distinguish models**

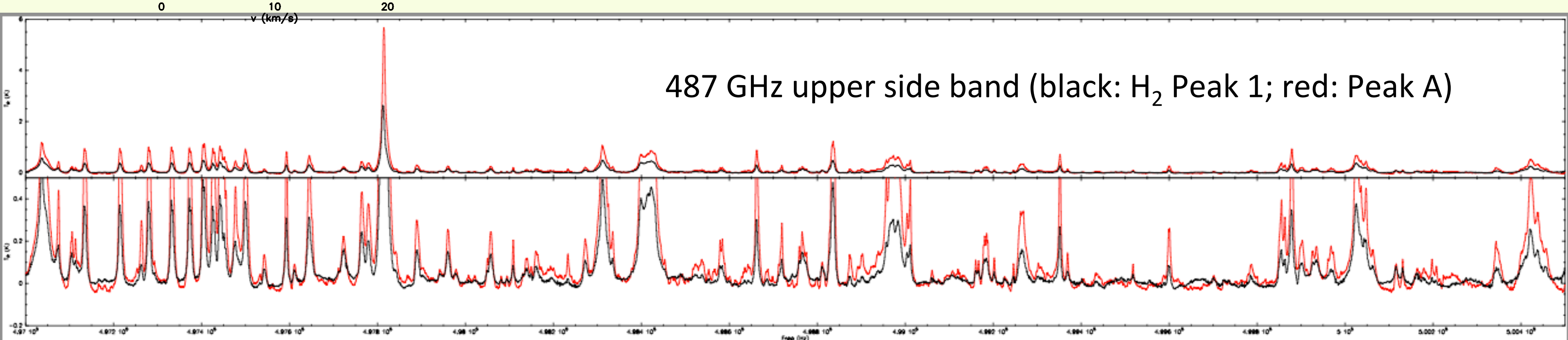
11 km/s



OT1 Results

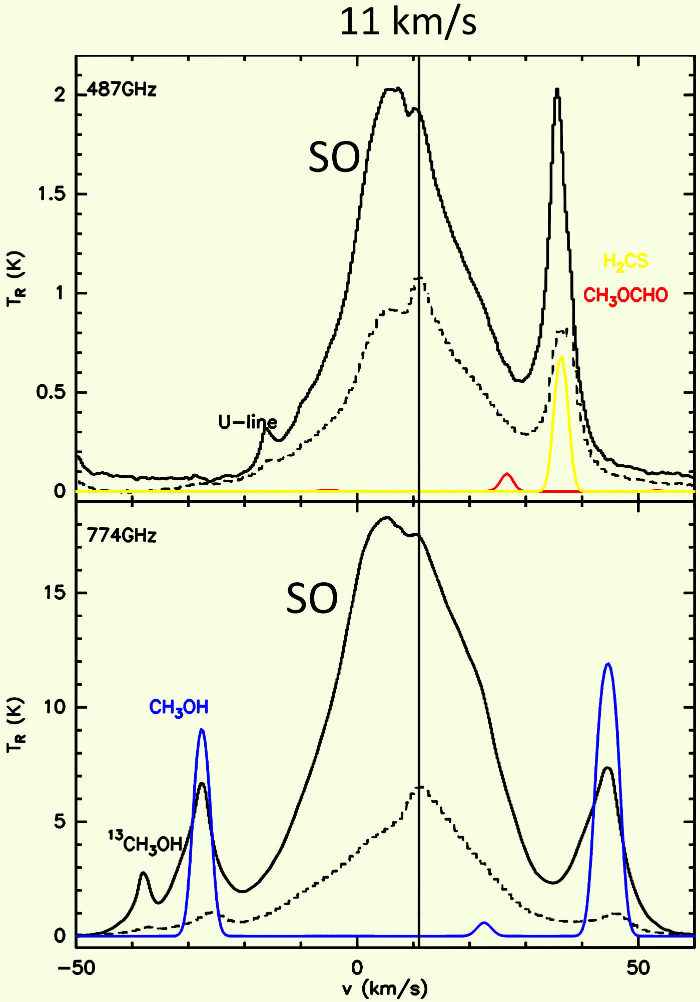
- 10-11 km/s lines detected at 487 GHz and 774 GHz with line width 3-4 km/s toward Peak A
- No detection at 1121 GHz toward Peak A
- At 487 GHz, line intensities toward H_2 Peak 1 and toward Peak A are comparable. At 774 GHz, the line is ~1.4 times stronger toward H_2 Peak 1
- The 6 km/s feature appears to be methyl formate.

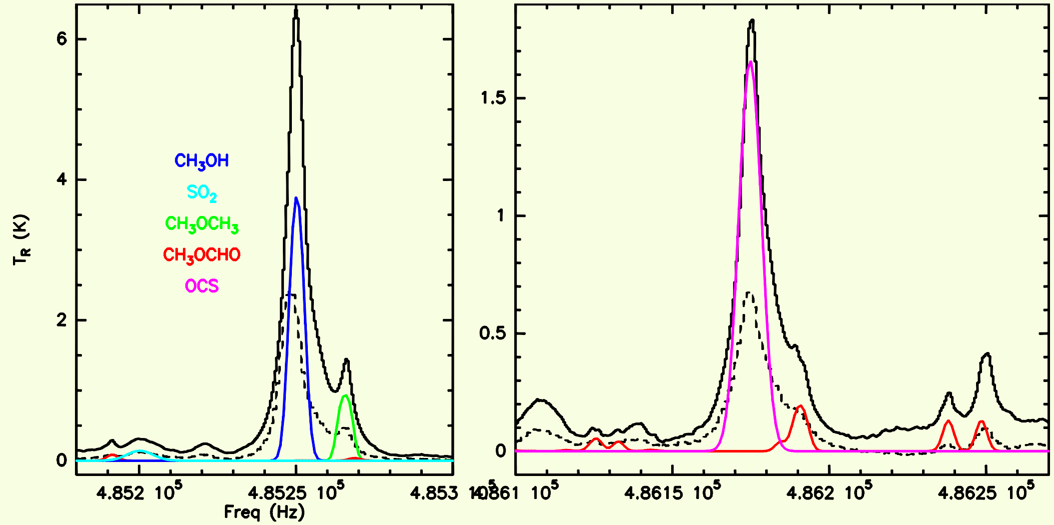
Solid: Peak A
Dashed: H_2 Peak 1 (Goldsmith et al. 2011)
Color: LTE models



487 GHz upper side band (black: H_2 Peak 1; red: Peak A)

Line Identification

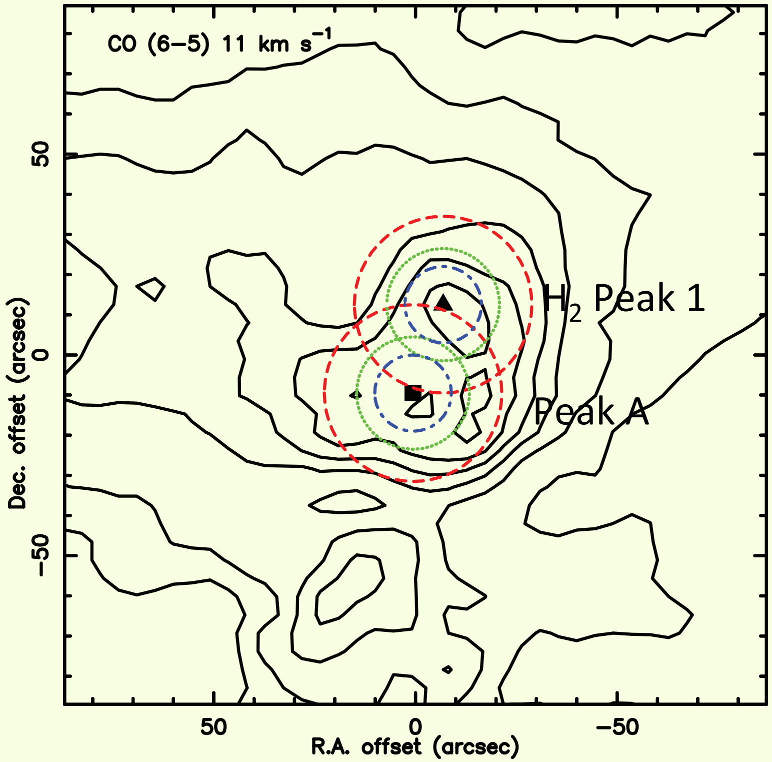




Solid: Peak A
Dashed: H_2 Peak 1 (Goldsmith et al. 2011)
Color: LTE models

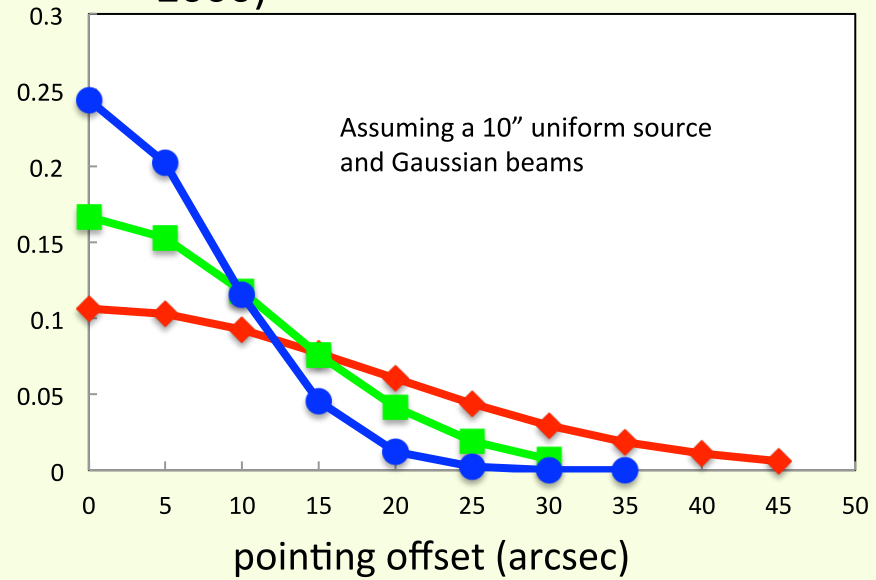
- Deep integration in Orion- lots of lines!
- LTE modeling with XCLASS (e.g. Comito et al. 2005) with JPL and CDMS catalog
- Identified species: CH_3OH, C_2H_5OH, CH_3OCH_3, CH_3OCHO, HNCO, $C_{17}O$, H_2CO, SO, SO_2, H_2CCO, NS, OCS, H_2CS
- Most species show emission at 7-8 km/s
  - ✧ SO has a 11 km/s feature toward H_2 Peak 1
  - ✧ CH_3OH

Where is the emitting source?



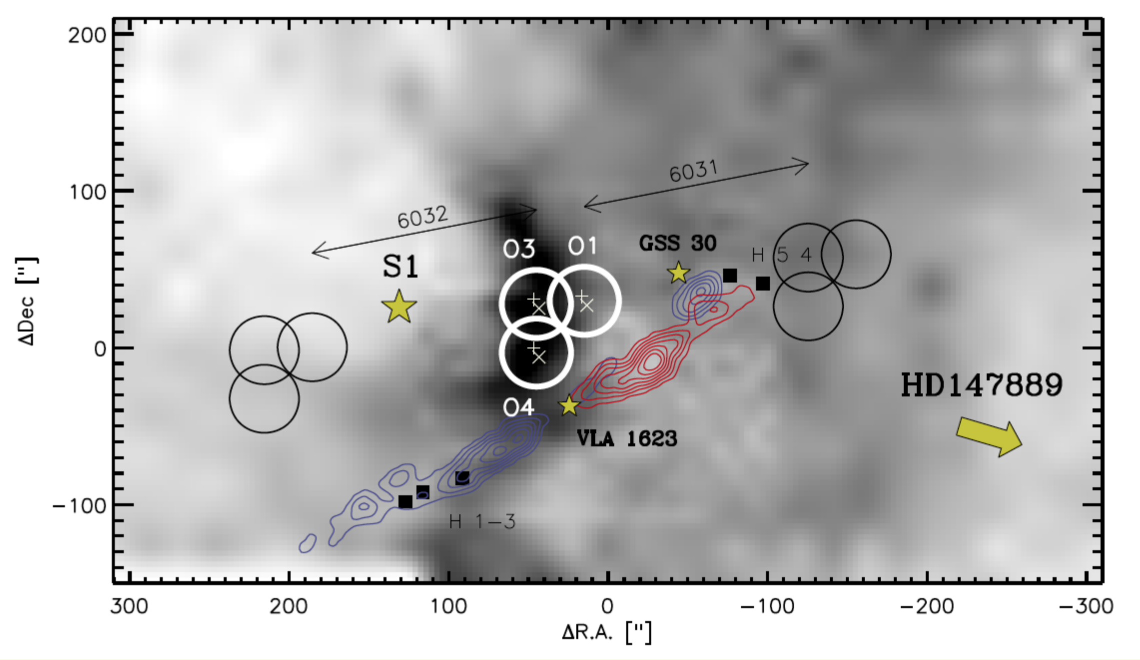
CO (6-5) map (Peng et al. 2012)
487 GHz (44”) 774 GHz (28”) 1121 GHz (19”)

- The O_2 emission is not from Peak A
- Favored explanation: low velocity shocks (~10 km/s, T_{max} ~ 400 K) (M. Kauffman)
  - Sulfur chemistry
  - CH_3OH could be enhanced (Garay 2000)

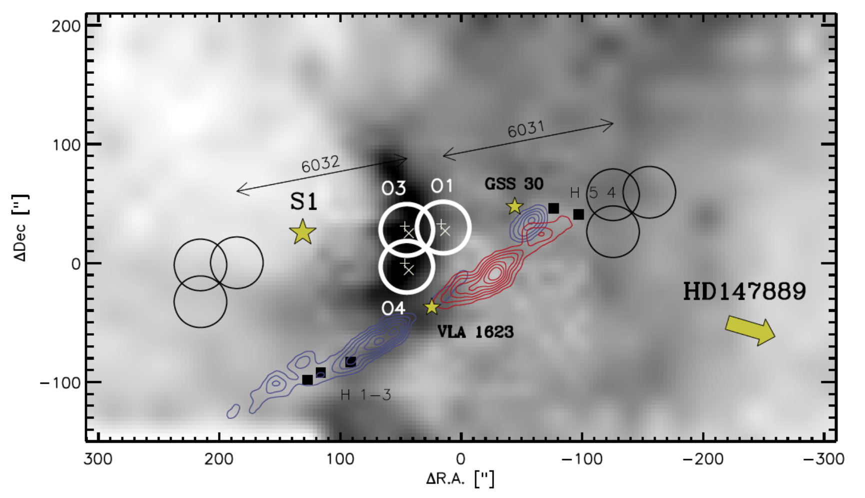


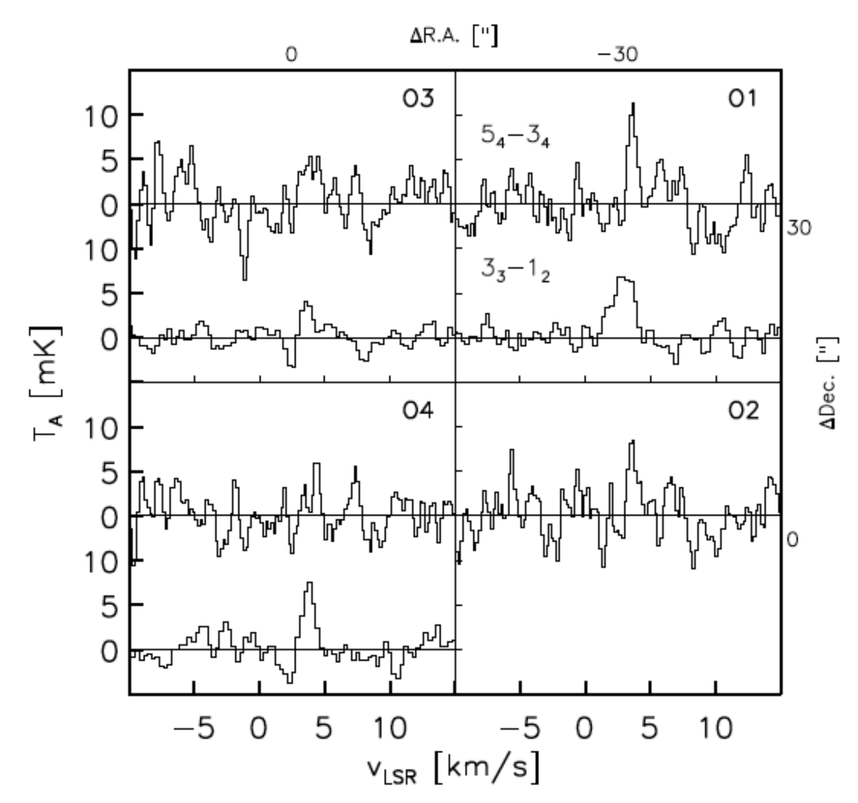
Detection: ρ Oph A (Liseau et al. 2012)

- Cold dense cores, A molecular outflow from a Class 0 protostar, and a PDR excited by nearby B-type stars
- O_2 detection at 119 GHz with Odin (Larsson et al. 2007)
- **Unique laboratory to test**
  - **UV-radiation controlled photochemistry**
  - **gas phase and grain surface reactions in dense cores**

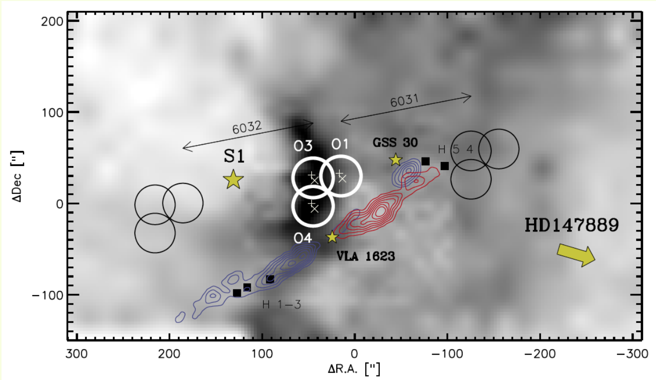


Grey: $C^{18}O$ (3-2)

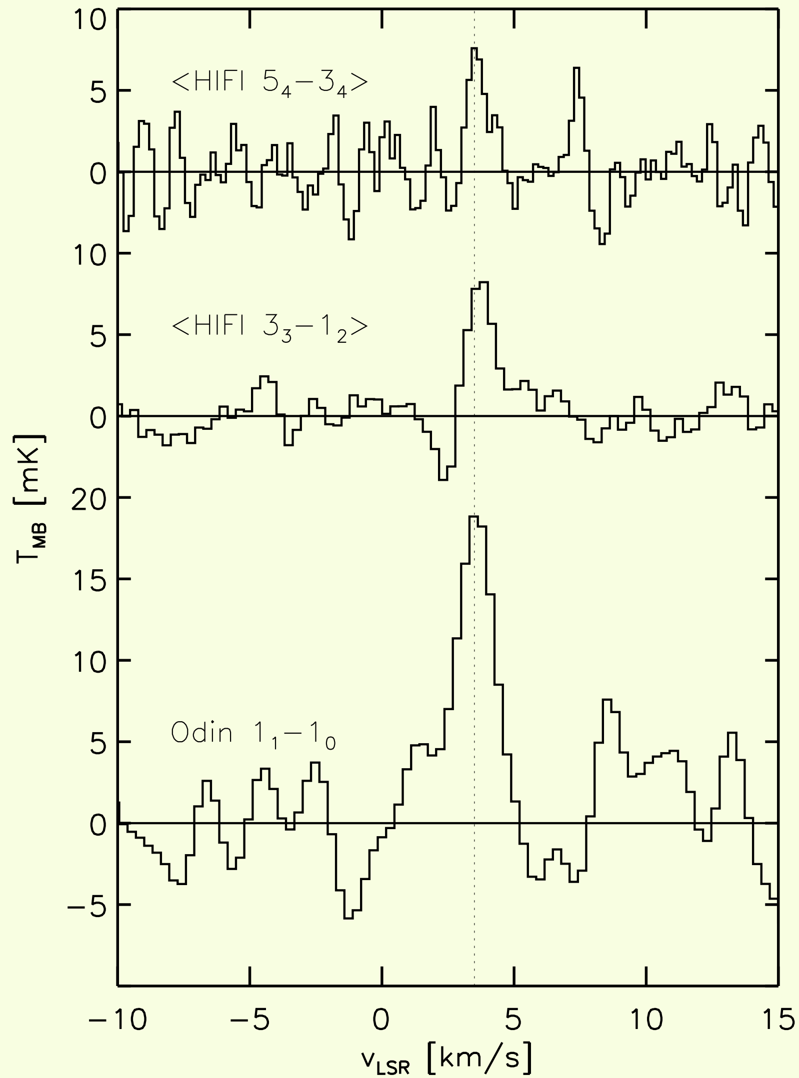




- Detection at both 487 and 774 GHz The strongest emission is seen toward O1
  - O1: the H_2O 557 GHz peak (Odin)
  - O4: the densest region
- Derived column densities
  - O1/O2: $N(O_2) = 5.5 \times 10^{15}$ cm^{-2}, $T > 50$ K
  - O3/O4 (densest regions): $N(O_2) = 6 \times 10^{15}$ cm^{-2}, $T < 30$ K
- $X(O_2) = 5 \times 10^{-8}$

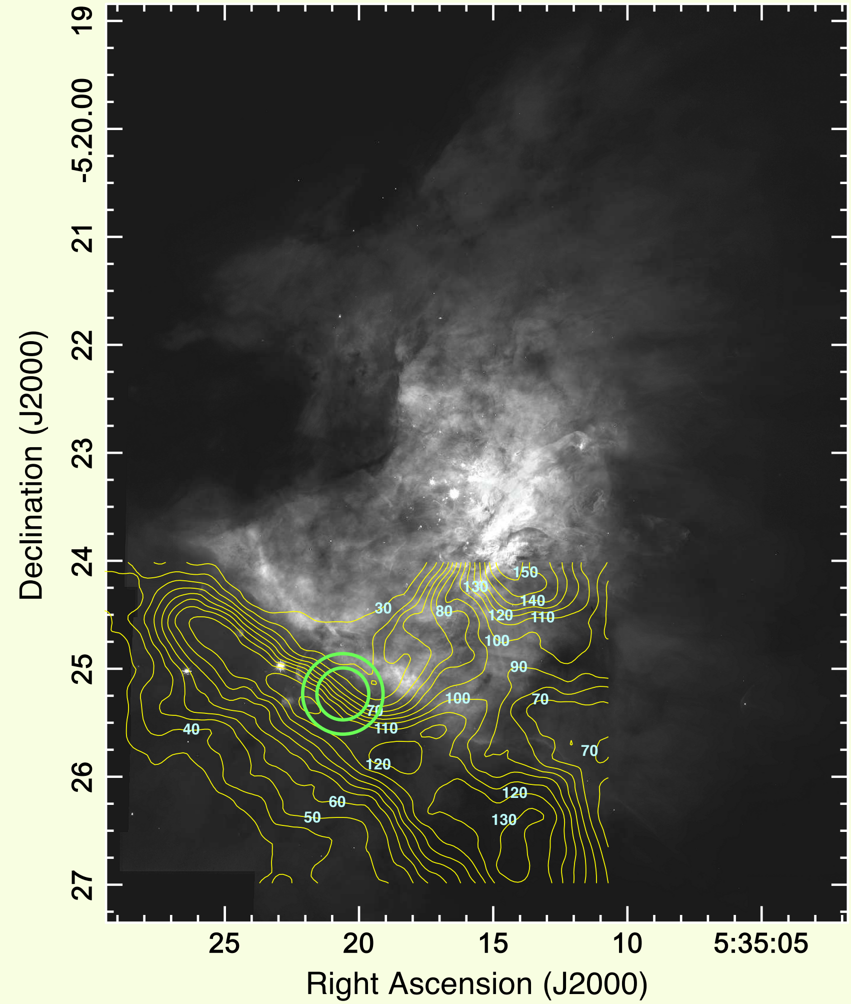


- Good agreement between the derived $X(O_2)$ with the Herschel data and the Odin 119 GHz line
- PDR model (Hollenbach et al. 2009)
  - two stellar sources with combined G_0 ~100
  - Good agreement between the observed and predicted $N(O_2)$; less convincing agreement for the temperature
- OT2 mapping



Non-detection: Orion Bar (Melnick et al. 2012)

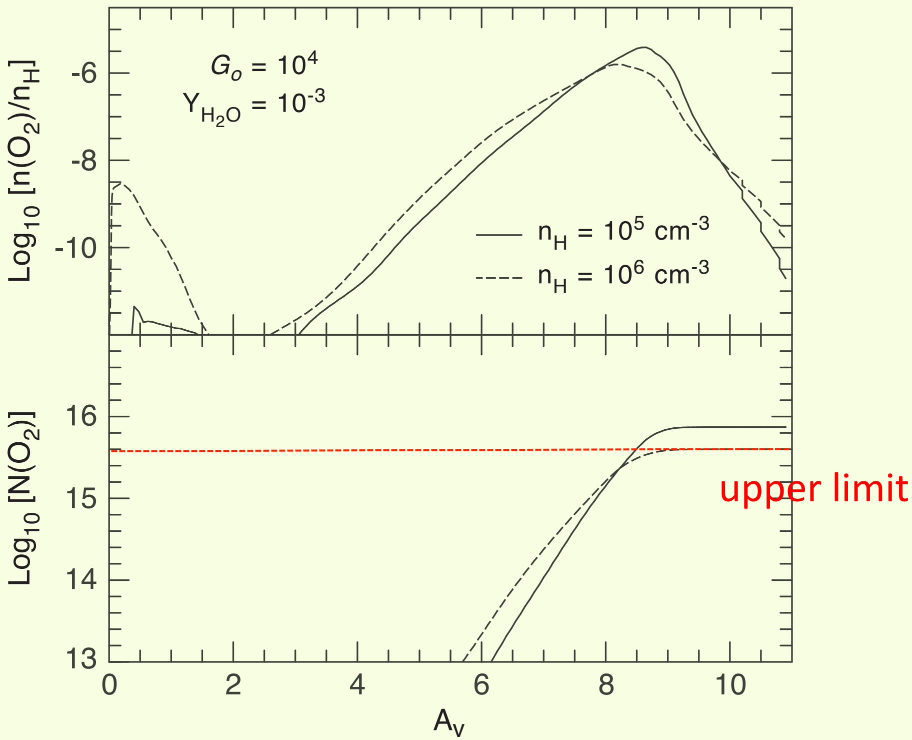
- Up to 12 hrs integration towards the surface layers of the FUV-illuminated Orion Bar
  – the thermal evaporation of O from the grain surfaces is enhanced
- Non-detection at both 487 and 774 GHz
- Upper limit $N(O_2)$ ~4 x 10^{15} cm^{-2} (face-on)



HST image (O'Dell & Wong 1996) with ^{13}CO 3-2 contours (Lis & Schilke 2003)

Test of current models for externally FUV-illuminated gas

- $X(O_2)$ is predicted to peak at intermediate depth of A_v (~8)
  - Some gas phase O is provided by FUV photodesorption of water ice
  - O_2 photodissociation is not extremely fast as the surface region
- The discrepancy between models and observations can be resolved if:
  - The adsorption energy of O > 800 K
  - The emission arises within small dense clumps
  - The total face-on depth within the bar correspond to Av ≤ 7
  - The density structure is different from model assumption



(Based on models from Hollenbach et al. 2009)

Summary

- We have detections of 3 O_2 transitions in Orion and 2 transitions in ρ Oph A
  - Favored explanation for Orion: low velocity shocks
- Most sources show no detectable O_2 emission
  - O_2 abundance is very low
  - O_2 is not a significant coolant or accounts for the unidentified depleted oxygen in dense clouds
- Complete HOP data set will provide sensitive limits to test important chemical processes during cloud and protostellar evolution