Initial Results from the Herschel Space Observatory Open Time Key Project

Herschel Oxygen Project

"HOP"

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Herschel Oxygen Project

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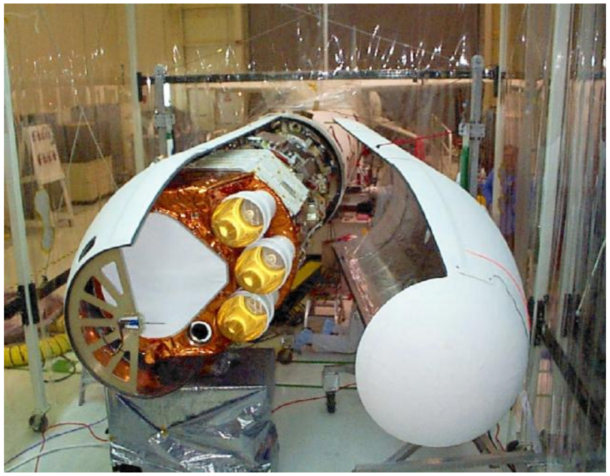
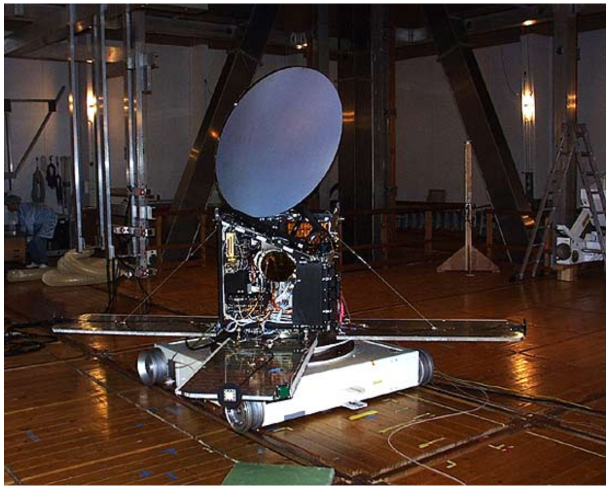
Why O_2 and Why at Submillimeter Wavelengths?





- **Astrophysical Importance** – O_2 is a simple molecule whose gas-phase chemistry is thought to be well understood
- **Large predicted abundance** – in relevant situations should be as large as $X(O_2) = n(O_2)/n(H2) = 3 \times 10^{-5}$ making O_2 a major oxygen reservoir
- **Critical transitions** fall in THz range
- **O_2 was major objective** of SWAS and Odin satellites, which gave very surprising results
- **Connection with life**
- **O_2 is a target of Herschel projects (GTKP & OTKP)**

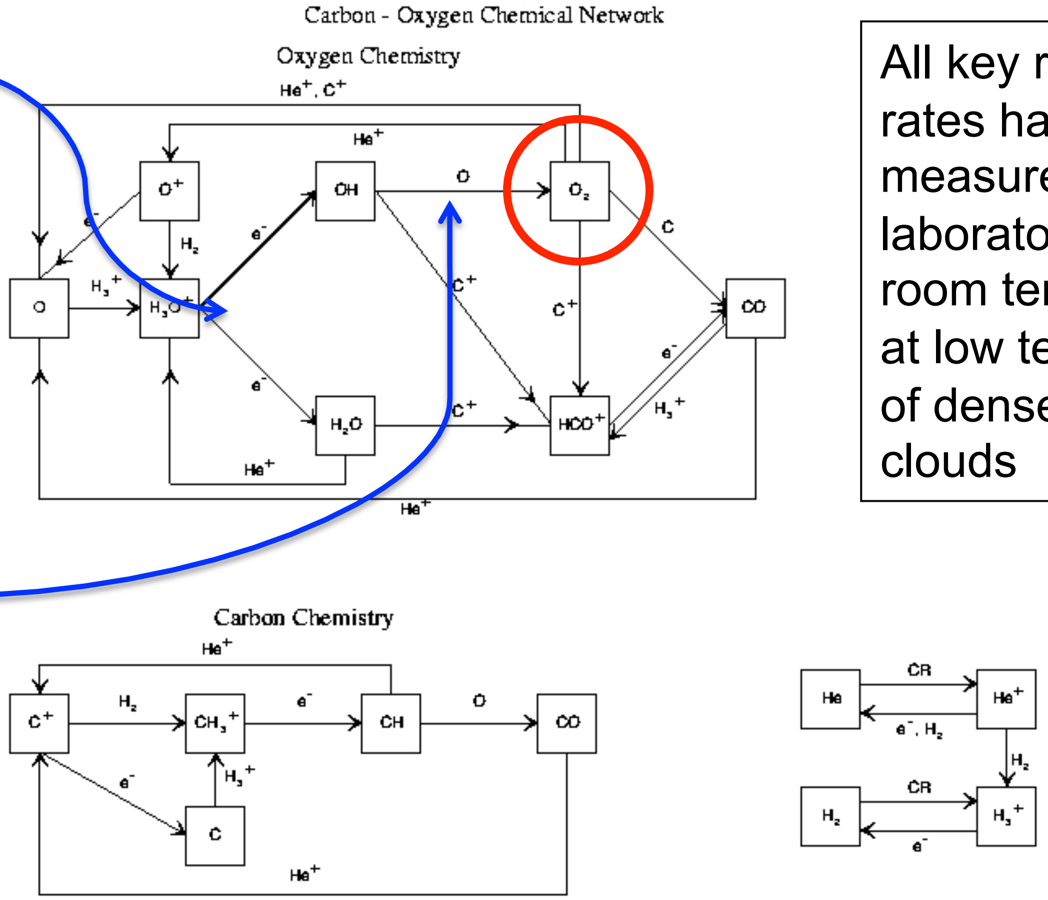
Gas Phase Chemistry for H_2O, O_2 and CO is Relatively Simple

Branching ratio measured by ASTRID and CRYRING experiments (Jensen et al. 2000; Neau et al. 2000)

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

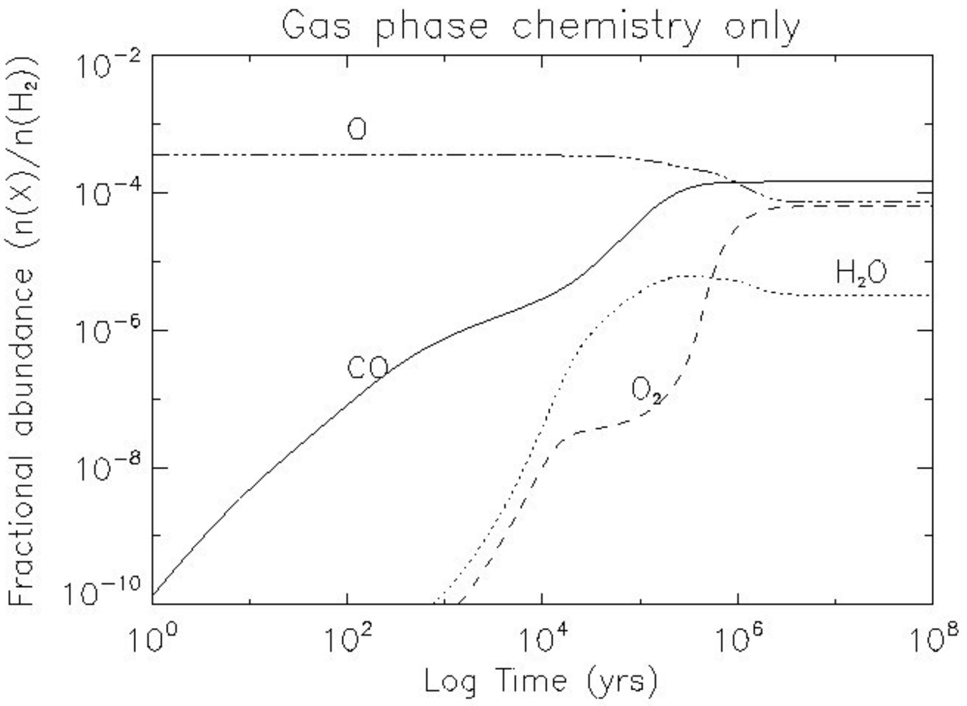
$OH + O \rightarrow O_2$ is an endothermic neutral-neutral reaction

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 low temperatures of dense interstellar clouds

Standard Gas-Phase Chemistry Models Predict Lots of O_2

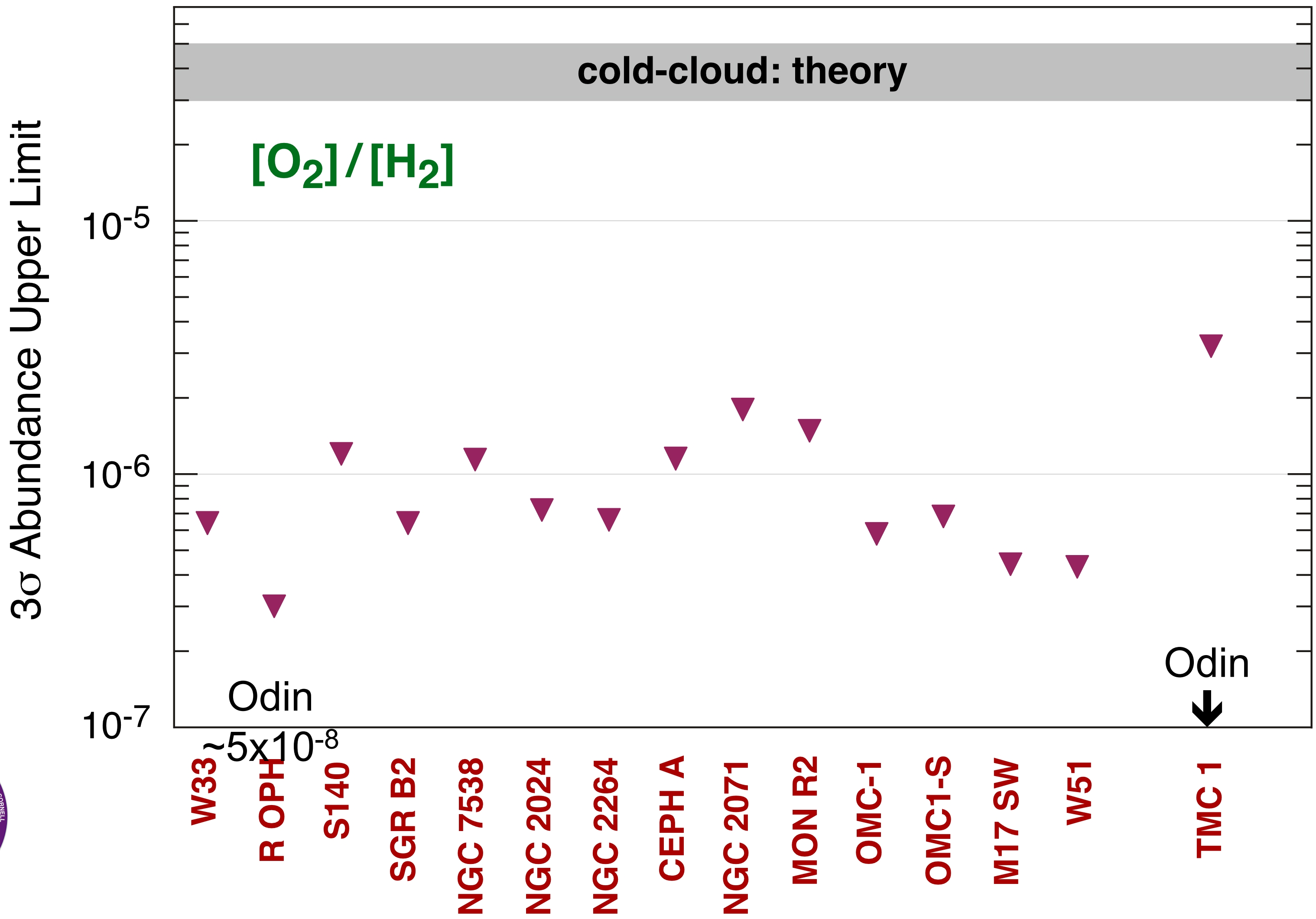


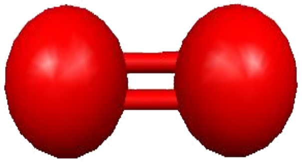
The time dependent evolution of a gas phase chemistry model.

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).

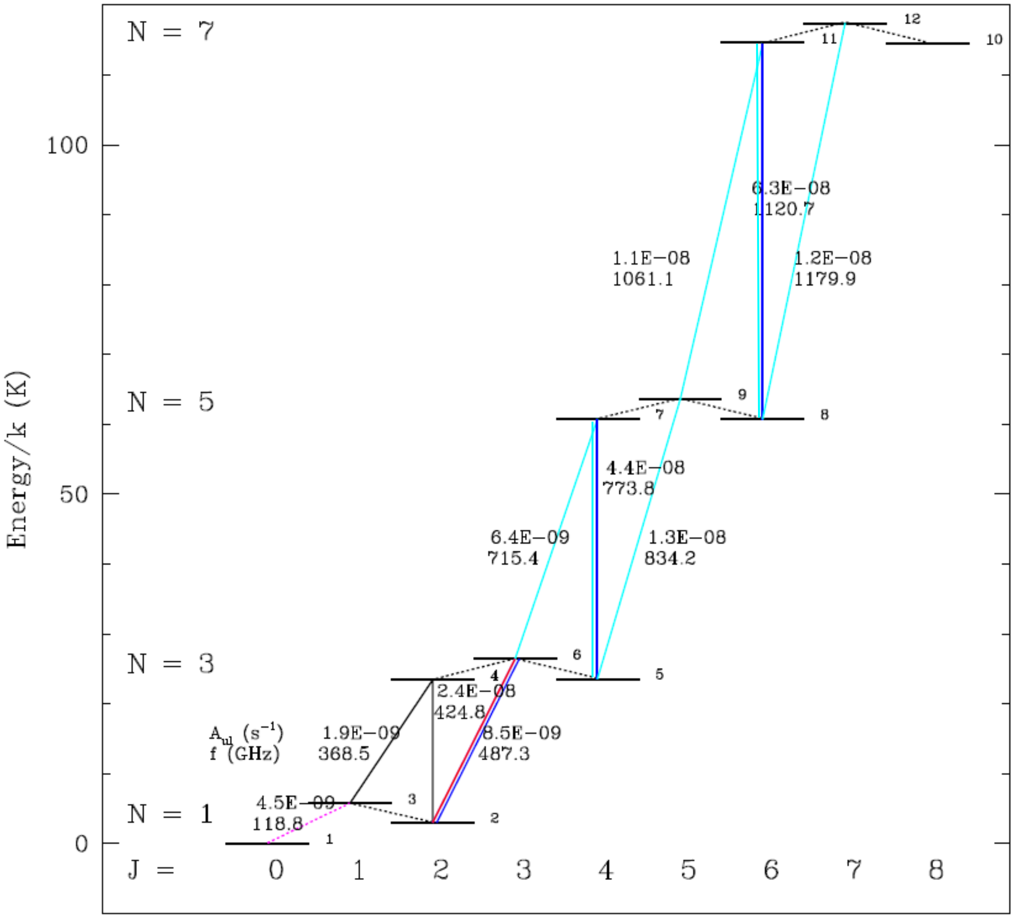
$X(O_2)$ in IS Clouds from Odin & SWAS is ≥ 100x less than Predicted by Gas-phase Chemistry





Lower Rotational Levels and Transitions of O_2

- O_2 rotational levels are connected by weak magnetic dipole transitions
- Quantum calculations of He-O_2 collisions carried out by Lique (2010)
  De-ex. rate coeffs ≅ 5×10^{-11} cm^3 s^{-1}
- Critical densities 200 – 1000 cm^{-3}
- Level populations will be in LTE
- Emission will be Optically Thin



Observed by SWAS
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Observed by Odin
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Observable with Herschel
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Most favorable transitions for Herschel
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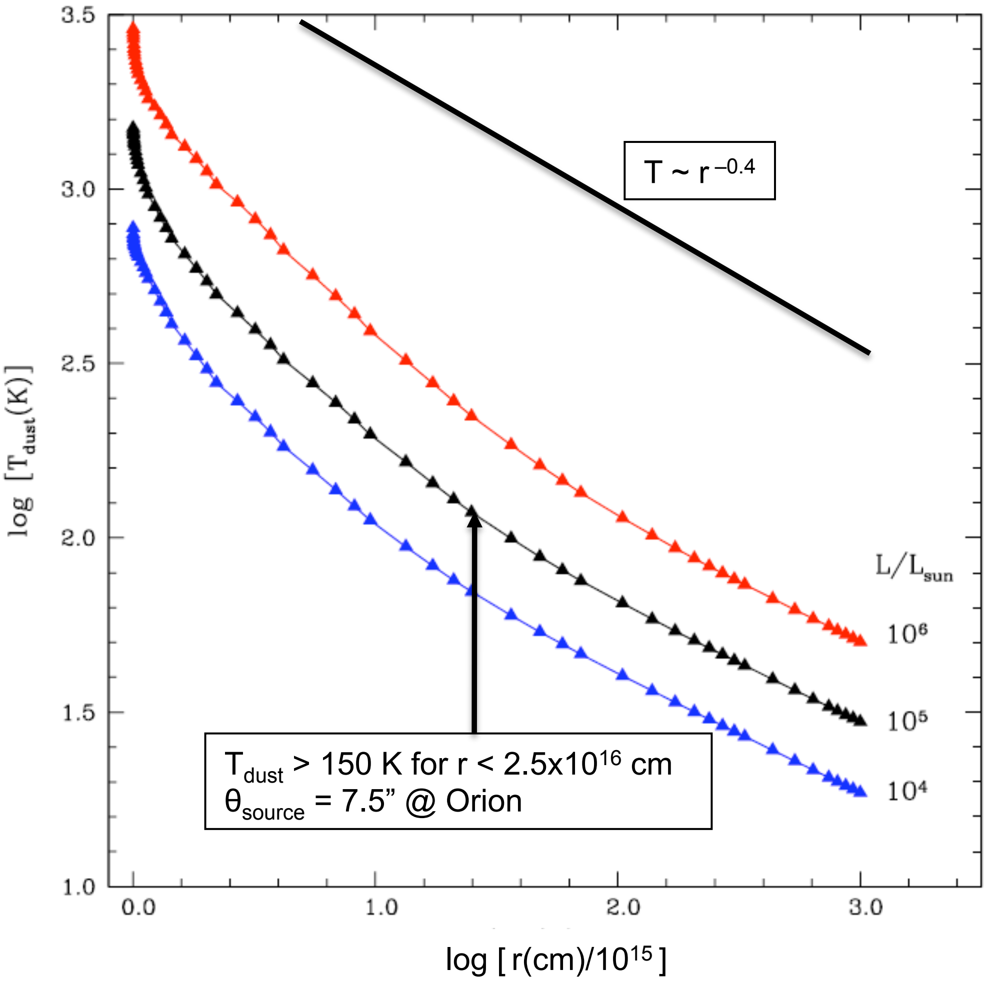
Key Regions for Probing O_2 in the Dense ISM

- **High column density regions** with embedded heating sources
  Grains too warm for significant atomic or molecular depletion
  ⇒ decisive test of gas phase chemistry
- **Photon dominated regions** (*PDRs*)
  Probe O_2 in transition zone between photodissociated outer layer and highly depleted inner region where oxygen has frozen onto grains
- **X-ray dominated regions** (*XDRs*)
  Explore effects of X-rays which are predicted to photodissociate CO making atomic O which → O_2
- **Shock-heated regions**
  High temp. enhances $O + H_2 \rightarrow OH + H$ which then → O_2
- **Infrared dark clouds** (*IRDCs*)
  Turbulence and accompanying dissipation may affect grain surfaces and/or promote disequilibrium chemistry

Model: Spherically Symmetric Dust Envelope Surrounding Massive Protostar

- Power law density distribution
  $n(r) = n(r_1)(r/r_1)^{-\alpha} \quad r_1 < r < r_{max}$
  $\alpha = 2$ (here)
- MRN grain size distribution
- $r_1 = 1\times10^{15}$ cm; r_{max} determined by $N = 1\times10^{24}$ cm^{-2} (Av = 1000)
- Form of the temperature distribution essentially independent of L
- Variation essentially given by
  $T \approx L^{0.2}.r^{-0.4}$ (for T^4)

Results obtained using DUSTY program (Ivezic & Elitzur 1997)



$T \sim r^{-0.4}$

$T_{dust} > 150$ K for $r < 2.5\times10^{16}$ cm
$\theta_{source} = 7.5''$ @ Orion

Warm Dust Surrounding Embedded Sources

⇒ Large $X(O_2)$

Consider region of a GMC surrounding an embedded massive star with $N(H_2) = 10^{23}$ to 10^{24} cm^{-2}

- Dust rapidly degrades dissociating UV and visible photons and is heated by IR radiation.
- O_2 binding very weak compared to that of H_2O so there will be ~ no O_2 on grains (Acharyya et al. 2007).
- Atomic O will start desorbing when T_d exceeds 25 K (Hasegawa & Herbst 1993).
- When T_d exceeds 110 – 130 K, H_2O will start desorbing (Fraser et al. 2001).
- With gas phase H_2O present, "normal" gas-phase chemistry will reassert itself in ~ $10^5 – 10^6$ yr, depending on density. Expect $X(O_2)$ at least 10^{-5} in "warm dust" regions.

$n(H_2) = 2x10^5$ cm^{-2}

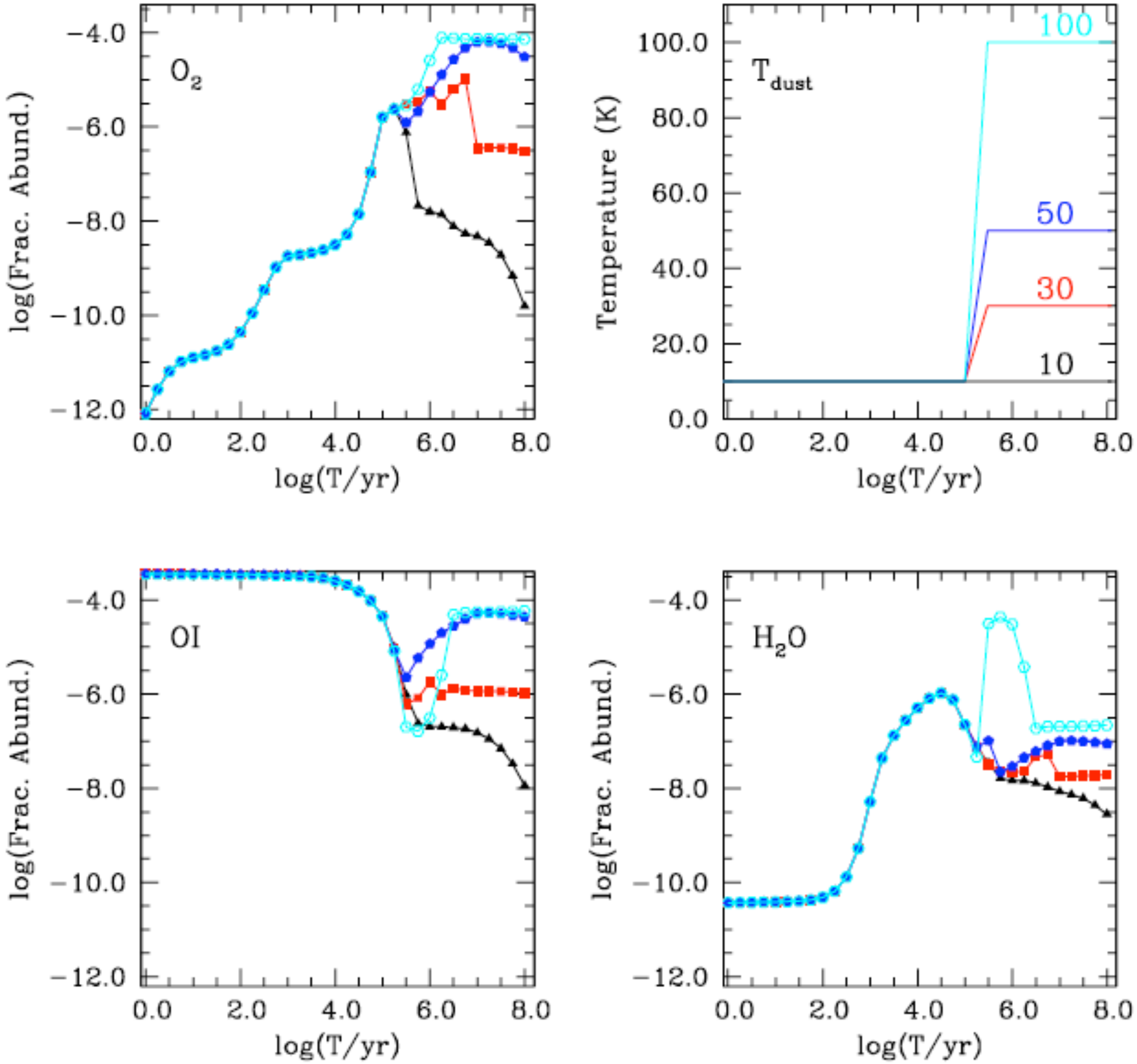
Gas-phase fractional abundances as function of time

Grain temp ramps up at $3x10^5$ yr over period of $2x10^5$ yr

Higher temperature has effect of:

- Modestly increasing $X(H_2O)$ following a post-heating spike
- Significantly increasing X(OI)
- Dramatically increasing $X(O_2)$

$X(O_2)$ ~ 10^{-4} for $T_d \geq 50$ K



Quan, Herbst, & Goldsmith (2010)

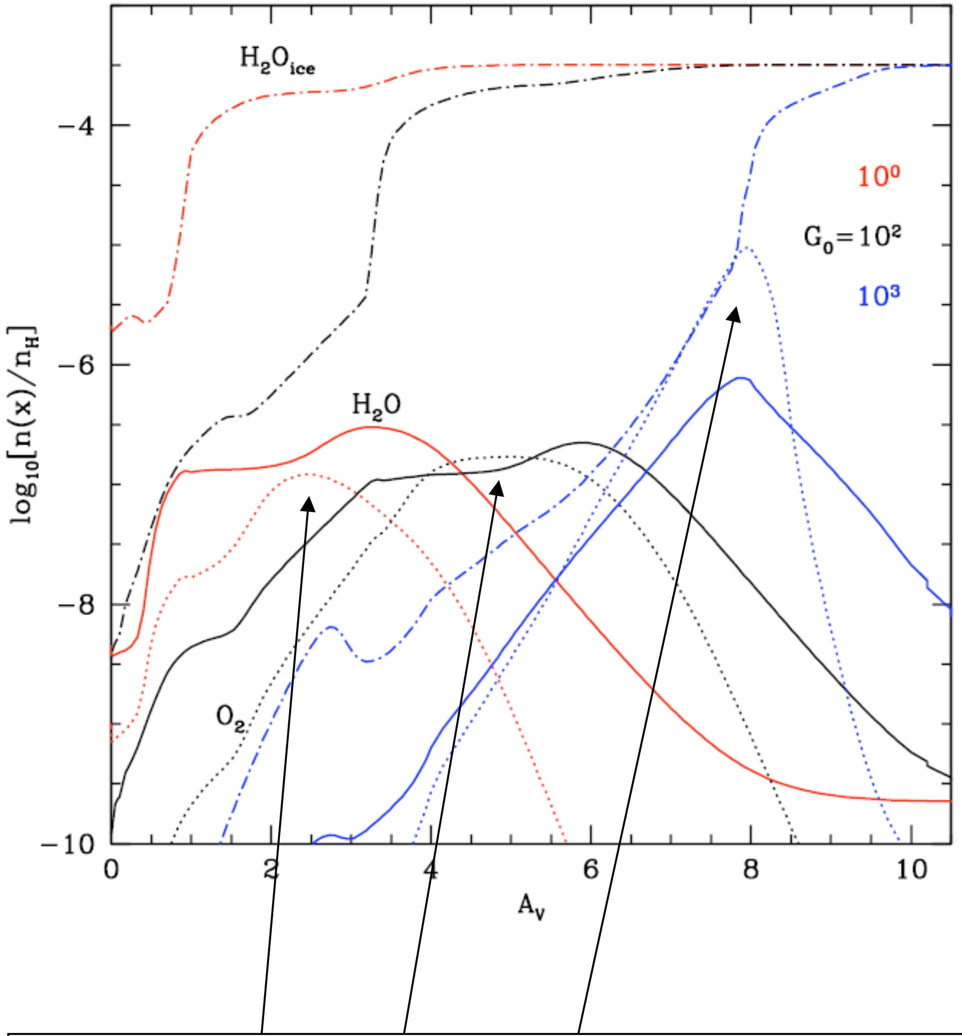
Water & Molecular Oxygen in PDRs

External radiation field:

- Destroys molecules by photodissociation (low A_v)
- Heats grains and photodesorbs ices

Molecules deplete on grain surfaces in well-shielded regions where grains are cold

⇒ Result is a "layer" of enhanced abundance of H_2O and O_2

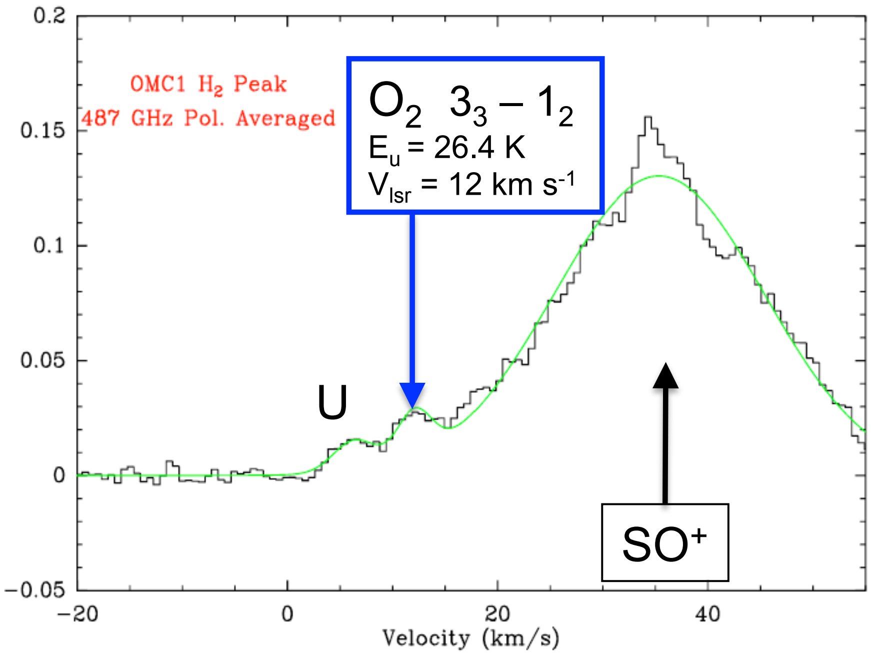


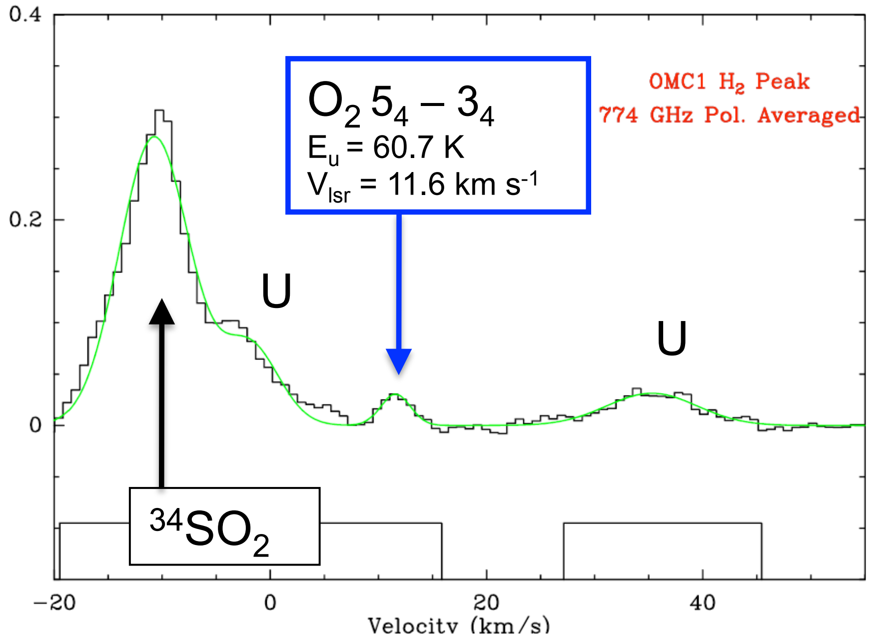
Region of enhanced $X(O_2)$ moves inwards as G_0 increases, leading to higher $N(O_2)$

Hollenbach, Kaufman, Bergin & Melnick (2008)

On the Trail of Interstellar Molecular Oxygen

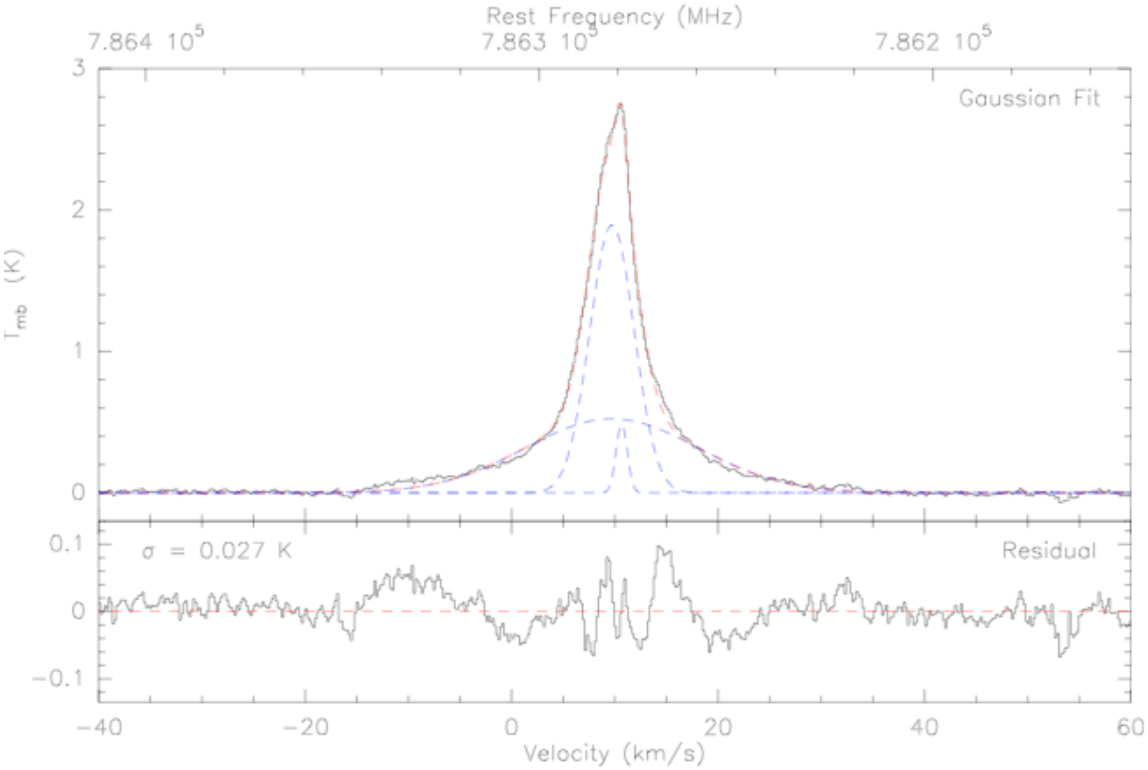
- HOP observed 6 sources in SDP/PSP in 3 different transitions
- Some instrumental issues, but basically things worked very well
- Double beam-switched mode with multiple LO settings to enable sideband deconvolution
- 2 hr integration per source per line; rms = few mK





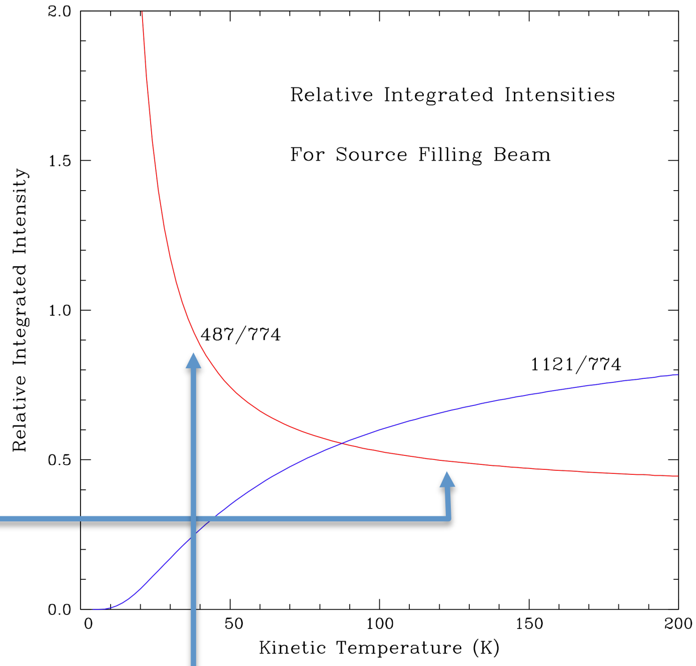
$C^{17}O$ J = 7 – 6 Transition Observed Simultaneously with O_2 774 GHz Line

- Two narrow components at 9.7 and 10.7 km s^{-1}
- It is not yet clear what to make of the somewhat higher velocities for O_2 lines, but higher signal to noise ratio will help
- O_2 line widths (3.3 and 5 km s^{-1}) are reasonable
- Low SNR O_2 detections in other sources agree with nominal source velocities (Ori S, Sgr B2 S, ρ Oph A; 487 GHz and 774 GHz)
- Need additional integration time which is being requested in revised AORs



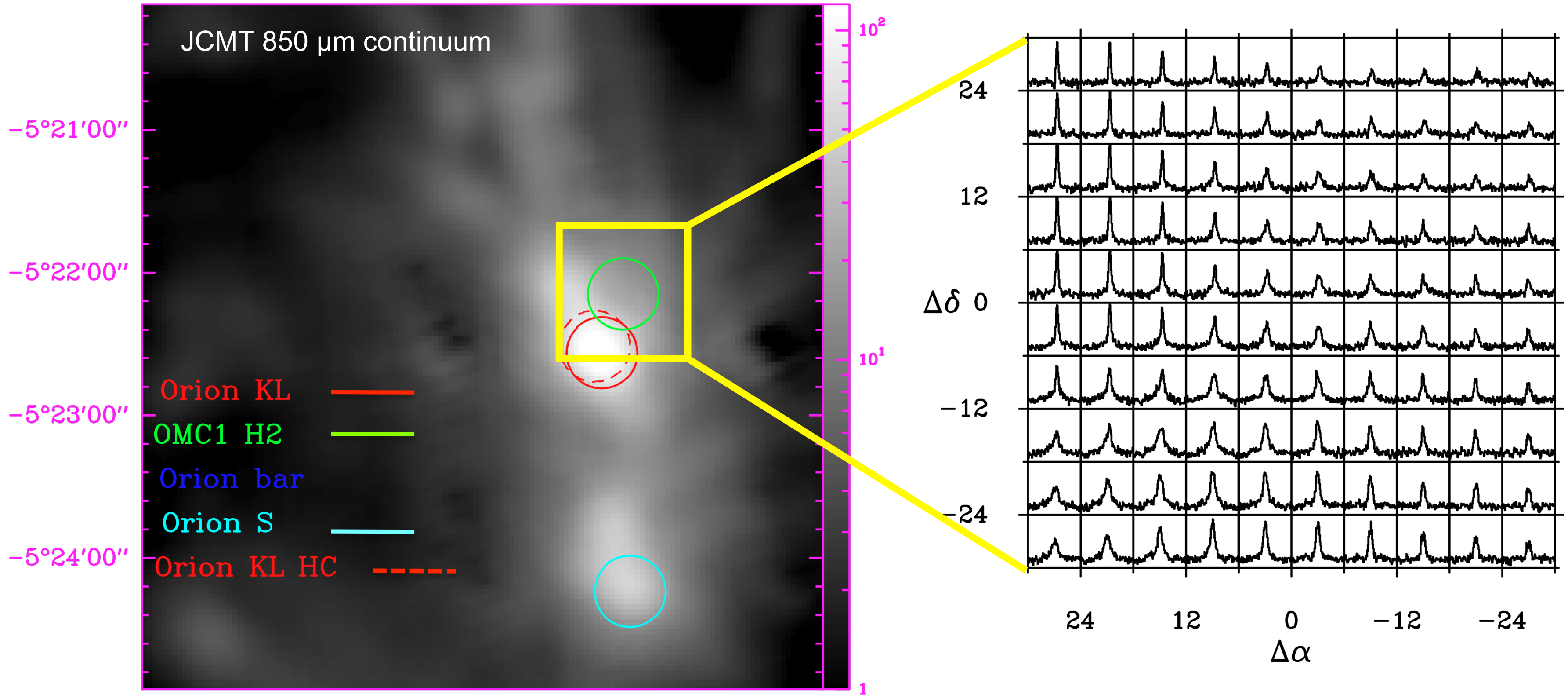
Determination of O_2 Column Density

- Assume detections are real
- Assume source fills both Herschel beams (28” and 20”)
- Assume optically thin LTE emission
- Ratio of 487 to 774 determines temperature of the O_2 emitting region
- R = I(487)/I(774) = 0.5 => T ~ 120 K
- Smaller source will produce larger beam dilution in lower frequency line than in higher, so increases R, shifting T to lower value



Column density not very sensitive to T
$N(O_2) = 3 – 6 \times 10^{16}$ cm^{-2} for 50 K ≤ T ≤ 150 K
To what can we compare this?

Comparison of O_2 with Other Tracers to Determine Fractional Abundance



H_2 Column density in Herschel Beam (with $X(C^{18}O) = 2x10^{-7}$) = $5x10^{23}$ cm^{-2}
Implied O_2 fractional abundance ≅ $1x10^{-7}$

Conclusions and Prospects for HOP

- We have statistically relatively significant detections of two O_2 transitions but definitive identification remains elusive
- PSP observations only 20% of total time so the situation should be much clearer with additional sources, lines, and deeper integrations in months ahead
- O_2 abundance is low, ~ 10^{-7}, consistent with previous results from SWAS and Odin (and other searches) with simplest source model, but could be larger if source is very small, clumpy, or if the O_2 is present only in limited regions
- Models for enhanced O_2 abundance have yet to confront HOP data in detail but our limits will test them severely
- If the low O_2 abundance is confirmed and expanded to include a variety of situations, the explanation will be a real challenge for astrochemical/astrophysical models