# The Herschel Oxygen Project
# *Herschel Space Observatory*
# Open Time Key Project

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# Herschel Oxygen Project

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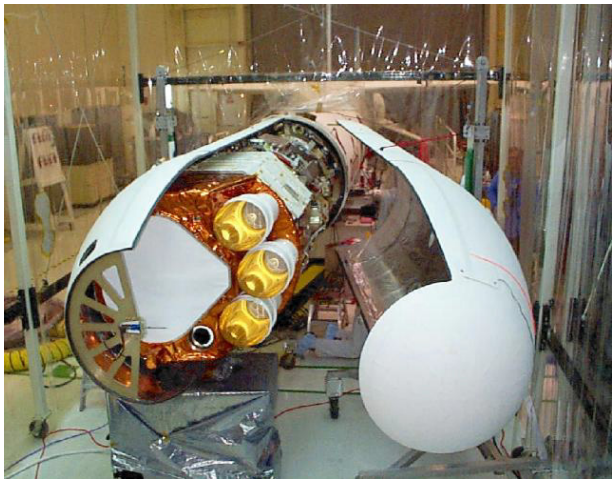
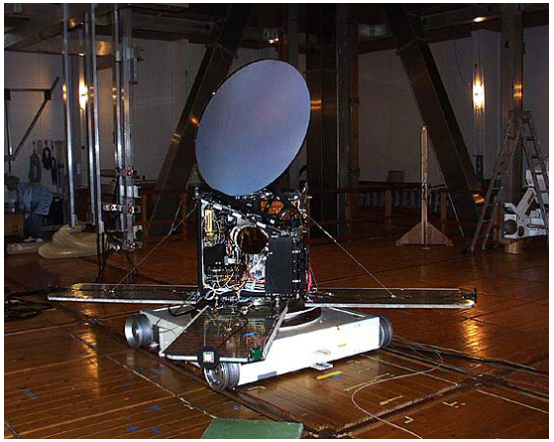
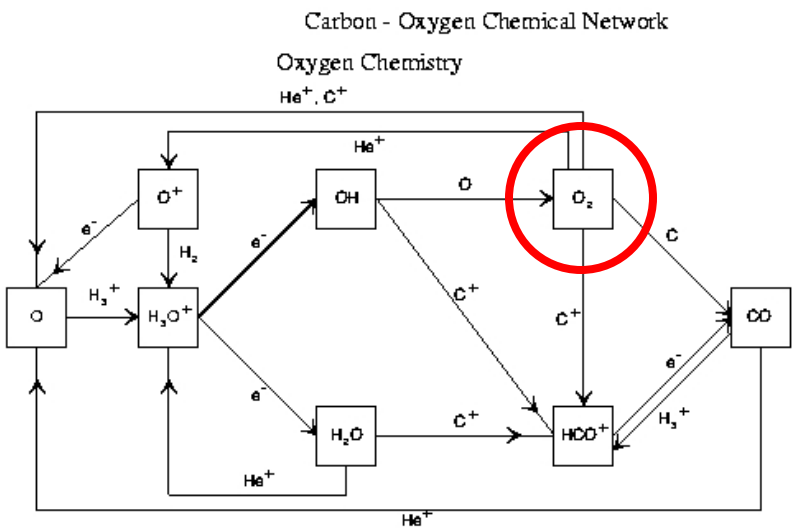
# Why $O_2$ and Why at Submillimeter Wavelengths?



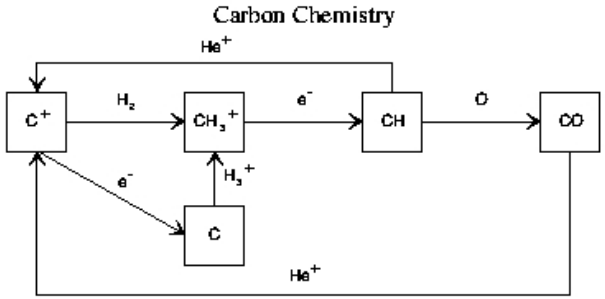
- **Astrophysical Importance** –$O_2$ is a simple molecule whose gas-phase chemistry is thought to be well understood
- **Large predicted abundance** - in relevant situations should be as large as $X(O_2) = n(O_2)/n(H2) = 3x10^{-5}$ making $O_2$ a major oxygen reservoir
- **Critical transitions** fall in THz range
- **$O_2$ was major objective** of SWAS and Odin satellites, which gave very surprising results
- **Clear connection with life**
- **Target of Herschel projects**

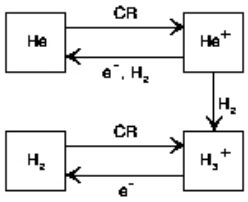


# Gas Phase Chemistry for $H_2O$, $O_2$, and CO is Relatively Simple




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

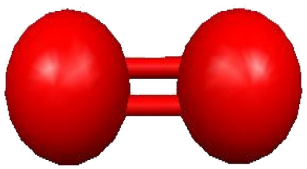


# Molecular Oxygen Structure

- $O_2$ is a homonuclear molecule with zero permanent electric dipole moment
- Last 2 electron spins are parallel, yielding S = 1
- Symmetry demands that rotational quantum number N must be odd
- Spin magnetic moment interacts with molecular rotation, splitting each rotational level into three levels having J = N-1, N, N+1
- Magnetic dipole transitions connect different levels but transitions are $10^4$ times weaker than those of $H_2O$
- Level populations easily thermalized by collisions (LTE)
- Photon trapping is unimportant but $O_2$ is difficult to detect because emission per molecule is so weak

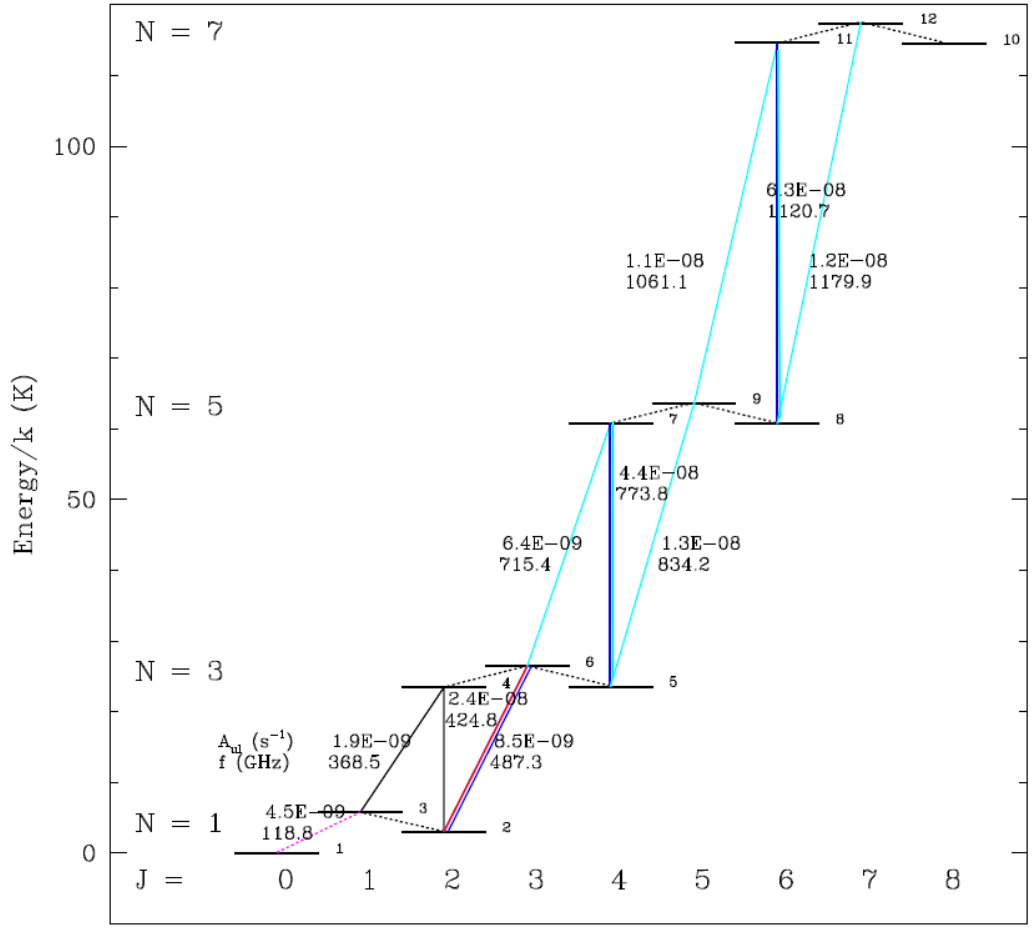
# Lower Rotational Levels and Transitions of $O_2$



$O_2$ Rotational Levels are Connected by Weak Magnetic Dipole Transitions

Level Populations in LTE

Emission will be Optically Thin



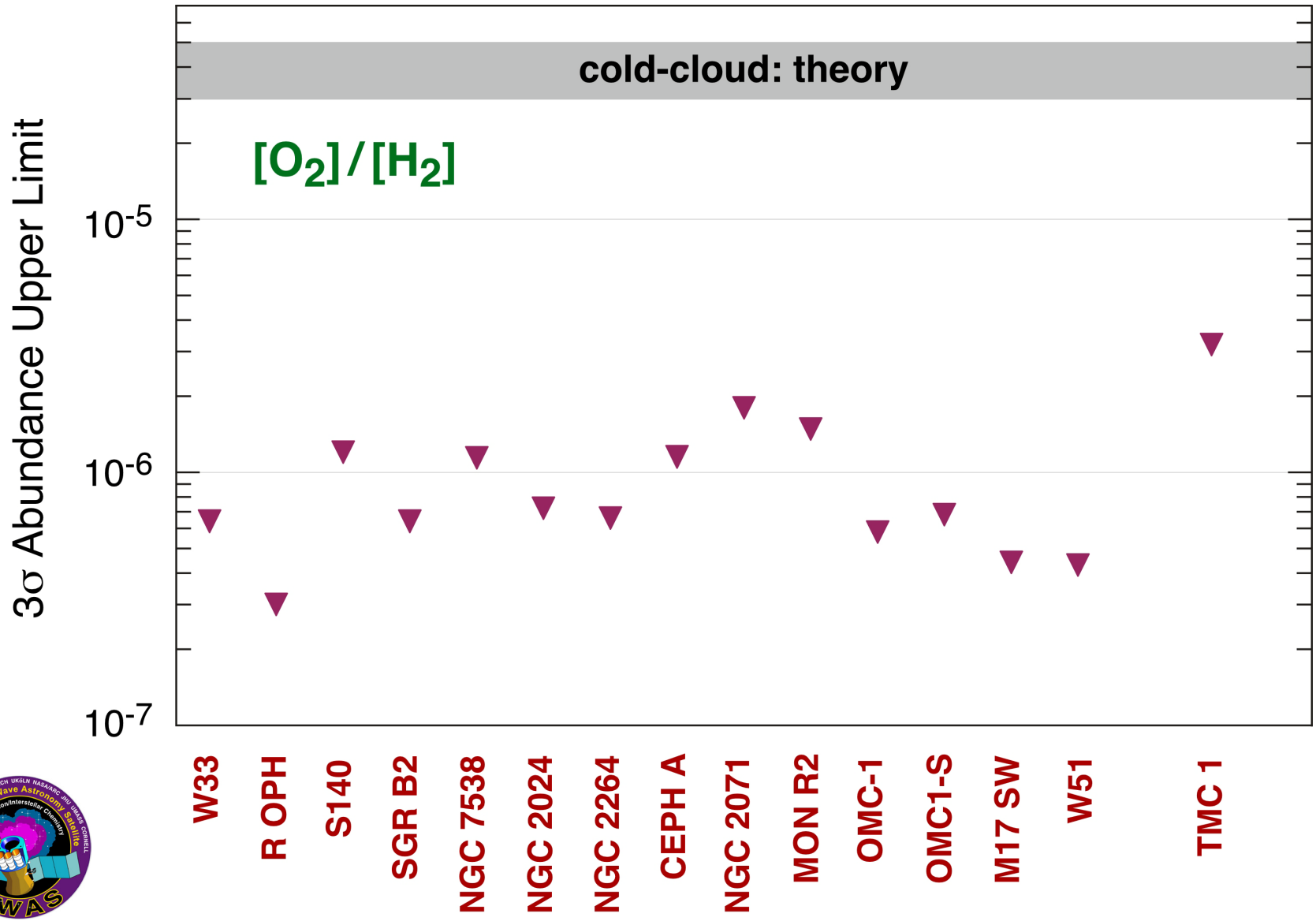

Observed by SWAS

Observed by Odin

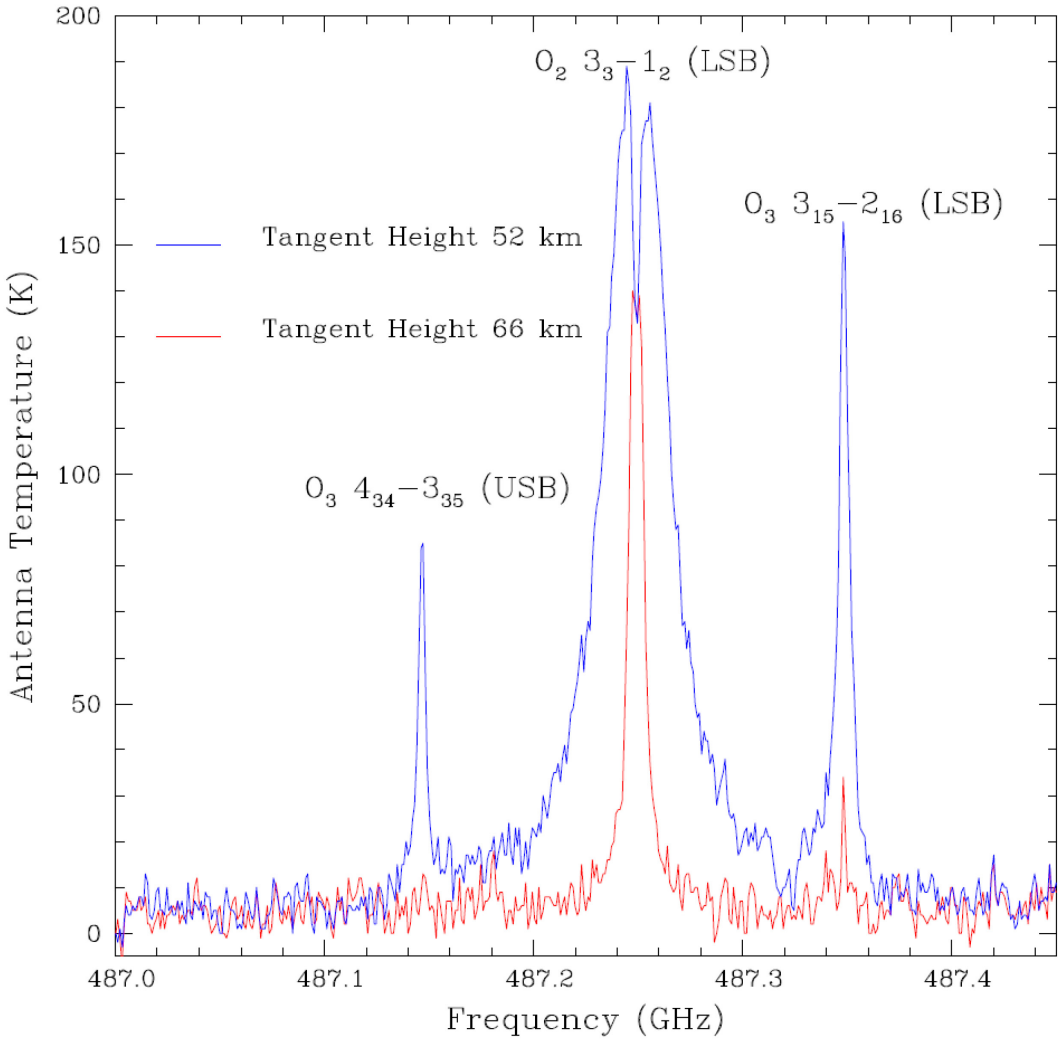
Observable with Herschel

Most favorable transitions for Herschel

# $O_2$ Abundance in Interstellar Clouds



# SWAS Spectra of Terrestrial $O_2$




**Atmospheric Limb Sounding**

For path including only very high altitude, we see pure emission with narrow line width and relatively weak lines

For path including lower altitudes, we see stronger emission with greater line width for $O_2$ and $O_3$

$O_2$ shows self-absorption produced by colder gas at higher altitude

Note: Sideband gain ratio implied by $O_3$ lines is ~ unity

(This option is not available for Herschel)

# What Herschel Offers HOP

- **Small Beam Size** (20” to 46”) - [compared to 4.2’ for SWAS and 10’ for Odin] allows probing compact, warm regions in which gas-phase chemistry should be dominant
- **Increased Sensitivity** - greatly improved due to L-He cooled submillimeter SIS and HEB receivers [20 X lower noise than SWAS]
- **Broad Frequency Coverage** - increases chance of unambiguous assignment of weak lines in sources having rich submm spectra [3 lines selected to cover range of source conditions]

# 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 on 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 temperatures enhance $O + H_2 \rightarrow OH + H$ which then → $O_2$
- **Infrared Dark Clouds** (*IRDCs*) ♦ Turbulence and accompanying dissipation may affect grain surfaces and/or promote disequilibrium chemistry

# HOP Sources and Strategy

- Observe 487 GHz, 774 GHz, and 1121 GHz transitions in a selection of sources
- Typical observing times are 3 hours per transition per source (plus additional "deep integration" time
- RMS antenna temperature sensitivity in 3 hr integration is 3 mK (487 GHz) to 15 mK (1121 GHz) with 1$\sigma$ column density sensitivity for $T_k$ = 100 K ~ $5 \times 10^{15}$ $cm^{-2}$.
- The $H_2$ column density in Herschel beam can significantly exceed $10^{23}$ $cm^{-2}$, so that we should be sensitive to $O_2$ fractional abundances as low as ~ $10^{-8}$.
- Total observing time = 140 hr
  - 5 Low mass embedded sources (incl. ρ Oph)
  - 8 High mass embedded sources
  - 2 PDRs
  - 2 XDRs
  - 2 Shock-heated sources
  - 2 IRDCs
- Observe 2 or 3 lines, with 487 GHz and 774 GHz having largest time allocation
- Use mini-spectral scan mode: 5 different LO settings employed with double beam switching.
  - Assumes relatively small source size
  - Allows resolving sideband ambiguity to be resolved
  - Should ensure good baseline quality necessary to exploit long integrations
- Various other transitions of interesting species will be (surely or plausibly or possibly) detected as result of very high sensitivity (e.g. SO, $H_2O$, $H_2{}^{18}O$, CS, HDCO, $D_2CO$, $^{13}CO$)

# HOP Data and Analysis

- Basic data product is deep, beam-switched spectra on a relatively limited number of positions/lines
  - 18 @ 487 GHz with t = 10845 s
  - 13 @ 774 GHz with t = 10830 s
  - 3 @ 774 GHz with t = 33930 s
  - 6 @ 1121 GHz with t = 10890 s
- Each has (possibly) an $O_2$ line along with other molecular line(s)
- We envision essentially hand-processing each spectrum
- We likely will want to look at shorter integration time blocks to verify radiometric performance, isolate “glitches”, etc.
- Major unknown is combination of data taken at different LO settings for definitive sideband identification of any feature seen (NHSC?)
- Need to have data in CLASS format (via FITS) from appropriate stage in pipeline
- Plan is for all data to flow from NHSC through Caltech/JPL to the HOP team members