Molecular Oxygen in the ISM: An Astrochemical Dilemma

Herschel Oxygen Project "HOP"

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for the HOP Team
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The Universe as seen by Herschel
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Herschel Oxygen Project

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Why O_2 and Why Observe this Molecule at Submillimeter Wavelengths?

- **Astrophysical Importance** – O_2 is a simple molecule whose gas-phase chemistry is thought to be well understood

- **Large predicted abundance** - in relevant situations $X(O_2) = n(O_2)/n(H_2)$ should be as large as 3×10^{-5} making O_2 a major oxygen reservoir

- **Critical O_2 transitions** fall in the THz range

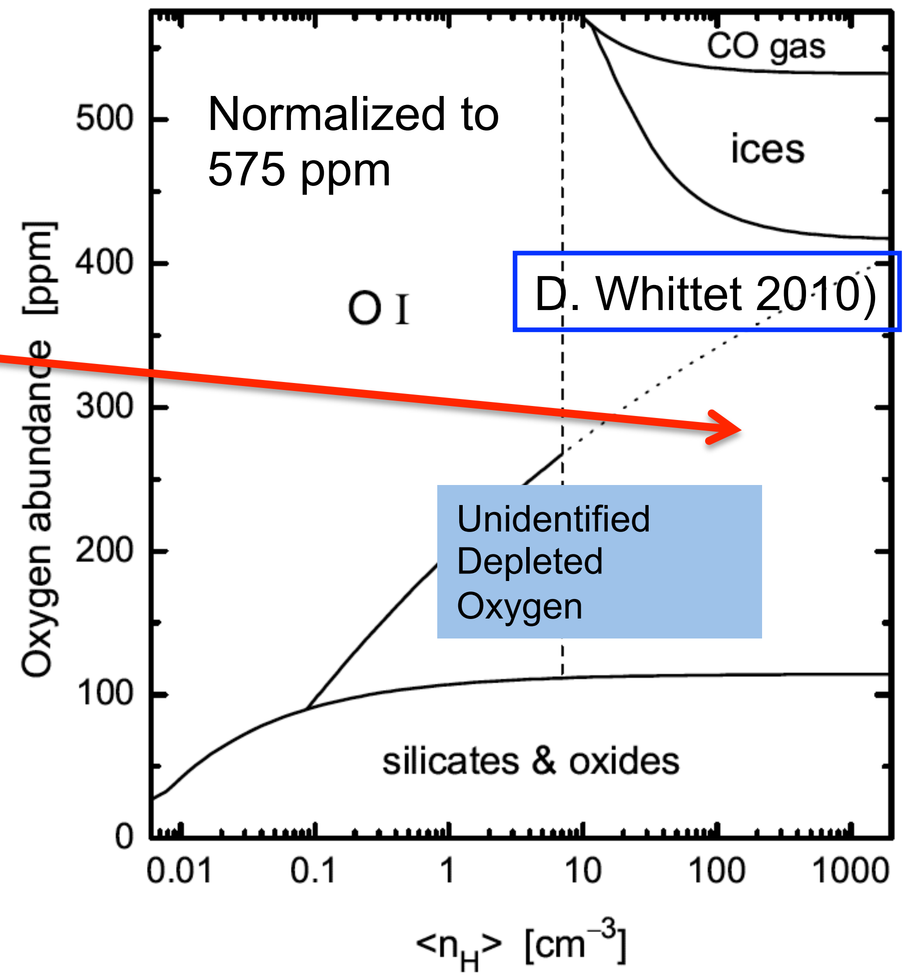
- **O_2 was a major objective** of SWAS and Odin satellites, which gave very surprising results. This has kept interest alive, with result that **O_2 is a target of Herschel projects (OTKP, OT1, OT2)**

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

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

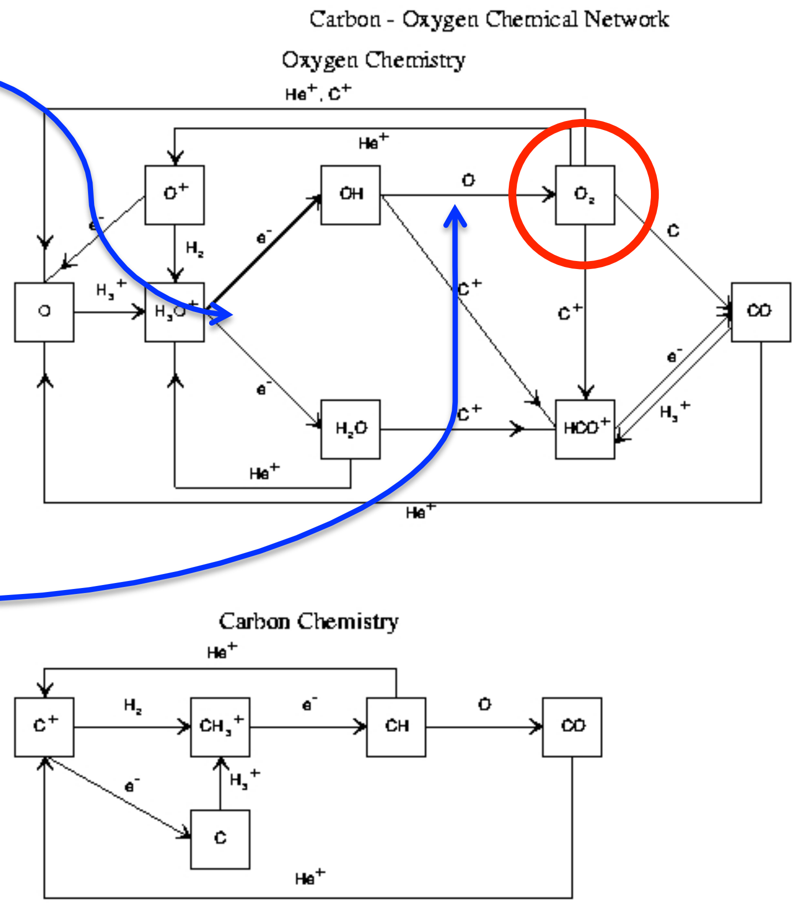
Caux et al. 1999;
Vastel et al. 2000:
Using ISO absorption measurements:
OI/CO = 10 – 50

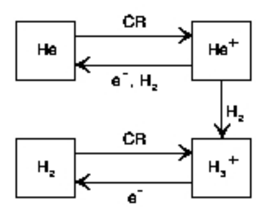
What kind of region are they observing?



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) $f(H_2O):f(OH) = 0.25:0.75$



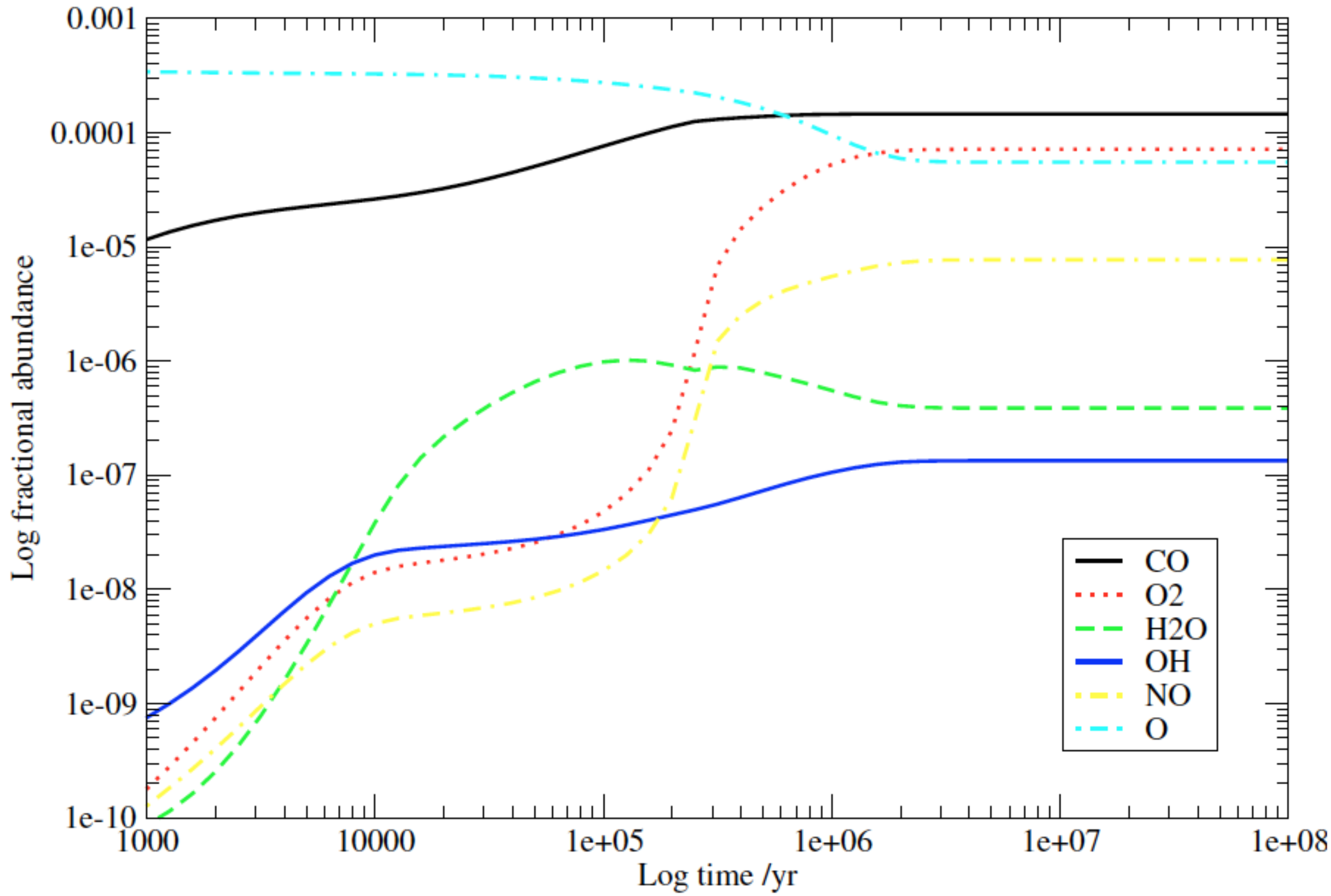


All key reaction rates have been measured in laboratory, both at room temperature & at temperatures of dense interstellar clouds

$OH + O \rightarrow O_2$ is an exothermic 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^3s^{-1}

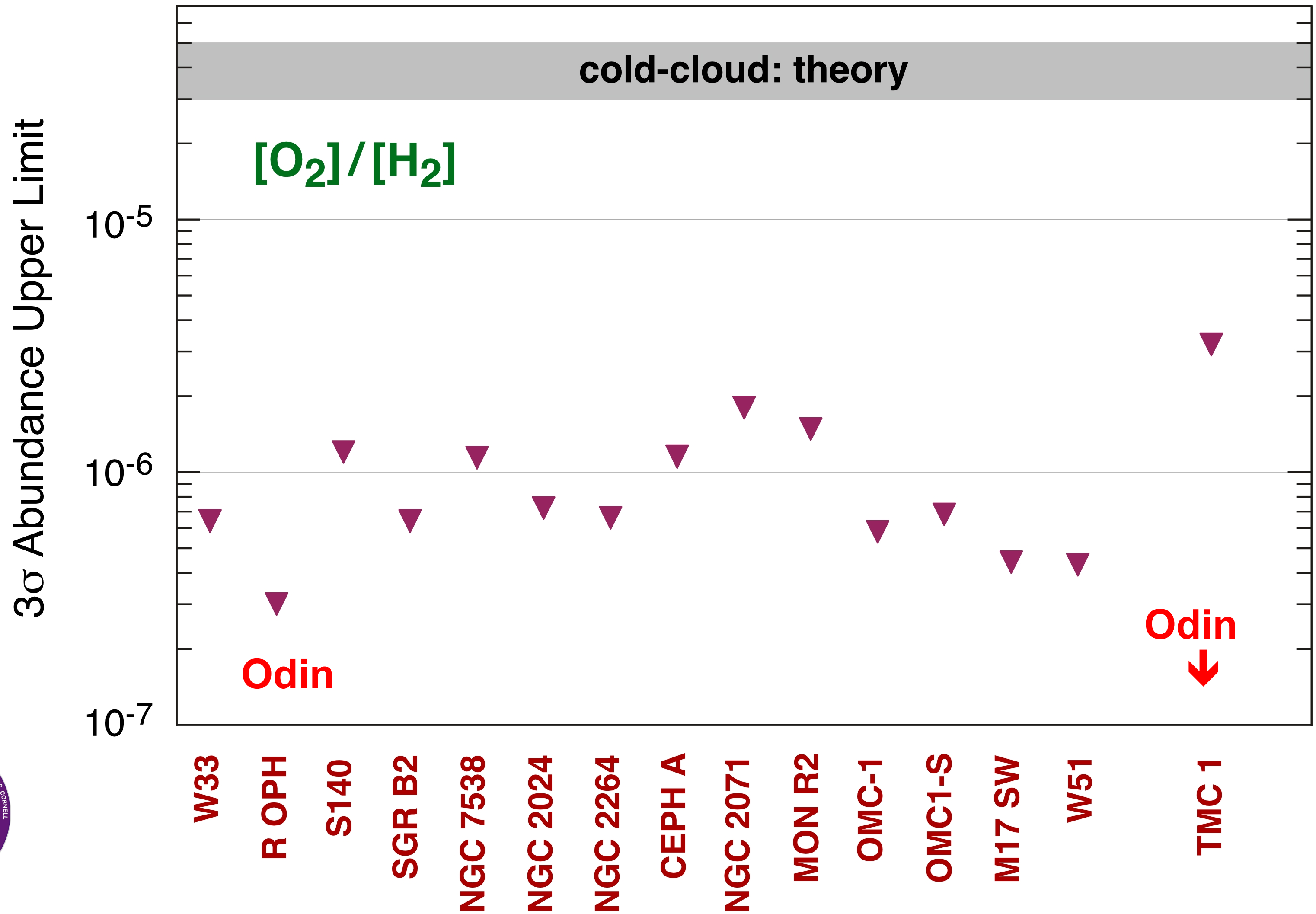
Standard Gas-Phase Chemistry Models Predict Large Abundance of O_2



Woodall et al. (2007)

Reality Intrudes:

$X(O_2)$ in IS Clouds from Odin & SWAS is More Than 100X Below that Predicted by Gas-Phase Chemistry



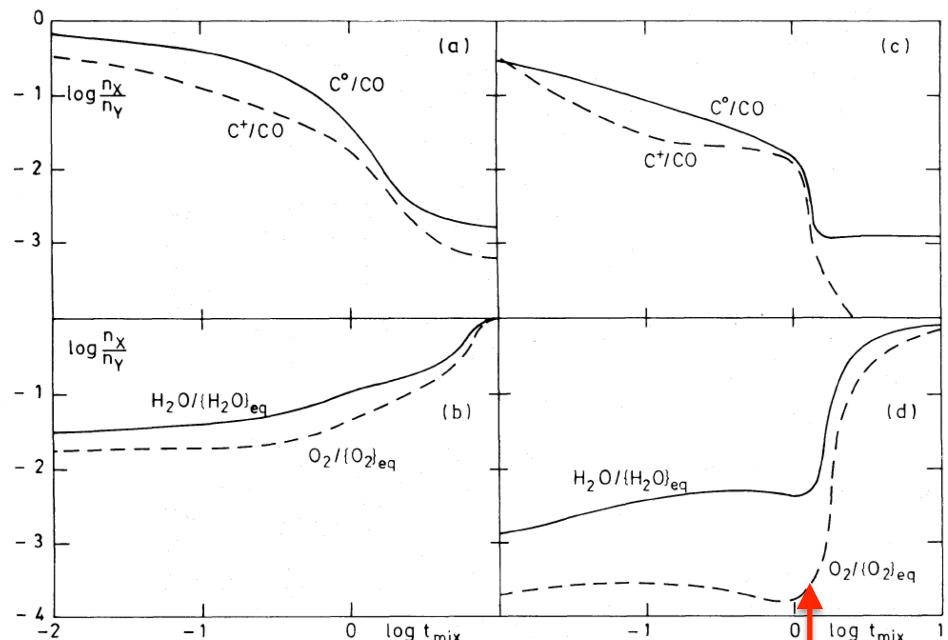
Why is the O_2 Abundance so Low? - I

Dynamical Mixing (circulation)

Chièze & Pineau des Forêts 1989

Model (a)
Moderate-Av core

Model (b)
Shielded core

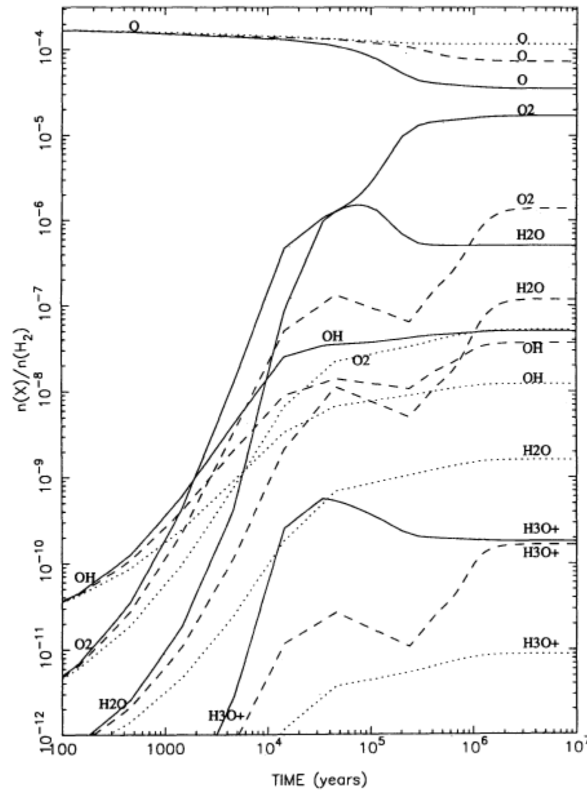


t_{mix} in units of 10^6 yr

Significant impact when dynamical timescale < chemical timescale ~ 10^6 yr

Turbulent Diffusion

Xie, Allen, & Langer (1995)



K=0

K=10^{23}

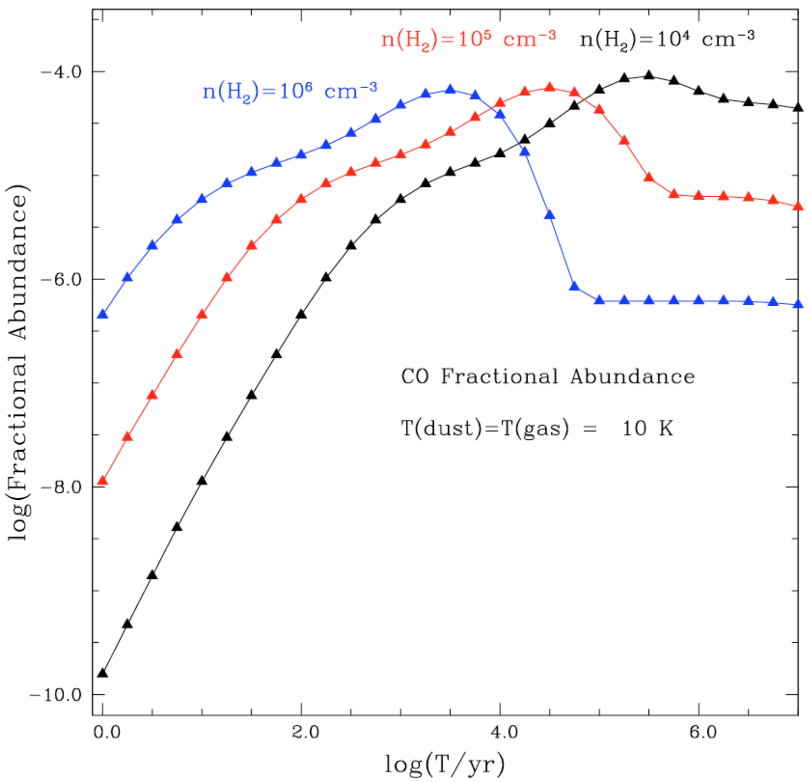
K=10^{24}

Transport due to concentration gradient
K = turbulent diffusion coefficient = $<V_t L>$
Turbulent velocity ~ 1 km s^{-1}
Mixing length due to turbulence very uncertain.
K = 1×10^{23} $cm^2 s^{-1}$ (?)

Why is the O_2 Abundance so Low?

Depletion of molecules onto dust grain surfaces in cold clouds (e.g. Bergin+ 2006; Maret & Bergin 2007)

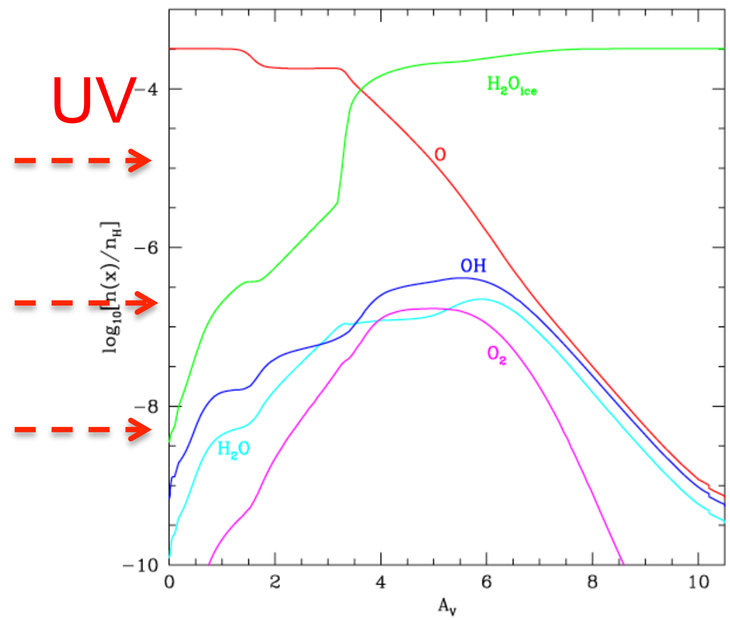
Same process will occur for O atoms, reducing gas-phase oxygen to form O_2



$t_{dep} = 10^{10}$ yr/n(H_2)

Photodestruction – Limits O_2 abundance at cloud edges

Hollenbach et al. (ApJ 2009) combine gas phase photochemistry with grain surface freezeout in cloud interior.



O_2 and H_2O are confined to a “layer” $3 \leq A_V \leq 7$ in which X ≅ 10^{-7} so that N(O_2) ~ $1\text{x}10^{15}$ cm^{-2}
Think of O_2 COLUMN DENSITY rather than fractional abundance

The Herschel Oxygen Project (HOP) – A *Herschel* Open Time Key Project to search for O_2 in variety of such environments to detect and measure molecular oxygen, and improve our understanding of astrochemistry

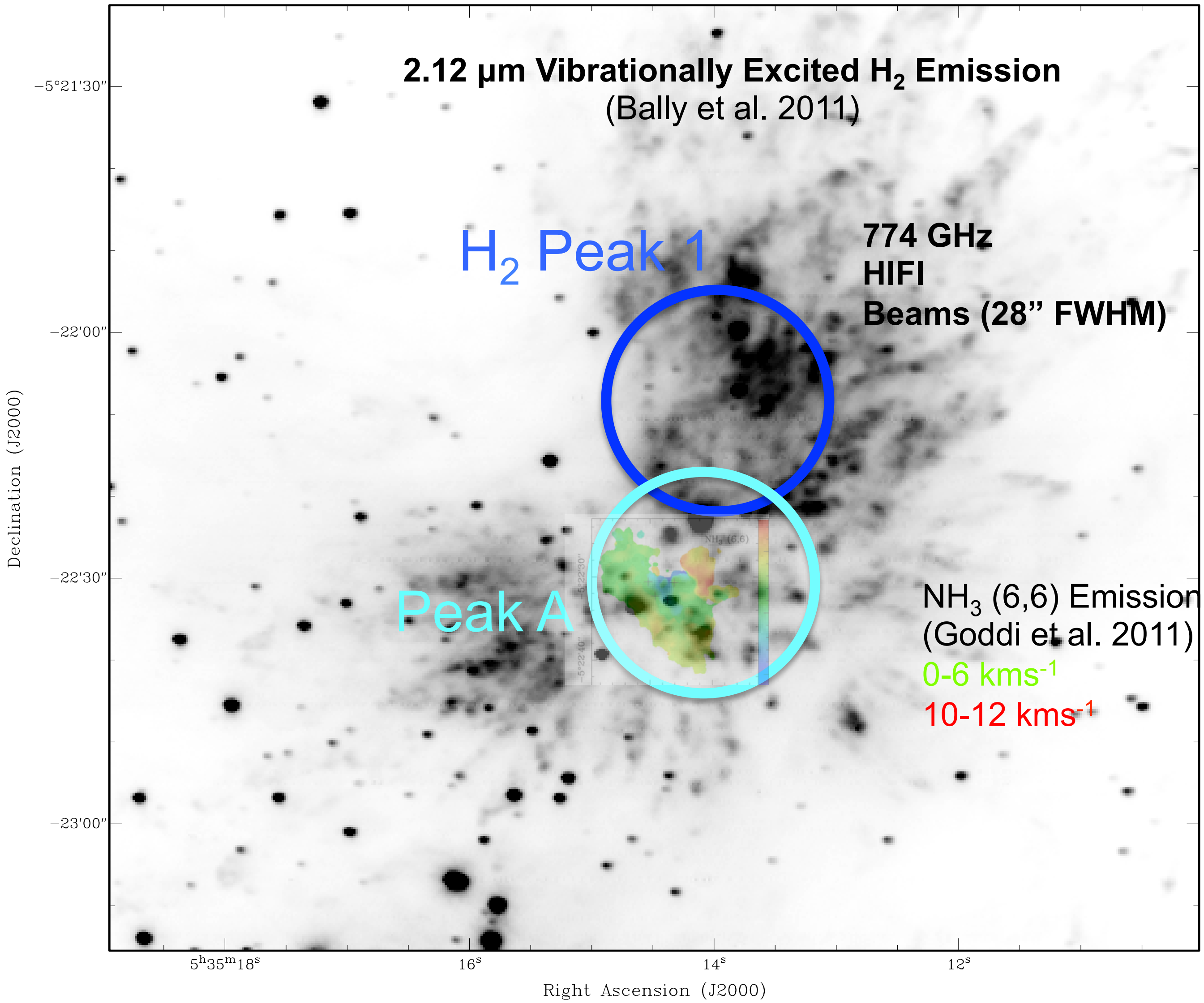
- Deep searches in three transitions of O_2 **487 GHz, 774 GHz, and 1121 GHz**
- Probe a variety of sources and environments
- Test chemical models
- Source list pruned after early observations showed that O_2 is a challenge even for HIFI

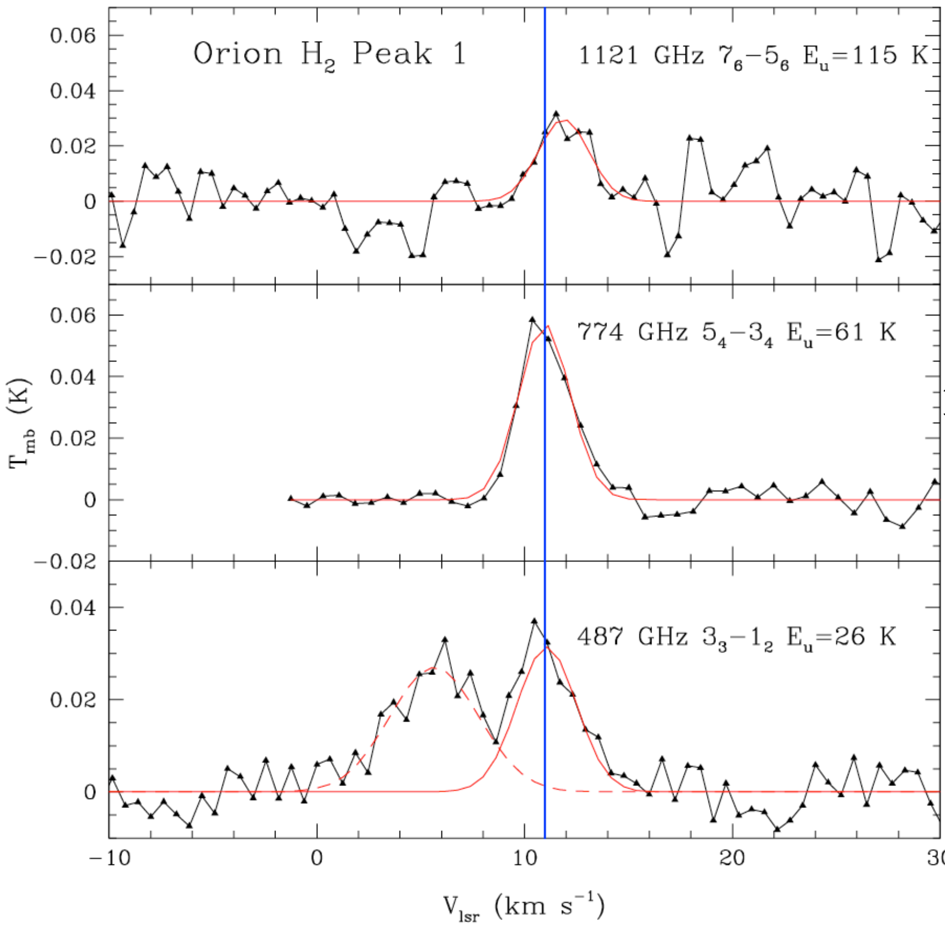
HOP Sources

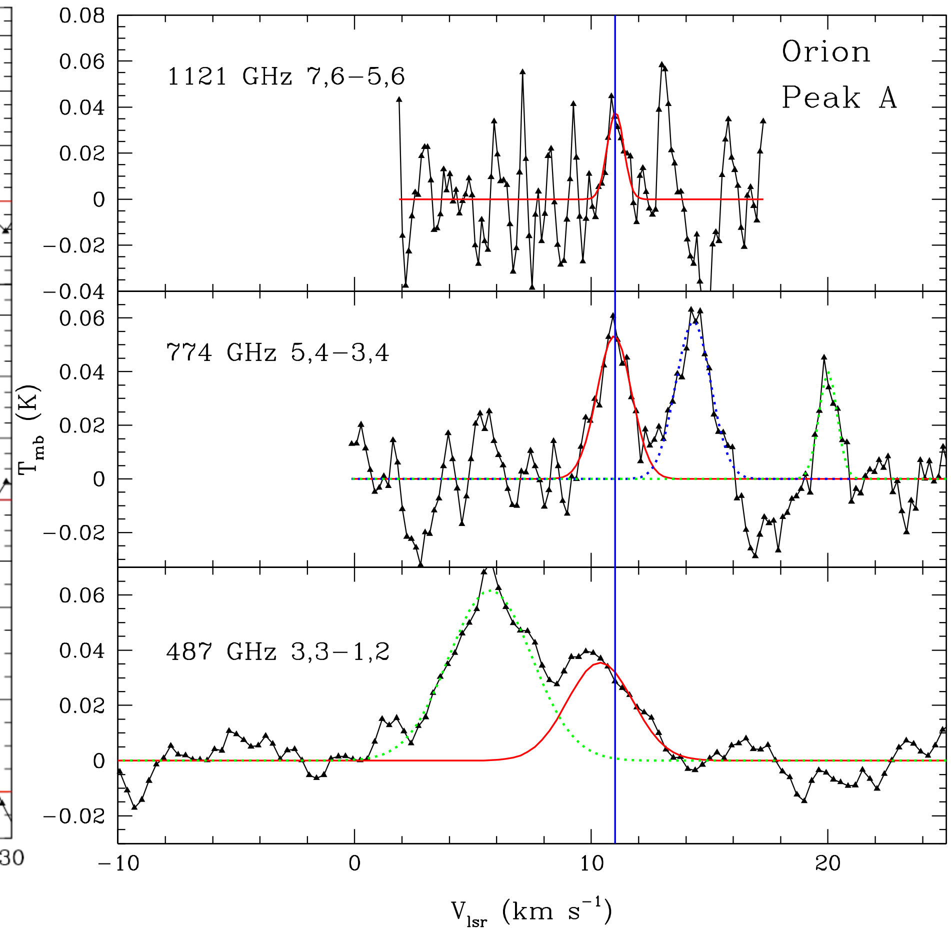
Orion Bar	PDR
AFGL2591	XDR
Orion H_2 Pk1	Postshock
Orion (S)	Embedded Source
NGC1333 IRS4A	"
NGC6334	Protostellar cluster
ρ Oph	Intermediate mass YSO
Sgr A 50 km s^{-1}	

OT1
Orion Peak A (Hot Core)
OT2
Rho Oph mapping –
Larsson et al. poster

3 O_2 Transitions Observed at 2 Positions in Ori A







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

First MULTITRANSITION DETECTION OF MOLECULAR OXYGEN IN THE ISM

Far more line confusion @ Peak A than H_2 Peak 1. Green = CH_3OCHO; Blue – U-line

487 GHz and 774 GHz lines detected @ 11 kms^{-1}

5 kms^{-1} feature is primarily CH_3OCHO

11 kms^{-1} feature is ~ same intensity as at H_2 Peak 1

SOURCE *IS NOT* PEAK A OR HOT CORE

Possible Explanations for O_2 Seen in Orion

If at Peak A/Hot Core: Dust heated by nearby massive stars:

Desorb water ice mantles; initially, there is spike in gas-phase X(H_2O), but eventually we regain "standard" gas-phase chemistry with large X(O_2)

Almost all species having emission in 10 - 12 km s^{-1} range have local maximum at Peak A/Western Clump/MF4/ Cnt D location

BUT THE INTENSITY OF 774 GHz LINE SHOULD HAVE BEEN > 10X GREATER AT PEAK A THAN AT H_2 PEAK 1

MEASUREMENTS SHOW ABOUT THE **SAME** INTENSITY! - Peak A/ Hot Core is NOT the source!

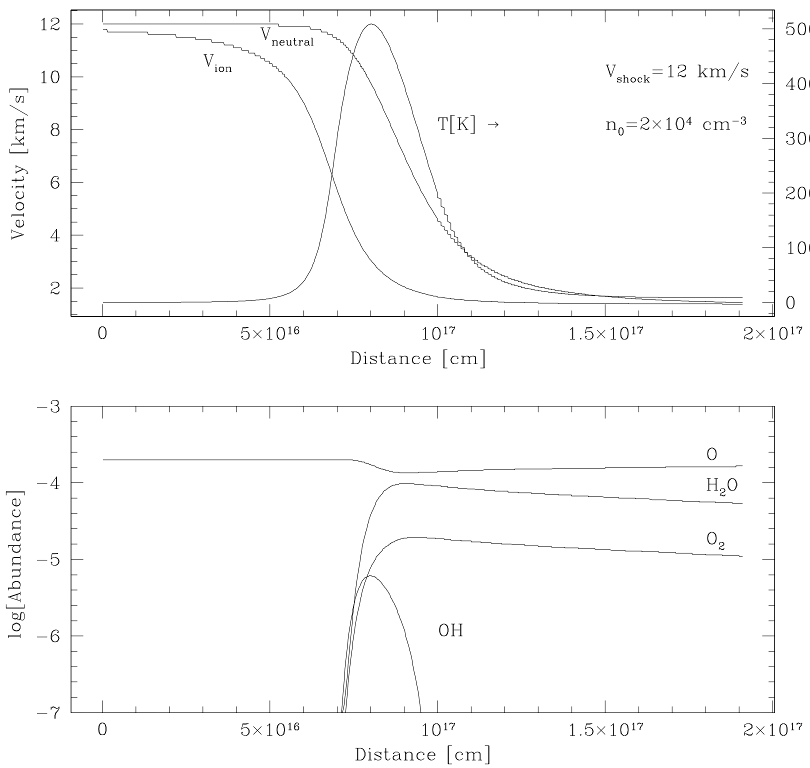
Where is the source?

Combined analysis of two sets of spectra gives best fit (for a single source) of size ~ 8" located about 7" from H_2 Peak 1

Relatively LOW Excitation Temperature, 30 K – 50 K. Since in LTE, this is from RELATIVELY COOL GAS

Location and Low Gas Temperature suggest postshock gas behind moderate velocity shock driven by disruptive event in center of Orion ~ 500 yr ago

Low-velocity Shocks are Effective at Producing O_2



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

$O + H_2 \rightarrow OH + O$

Followed by

$OH + O \rightarrow O_2 + H$

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

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

(from M. Kaufman)

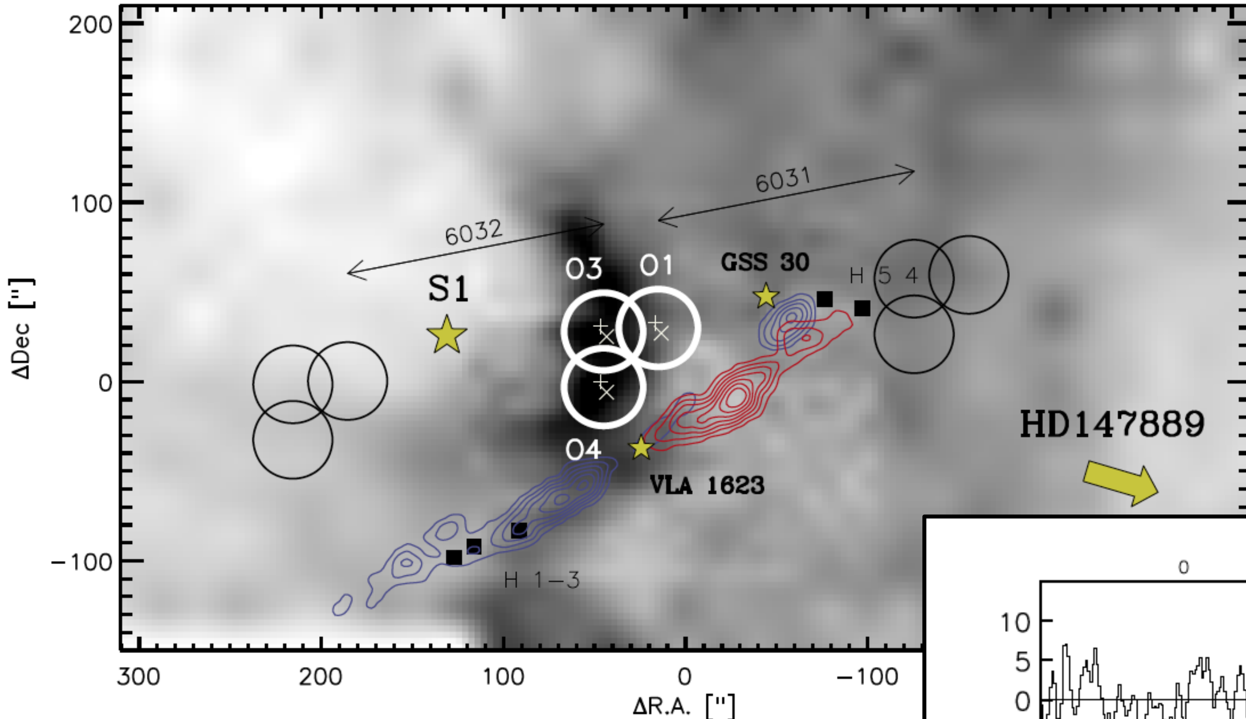
ISSUES:

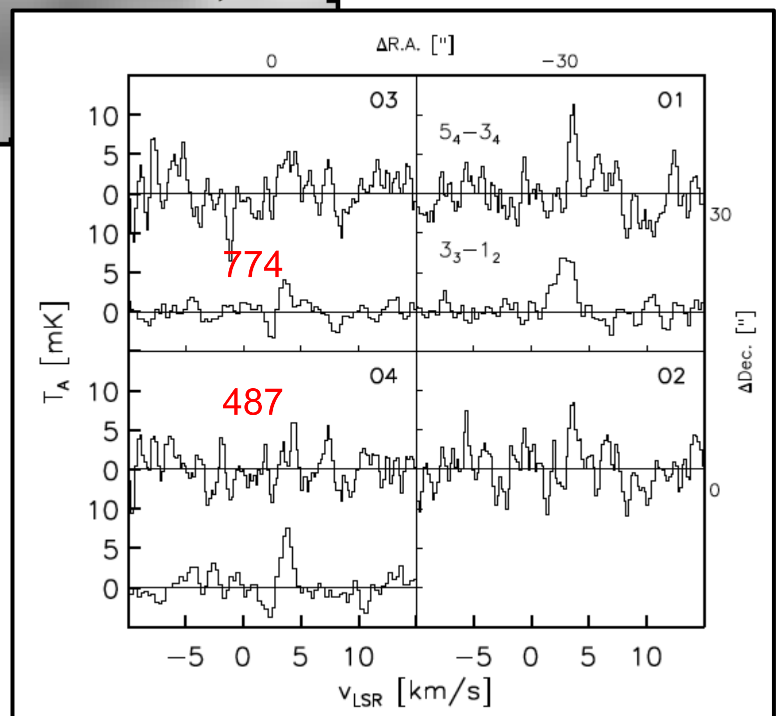
Need to have atomic oxygen in preshock gas; would lead to O_2 on longer timescale w/o shock

Narrow line width and lack of significant velocity shift

O_2 in Rho Oph

Liseau et al. A&A 2012
Larsson et al. poster this conference: more extensive mapping results





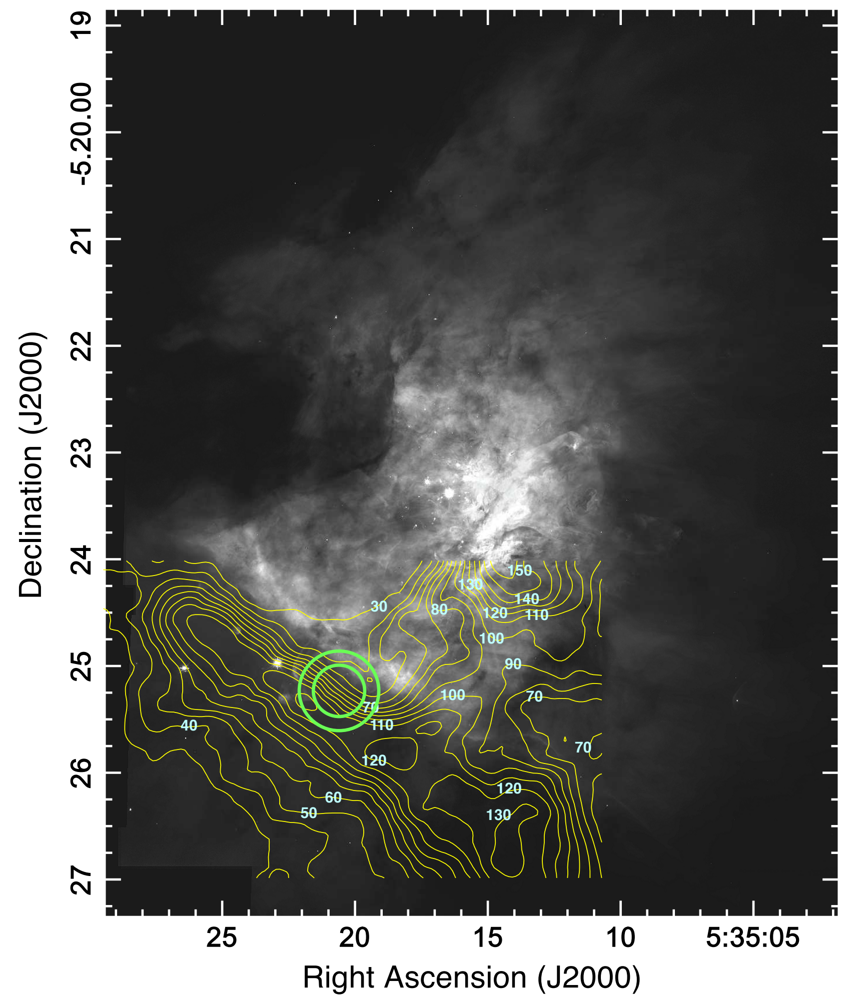
Pos.	$N(O_2)$ /cm^{-2}
O1	5×10^{15}
O4	$> 6 \times 10^{15}$
ALL	$< 5 \times 10^{15}$

$X(O_2) \sim 5 \times 10^{-8}$ (relative to total N)

Narrow lines at quiescent cloud velocity. Fair agreement with PDR model (G_0 = 200). Geometry and source are not clear. **OT2 data: Larsson poster**

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)



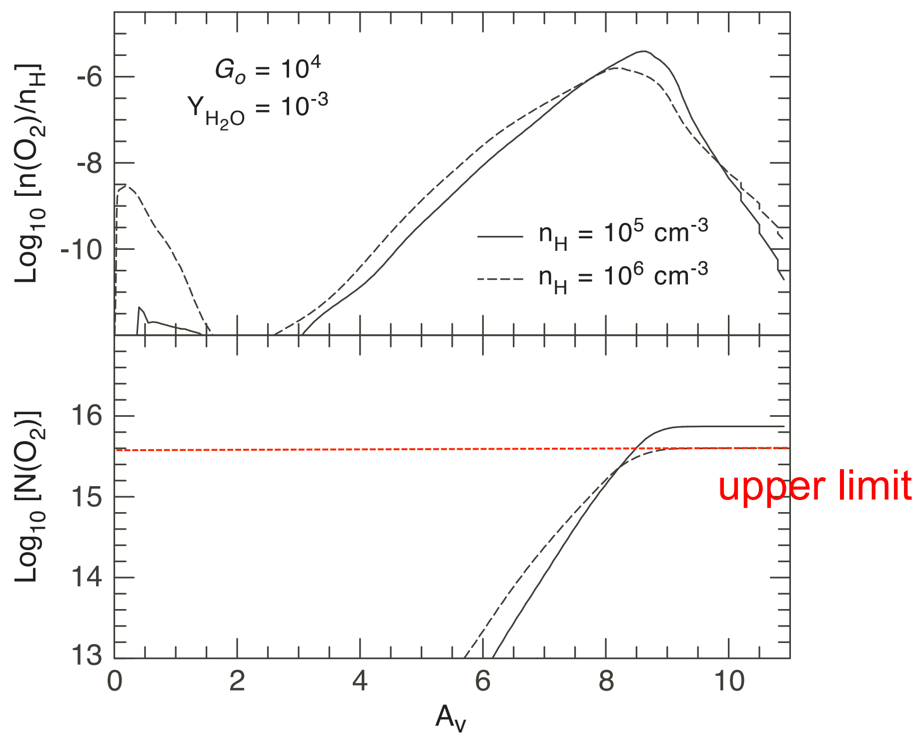
HST image (O'Dell & Wong 1996) with ^{13}CO 3-2 contours (Lis & Schilke 2003)

Orion Bar O_2 Observations: Test of Current Models of Externally FUV-illuminated Gas

- $X(O_2)$ is predicted to peak at intermediate depth of $A_v \sim 8$
  - Some gas phase O is provided by FUV photodesorption of water ice
  - Most O_2 formed in gas phase
- Observed upper limit is a factor of a few below model prediction
- The discrepancy between models and observations can be resolved in a number of ways. One promising one is if

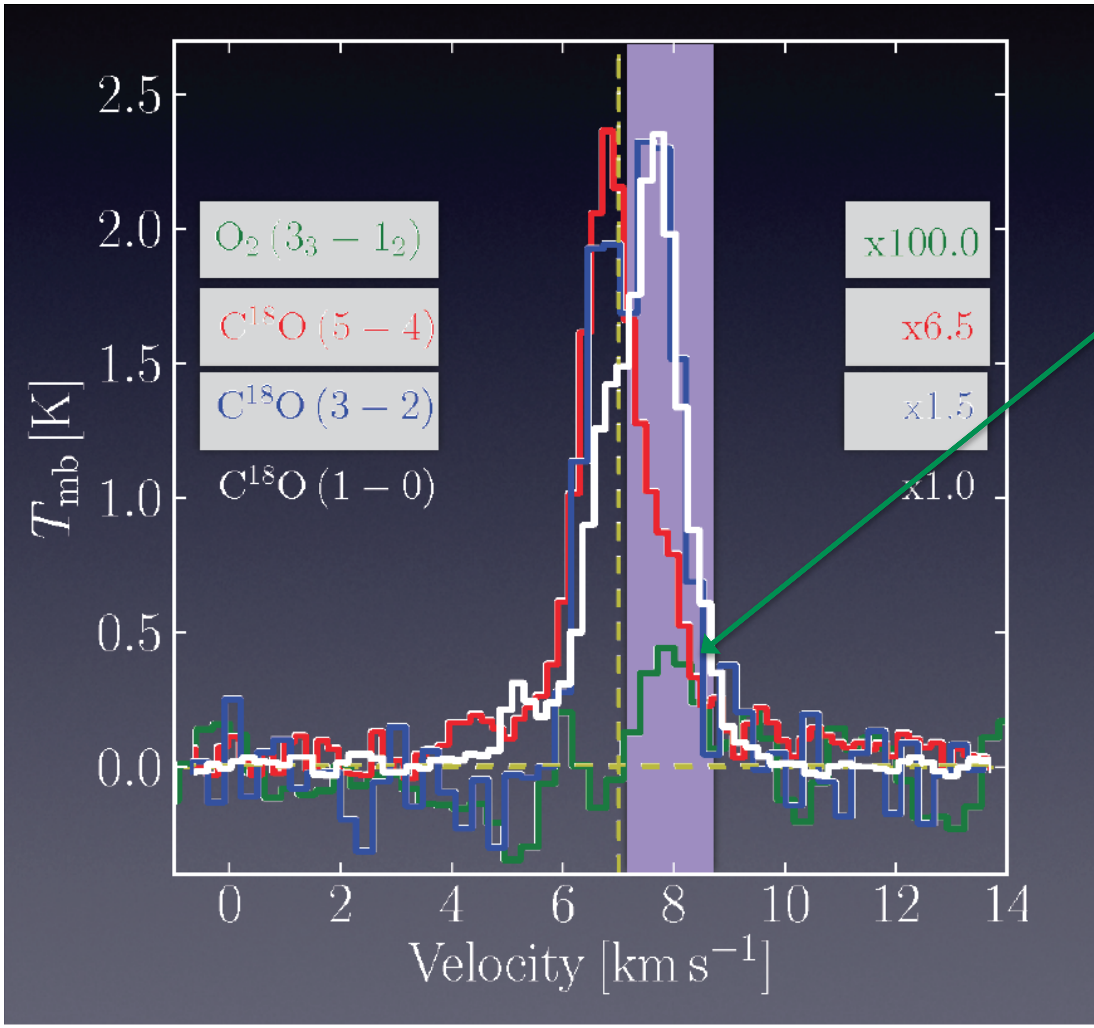
The adsorption energy of O on dust grains is greater than 800 K

- Keeps O on grains and thus ready for hydrogenation and in consequence keeps gas-phase abundance of O very low
- Results are **lower abundances of O_2 and H_2O** in the gas phase



O_2 in NGC1333 IRS4A

(Yildiz et al. 2013)



O_2 emission velocity agrees with $C^{18}O$ 1-0 from cold 8 kms^{-1} cloud

$X(O_2) \cong 10^{-8}$

Binary Class 0 protostar has v = 7.0 kms^{-1}

$X(O_2) < 6x10^{-9}$

$C^{18}O$ 3-2 has 8 kms^{-1} and 6.5 kms^{-1} components

Cloud collision ?

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 $x10^{-8}$ if compared to total $N(H_2)$ along line of sight

These results confirm and extend SWAS and Odin results: O_2 is **not** a significant coolant and is **not** a major contributor to overall oxygen budget.

O_2 in ρ Oph has been confirmed with 2 Herschel lines (+ Odin 118 GHz line)

Detection in NGC1333 cloud (not protostar envelope) with $X(O_2) \sim 10^{-8}$

Significant detections of three O_2 transitions in Orion: narrow lines with velocity 11 – 12 km/s; most likely due to shock chemistry

Complete HOP data set

- confirms that pure gas-phase chemistry is not applicable to dense regions of molecular clouds
- suggests that PDR chemistry, while promising, may need adjustment
- indicates that shock chemistry could be important in some regions

Thanks to all who worked for so long to make Herschel a great success!