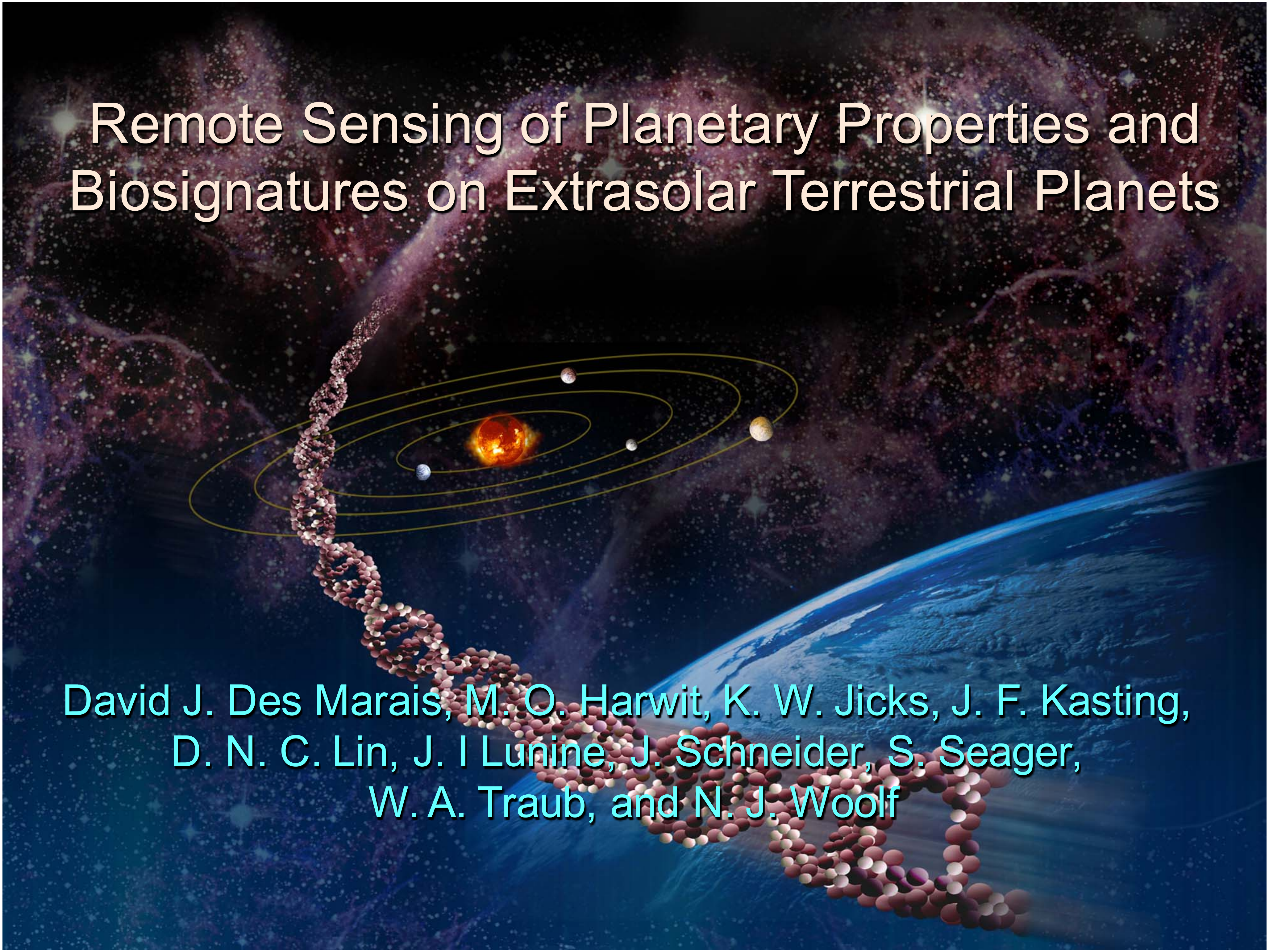
Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets



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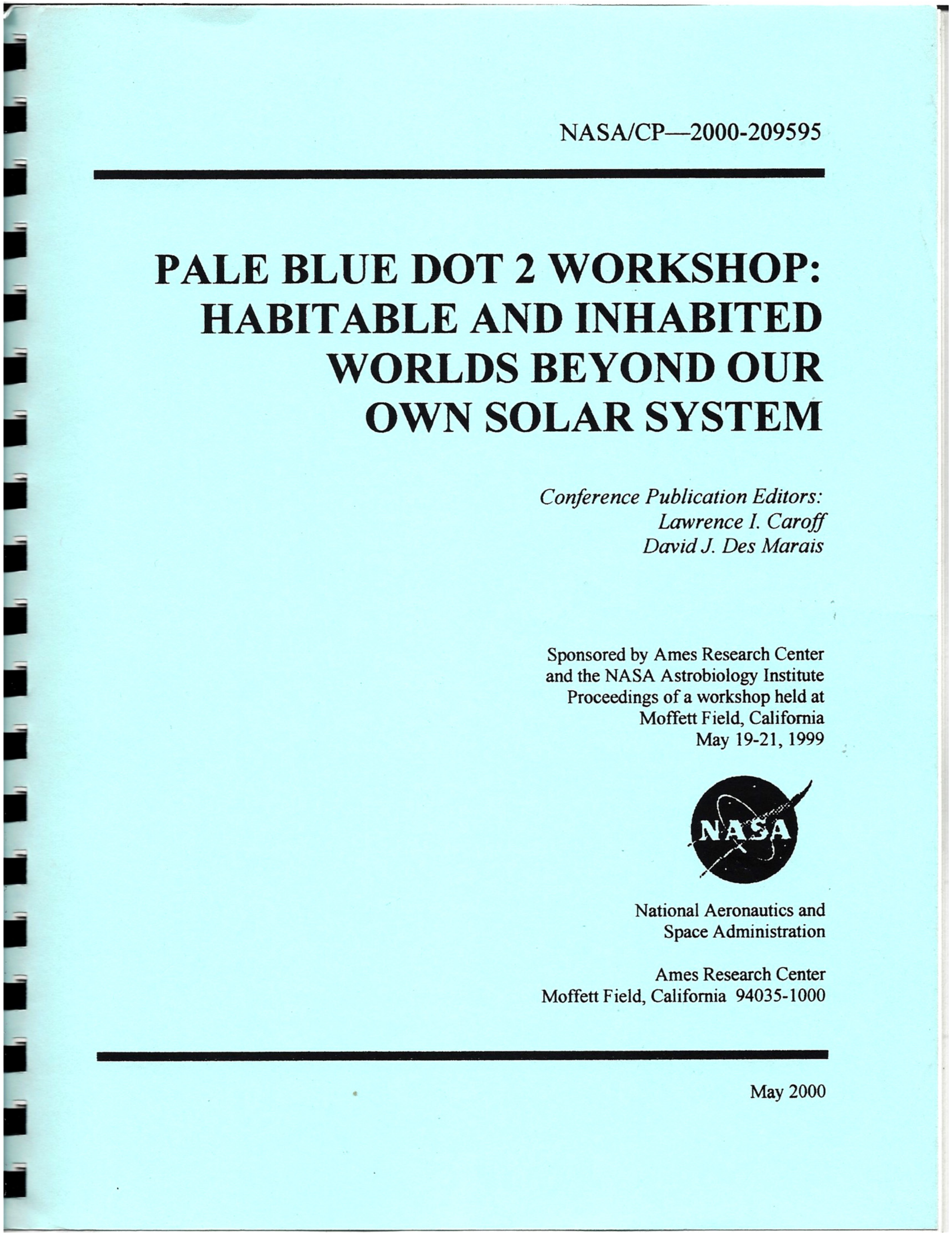
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PALE BLUE DOT 2 WORKSHOP: HABITABLE AND INHABITED WORLDS BEYOND OUR OWN SOLAR SYSTEM

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David J. Des Marais

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Moffett Field, California 94035-1000

May 2000

PBD2 Workshop, May 1999

Opportunities in Astronomy

Origins missions
Formation & abundance of planets

Habitable Planets

Geological processes
Early atmospheres
Climates
Spectroscopy

Biogeochemistry

Anaerobic ecosystems
Evolution of Earth's early biosphere

Inhabited Planets

Biological processes-Global budgets
Atmospheric chemistry
Clouds, chemistry & climate
Spectroscopy

Finding Pale Blue Dots, discussion

Astronomy
Habitable planets
Biogeochemistry
Inhabited planets

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Research Paper

Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets

DAVID J. DES MARAIS,[1] MARTIN O. HARWIT,[2] KENNETH W. JUCKS,[3]
JAMES F. KASTING,[4] DOUGLAS N.C. LIN,[5] JONATHAN I. LUNINE,[6]
JEAN SCHNEIDER,[7] SARA SEAGER,[8] WESLEY A. TRAUB,[3]
and NEVILLE J. WOOLF[6]

ABSTRACT

The major goals of NASA's Terrestrial Planet Finder (TPF) and the European Space Agency's Darwin missions are to detect terrestrial-sized extrasolar planets directly and to seek spectroscopic evidence of habitable conditions and life. Here we recommend wavelength ranges and spectral features for these missions. We assess known spectroscopic molecular band features of Earth, Venus, and Mars in the context of putative extrasolar analogs. The preferred wavelength ranges are 7–25 μm in the mid-IR and 0.5 to ~1.1 μm in the visible to near-IR. Detection of O_2 or its photolytic product O_3 merits highest priority. Liquid H_2O is not a bioindicator, but it is considered essential to life. Substantial CO_2 indicates an atmosphere and oxidation state typical of a terrestrial planet. Abundant CH_4 might require a biological source, yet abundant CH_4 also can arise from a crust and upper mantle more reduced than that of Earth. The range of characteristics of extrasolar rocky planets might far exceed that of the Solar System. Planetary size and mass are very important indicators of habitability and can be estimated in the mid-IR and potentially also in the visible to near-IR. Additional spectroscopic features merit study, for example, features created by other biosignature compounds in the atmosphere or on the surface and features due to Rayleigh scattering. In summary, we find that both the mid-IR and the visible to near-IR wavelength ranges offer valuable information regarding biosignatures and planetary properties; therefore both merit serious scientific consideration for TPF and Darwin. Key Words: Spectroscopy—Biosignatures—Extrasolar planets—Terrestrial Planet Finder—Darwin—Habitable planets. Astrobiology 2, 153–181.

Why Conduct a Spectroscopic Search for Life in the Cosmos?

Basic Science Goals in the Search for Spectral Signatures of Extrasolar Life, and the Broad Diversity of Terrestrial Planets

Interpretation of Visible and IR Spectra of Terrestrial Planets

- Continuum observations
- Observations of bands
- Determining parameters from visible and near-IR bands
- Effects of dust rings, binary planets, and dust trails

IR and Visible Molecular Band Features

- Model
- Clouds
- Water
- Carbon dioxide
- Ozone
- Methane
- Nitrous oxide
- Oxygen

Spectral Features from the Planet's Surface

Conclusions: Wavelength Ranges and Prioritization of Spectral Features

Coda: Some Cautionary Tales from Recent History

Why Conduct a Spectroscopic Search for Life in the Cosmos?

Deepen our understanding of Life :

Origins of Life: Determinism vs Contingency (random chance)

"Rewind & replay the evolutionary tape of life" – different outcomes?

Focus on detecting biological products only, not including technology

Basic Science Goals in the Search for Spectral Signatures of Extrasolar Life & the Broad Diversity of Terrestrial Planets

Multiple independent origins of life? Broadest possible diversity of life?

Diversity of rocky planets probably exceeds that in our solar system (SS)

Orbital architectures probably more diverse than our SS

Stellar diversity

Circumstellar habitable zones

Telescope performance must be able to capture key aspects of diversity

Develop spectroscopic strategies to discern conditions & compositions

Interpretation of Visible & IR Spectra of Terrestrial Planets

Key Parameters: Effective temperatures, surface temperature, planet size & mass, cloud coverage & its consequences, etc.

Continuum observations: planetary temperatures, radii and masses (MIR), consequences for O_2 detections

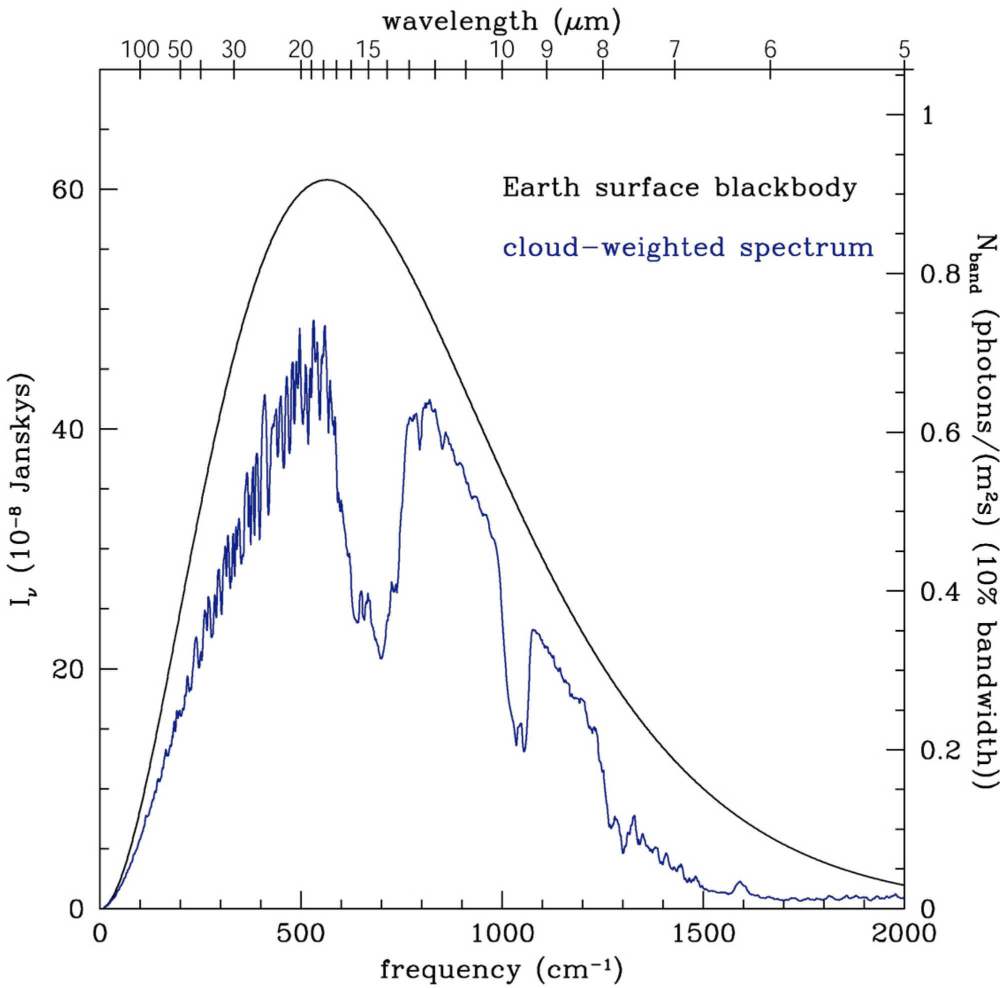
Observations of bands

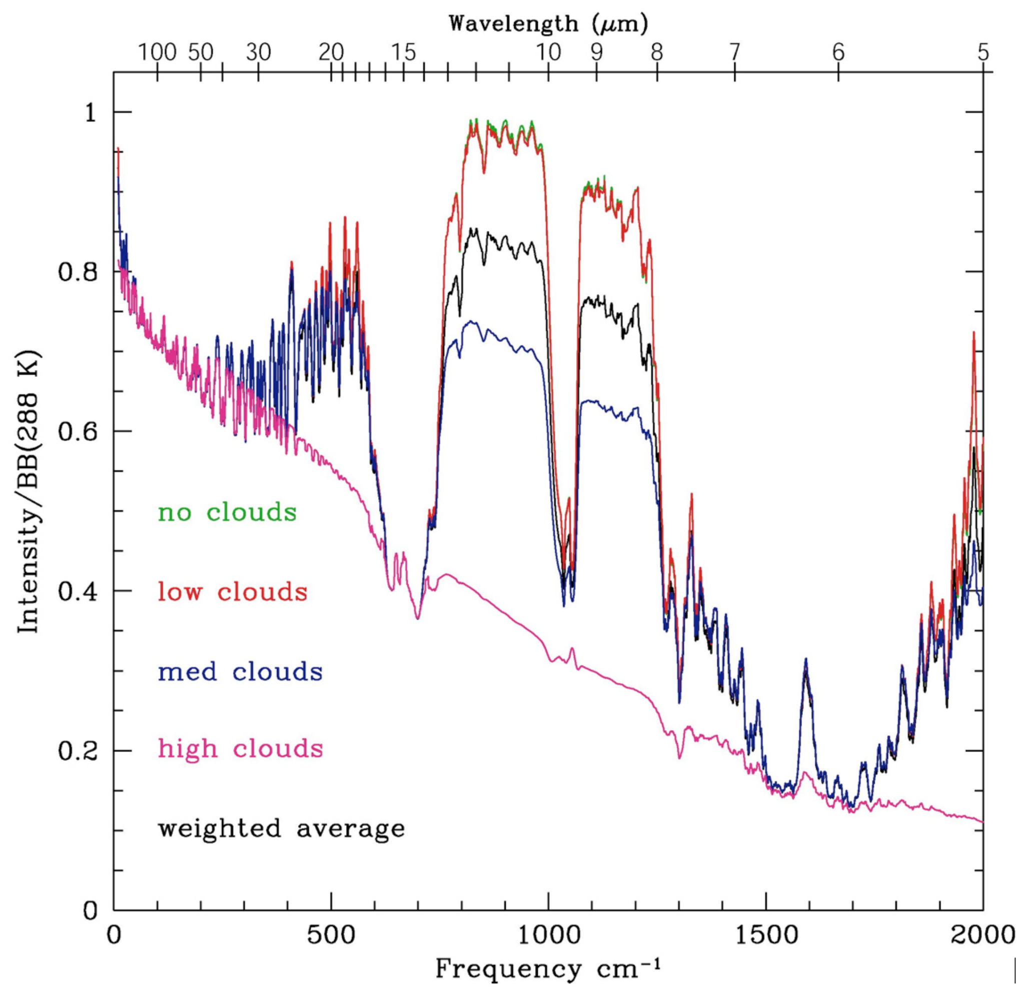
Determining parameters from visible and near-IR bands

Effects of dust rings, binary planets, and dust trails - artifacts

IR and Visible Molecular Band Features

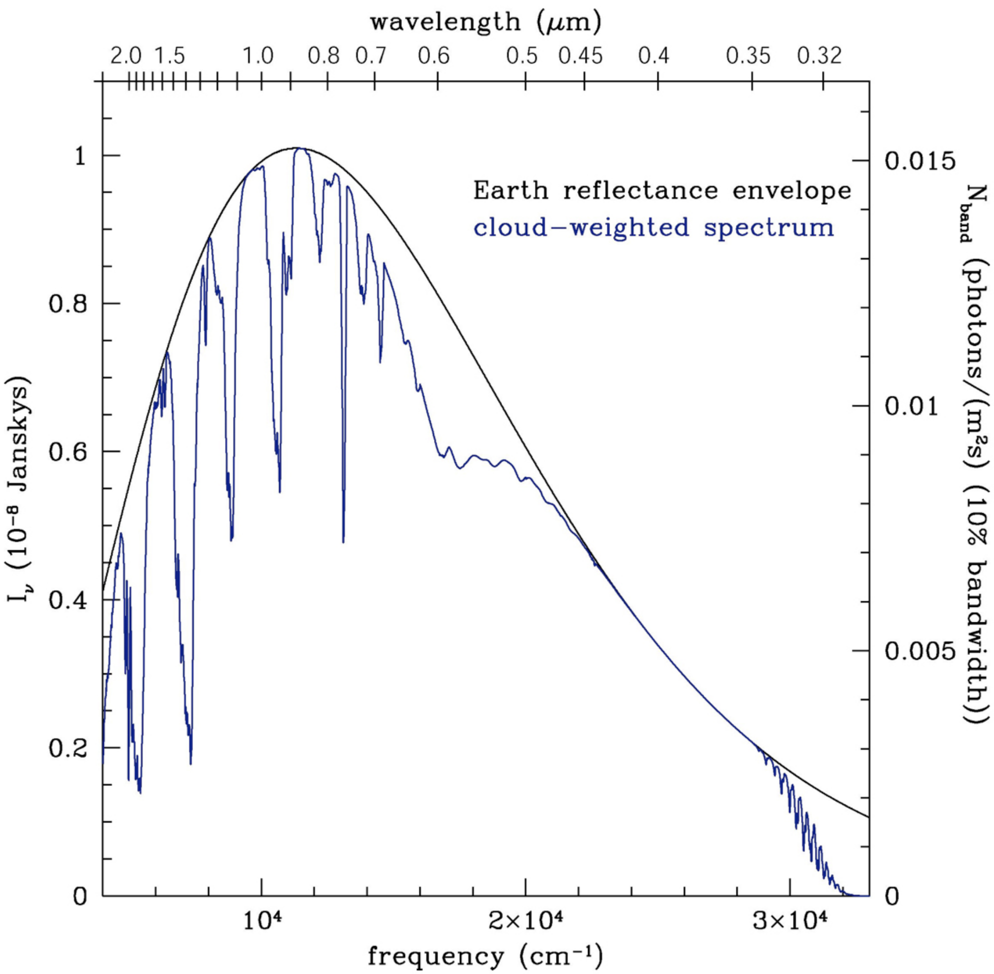
Atmosphere & Clouds : Figs. 2 & 4 (MIR)

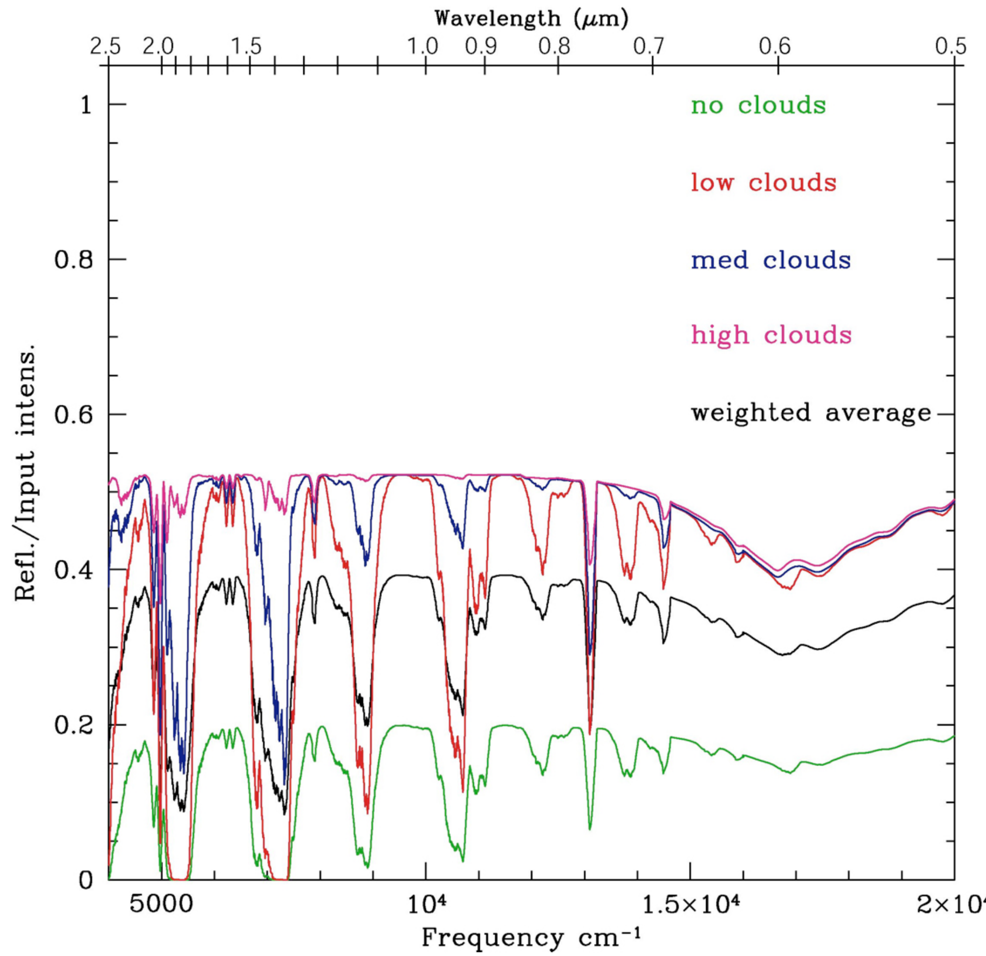




IR and Visible Molecular Band Features

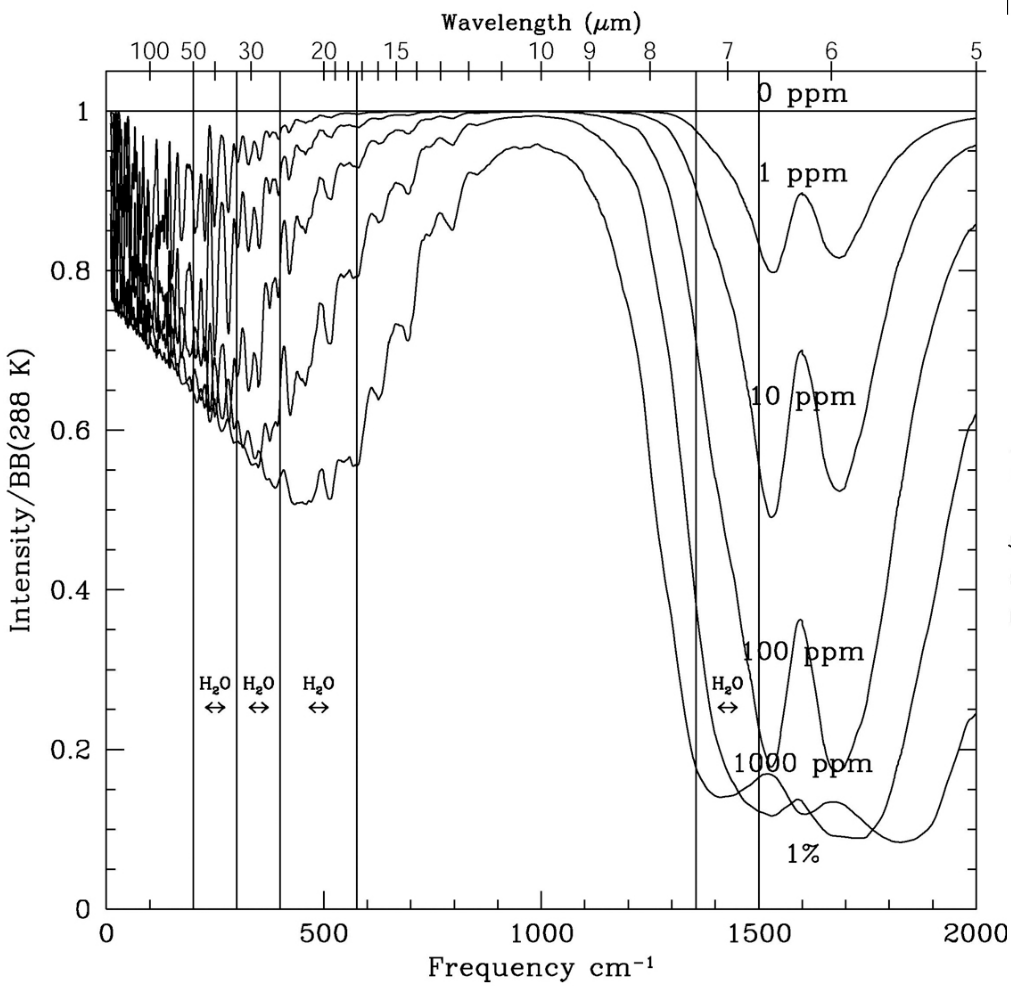
Atmosphere & Clouds : Figs. 3 & 5 (VIS-NIR)

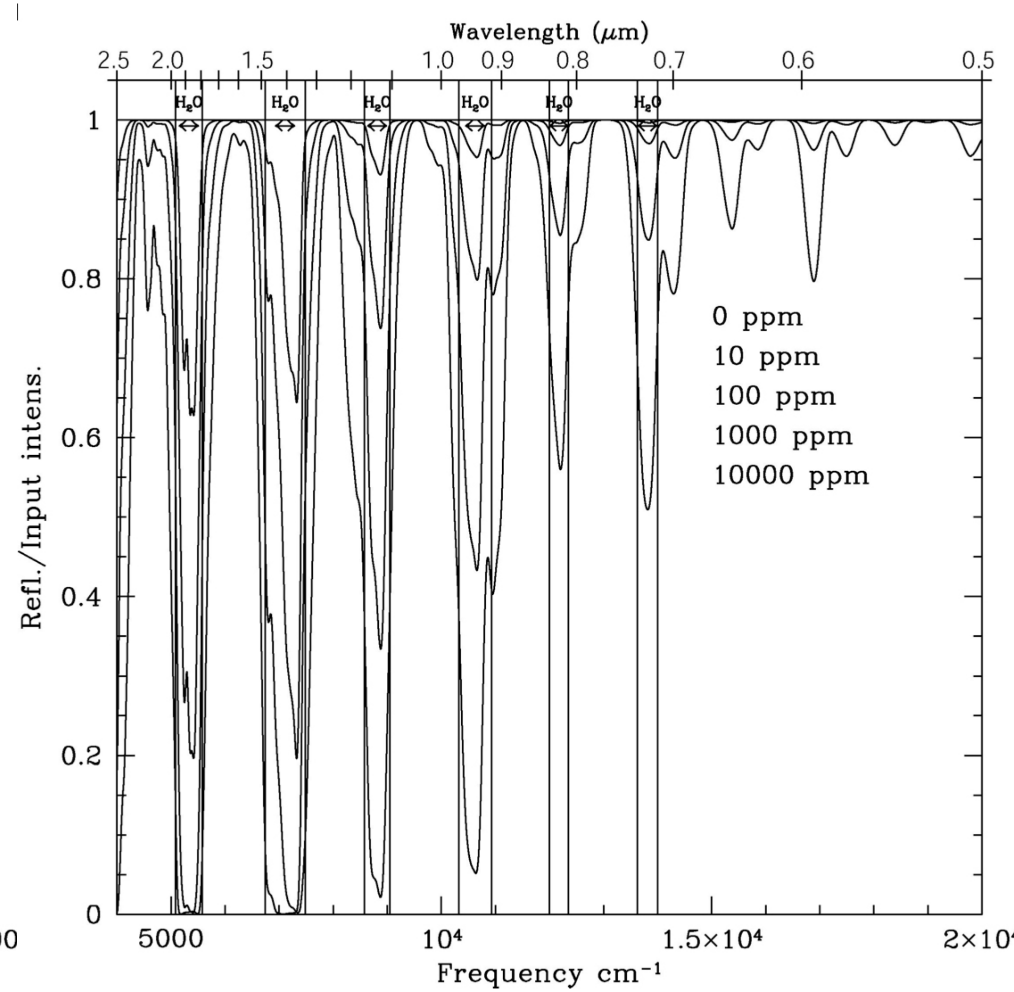




IR and Visible Molecular Band Features

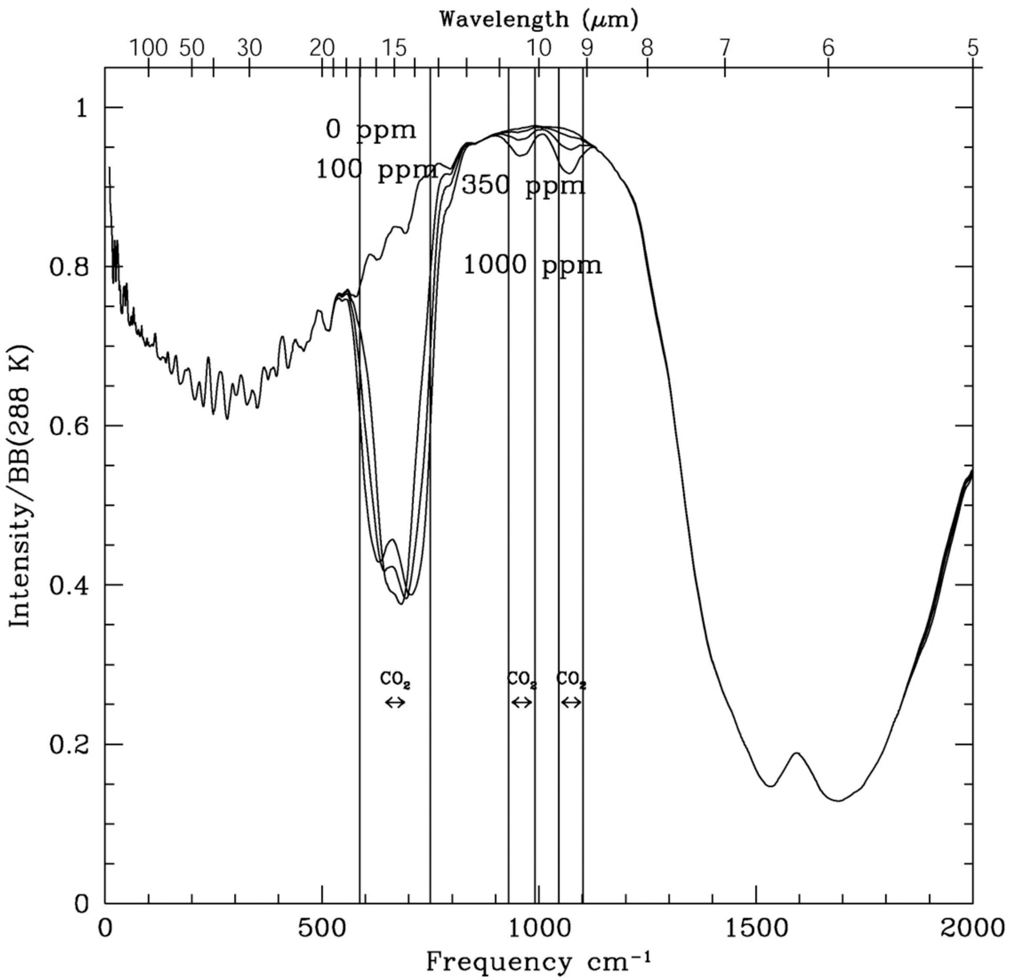
Water Vapor: Figures 6 (MIR) & 7 (VIS-NIR)

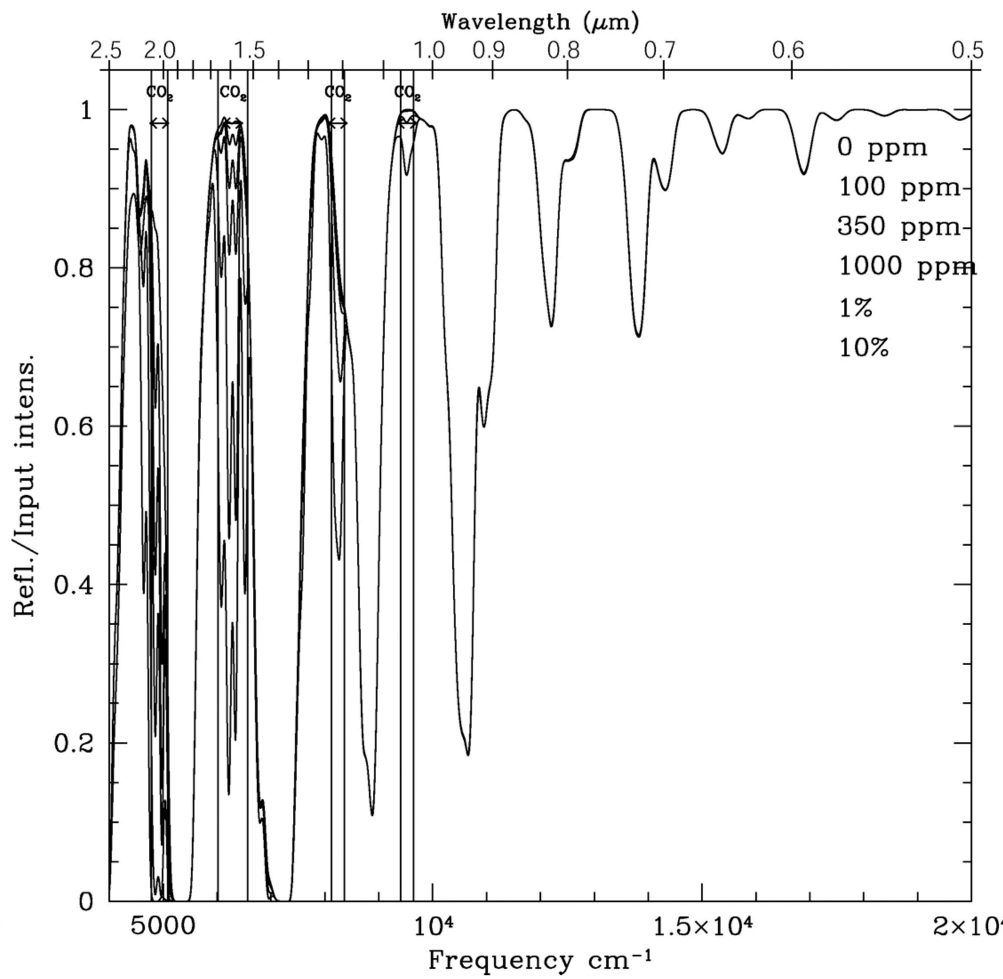




IR and Visible Molecular Band Features

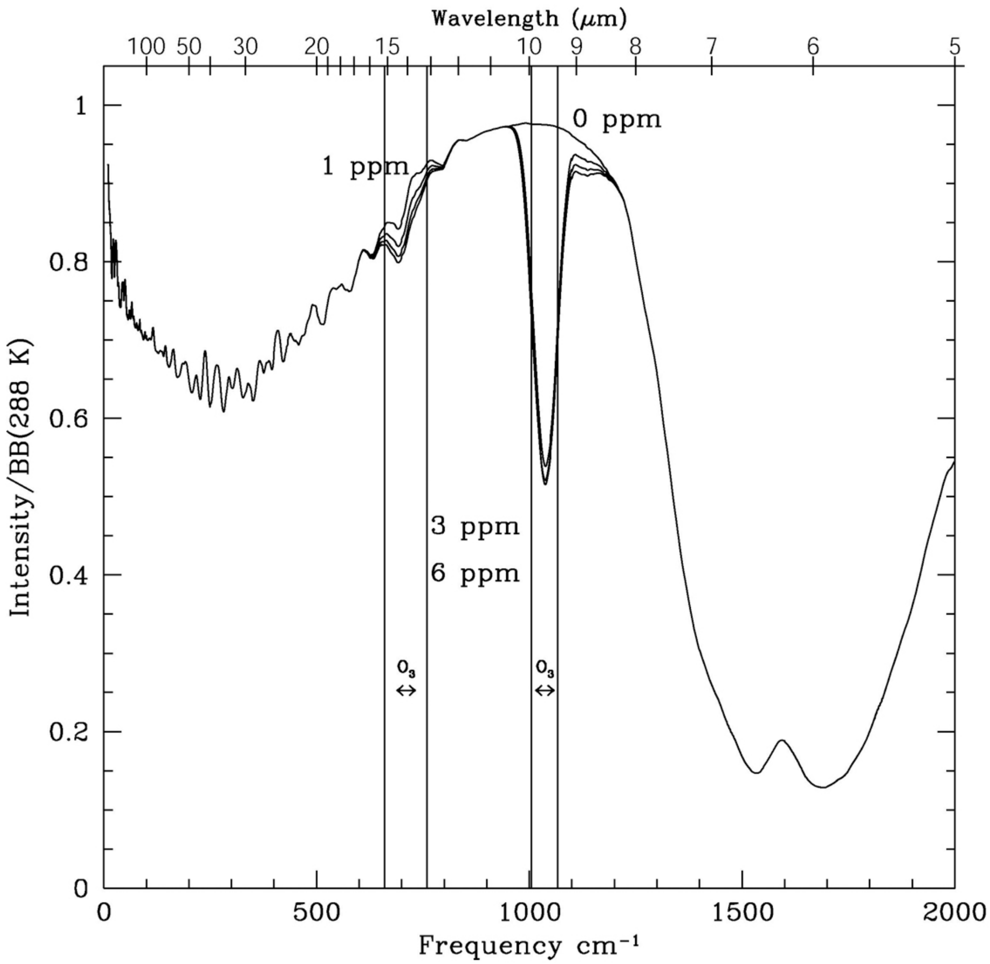
Carbon Dioxide: Figures 8 (MIR) & 9 (VIS-NIR)

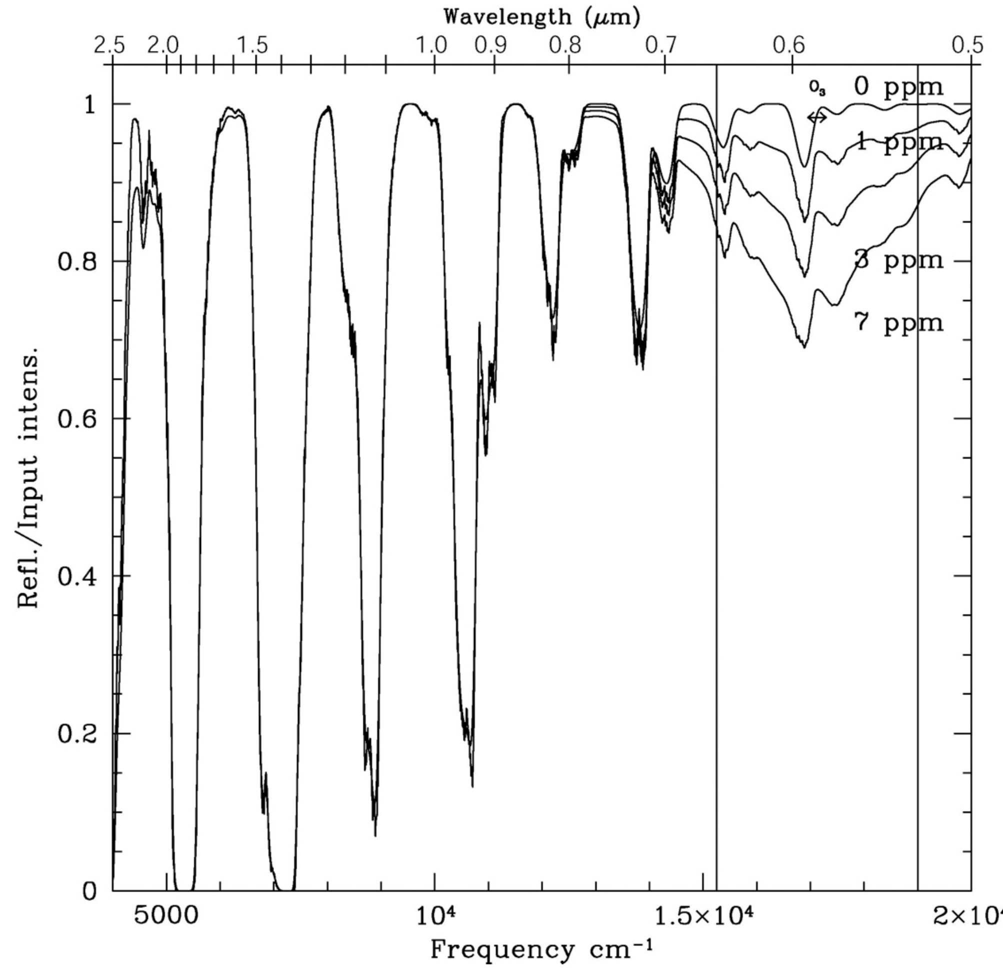




IR and Visible Molecular Band Features

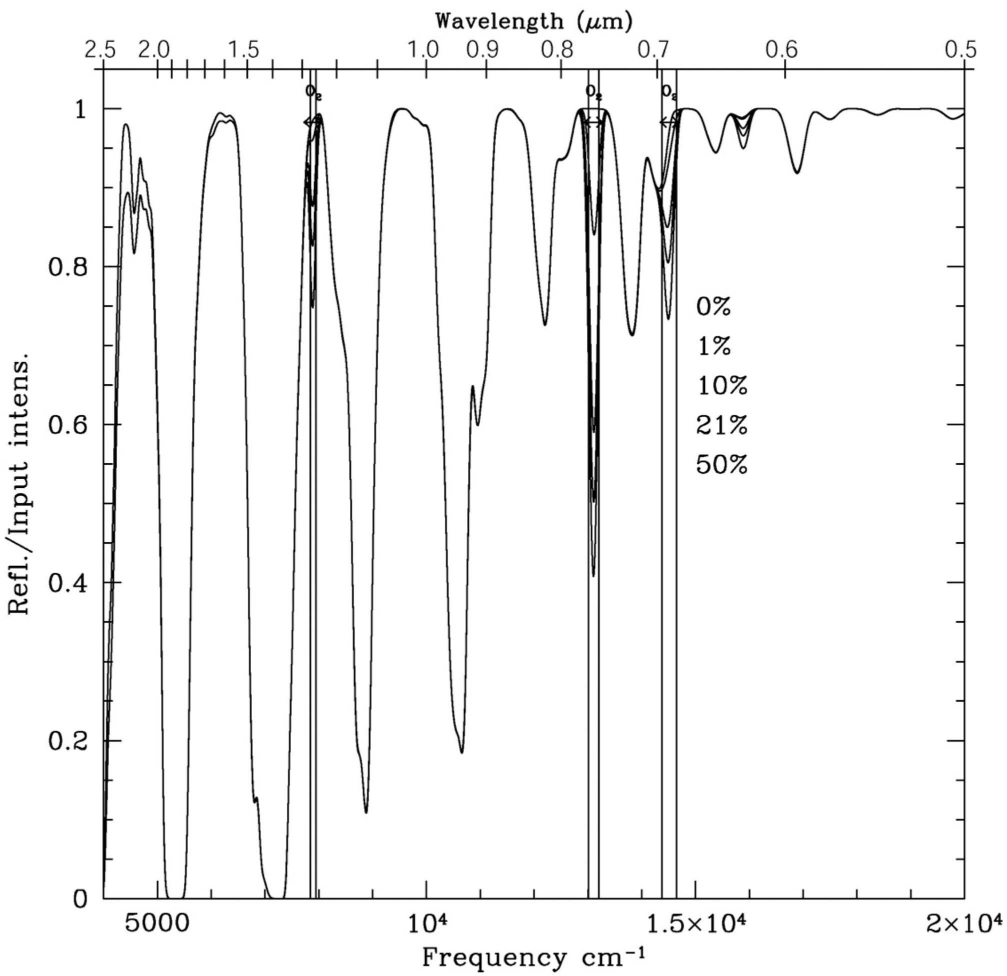
Ozone: Figures 10 (MIR) & 11 (VIS-NIR)



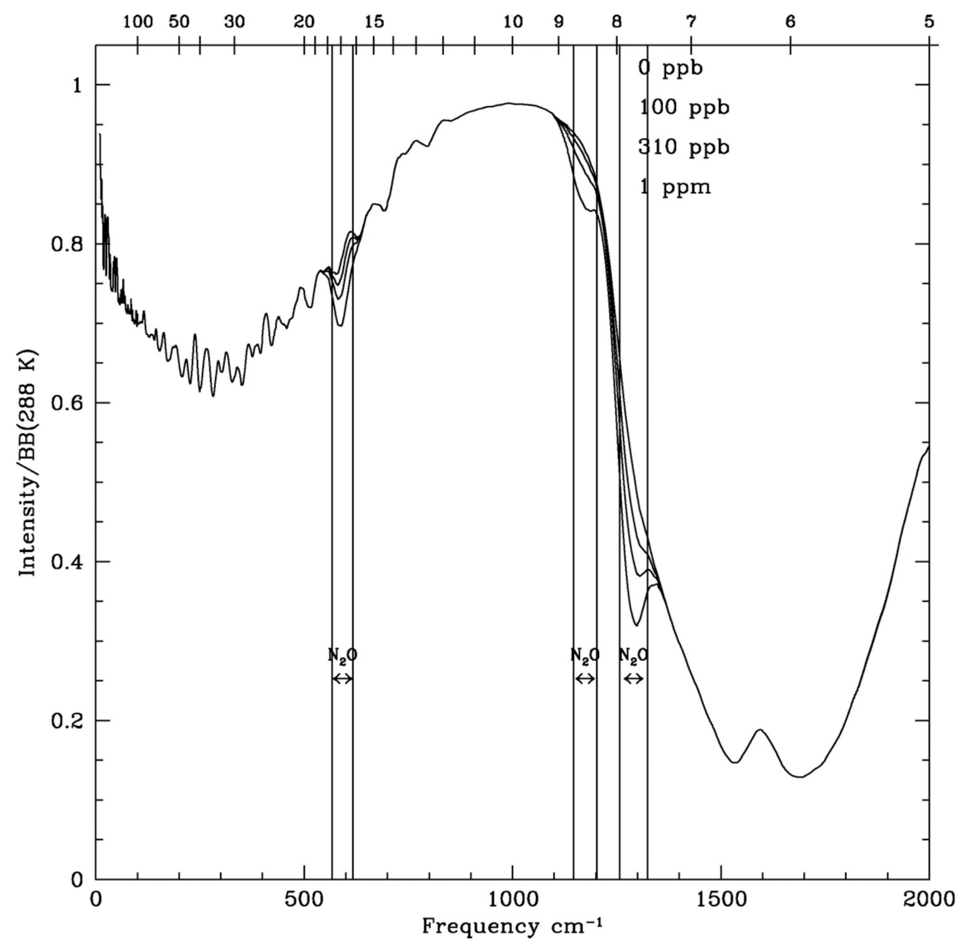


IR and Visible Molecular Band Features

O_2 : Figure 16 (VIS-NIR)

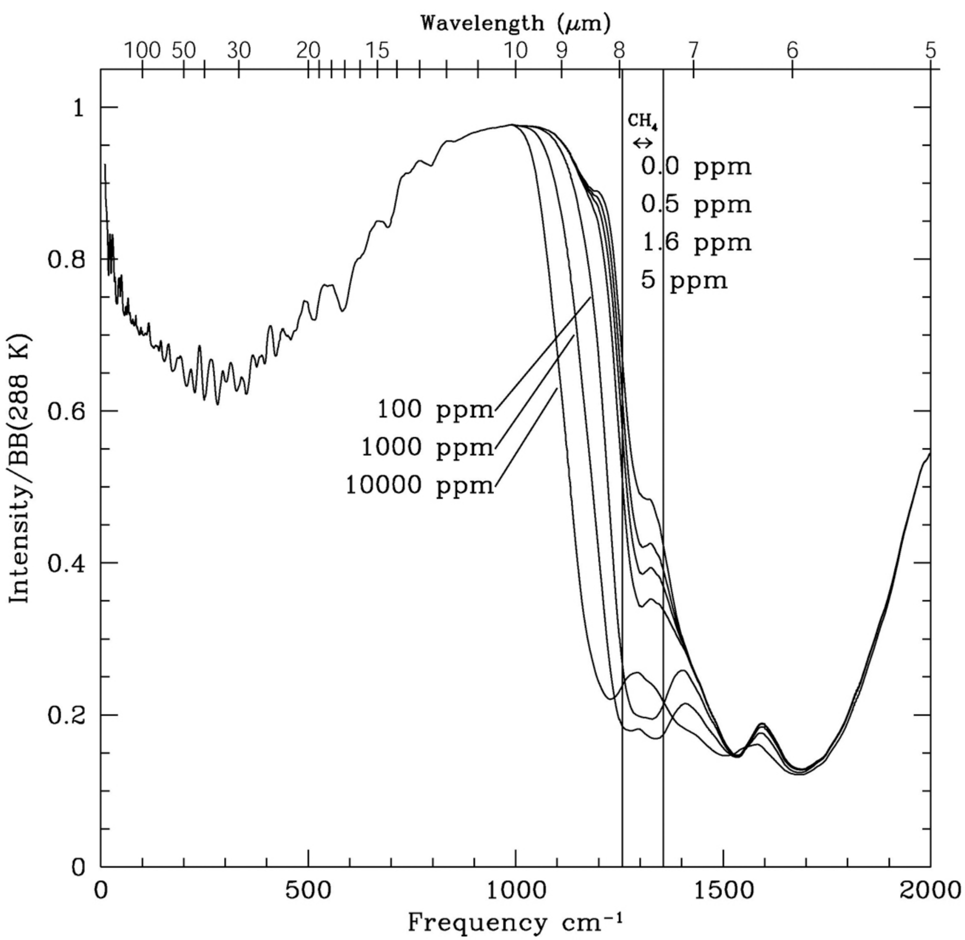


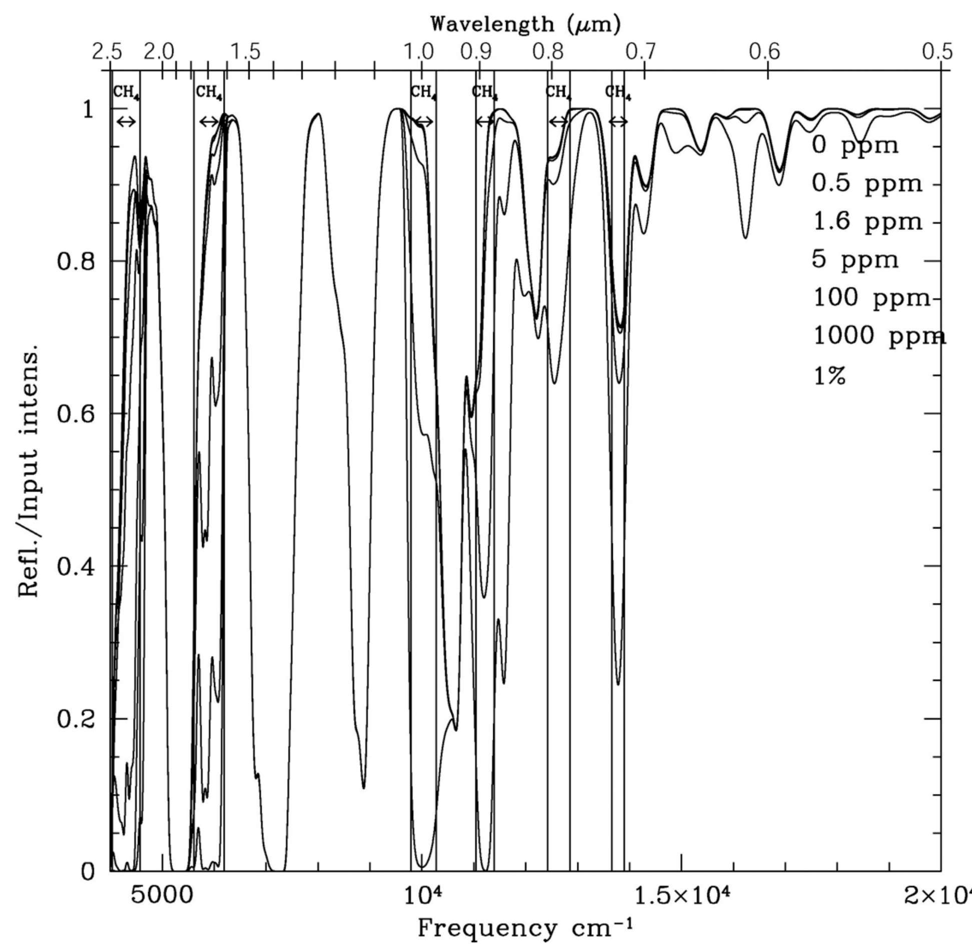
N_2O : Figure 15 (MIR)

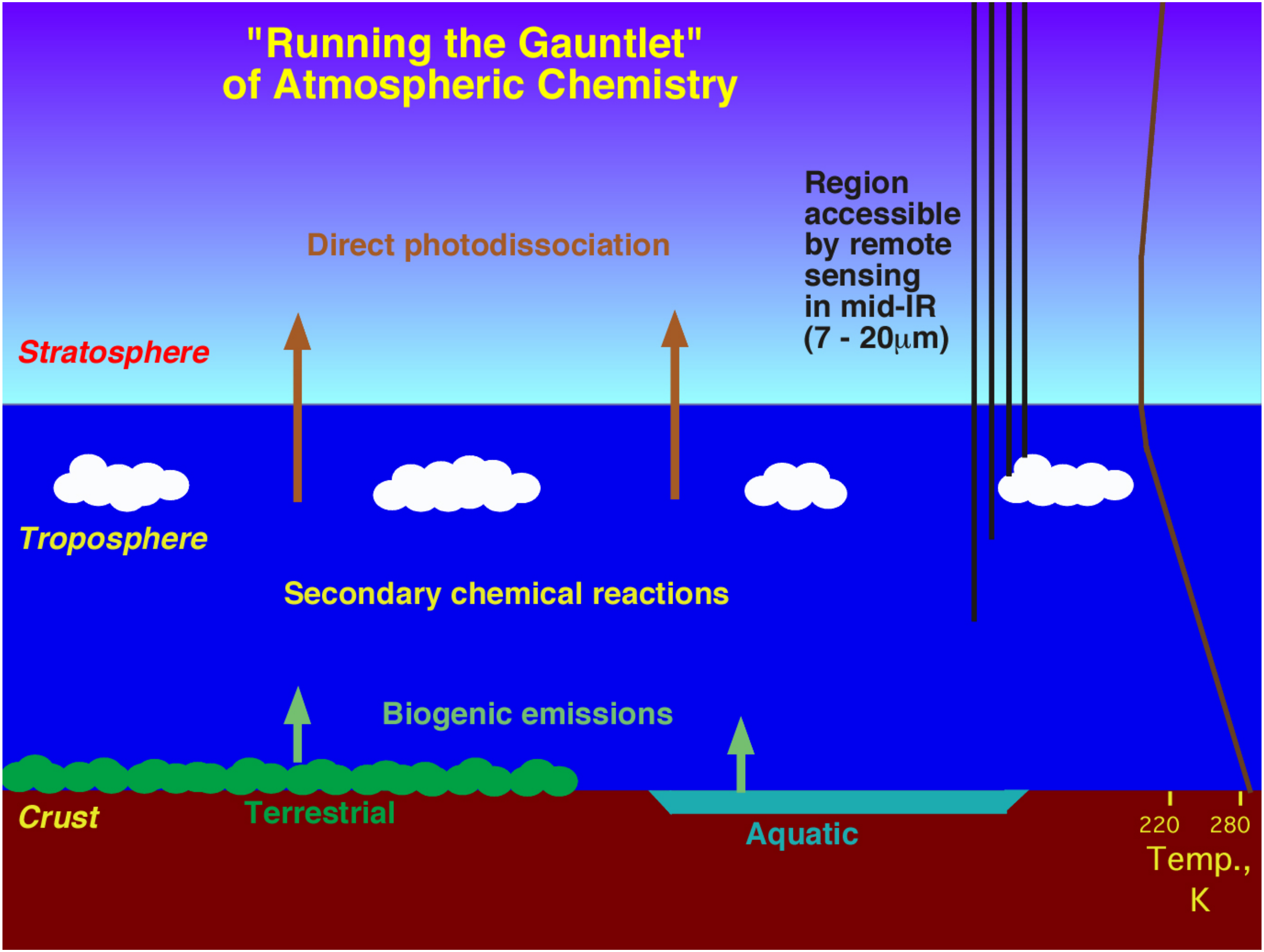


IR and Visible Molecular Band Features

Methane : Figures 13 (MIR) & 14 (VIS-NIR)






"Running the Gauntlet"
of Atmospheric Chemistry
Region accessible by remote sensing in mid-IR (7 - 20μm)
Direct photodissociation
Stratosphere
Troposphere
Secondary chemical reactions
Biogenic emissions
Crust
Terrestrial
Aquatic
220
280
Temp., K

Spectral Features from the Planet's Surface

Seasonal changes - MIR

Weather

Different surface types viewed during rotation

Albedo of oceans, land and ice

Planet rotation – rate, MIR vs VIS/NIR effects, cloud obscuration

Photosynthetic organisms – spectral features, pigments, red edge

Earthshine spectra from lunar observations

Conclusions: Wavelength Ranges and Prioritization of Spectral Features

1. O_2 (VIS/NIR) or its photolytic product O_3 (MIR) – a key biosignature but be careful of potential abiotic sources, need additional information about planetary environment

2. O_3 (MIR) – easier to detect at low concentrations, but a poorer indicator of O_2 abundance

3. Water Vapor (MIR, VIS/NIR) - key for life, estimate temperature

4. CO_2 (MIR) and CH_4 (VIS/NIR) – C is key for life, CO_2 can be evidence of a terrestrial planet, CH_4 is potential biosignature but also has abiotic sources

5. Planet size (MIR) – geological activity, temperature