The Astronomical Detection of Biosignatures on Extrasolar Terrestrial Planets: The Virtual Planetary Laboratory

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Abstract

NASA and ESA are designing space-based observatories to detect and characterize extrasolar terrestrial planets. Because these systems will initially resolve planets only as point sources, we must learn to distinguish habitable worlds and to discriminate between planets with and without life based entirely on the interpretation of remote sensing observations of disk-averaged spectra. The Virtual Planetary Laboratory (VPL) is being developed to assess the information content of such observations and to optimize the designs and search strategies for future missions.

The VPL is a suite of computer models that simulates environmental processes that contribute to a planet's spectrum. Its core consists of coupled radiative transfer, climate, and atmospheric chemistry models that have been validated in studies of the Earth and our neighboring planets. Geologic, biospheric, and exogenic modules are being added to simulate a broad range of environments on planets in orbit around stars with different luminosities and stellar types. A self consistent description of these physical, chemical, and biological processes is essential for assessing the detectability of spectral biosignatures because these processes can conspire to exaggerate or mask discriminating spectral features.

Given initial conditions (stellar type, orbit characteristics, mass, radius, rotation rate, surface and atmospheric bulk composition, surface type, volatile inventory, etc.), the VPL marches forward in time to generate an equilibrium environment. It then produces a disk-averaged spectrum for a specified viewing geometry, processes this spectrum with an instrument simulator model, and analyzes it to assess the detectability of biosignatures with instruments like those being considered for NASA's Terrestrial Planet Finder and ESA's Darwin missions.

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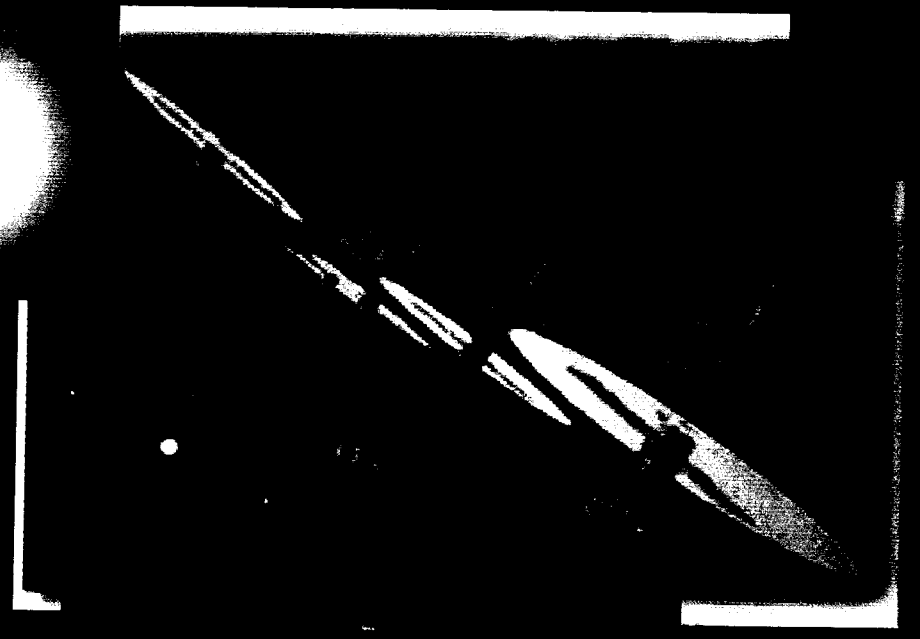
NASA

Terrestrial Planet Finder and Darwin

Nulling Interferometers



Coronagraphs

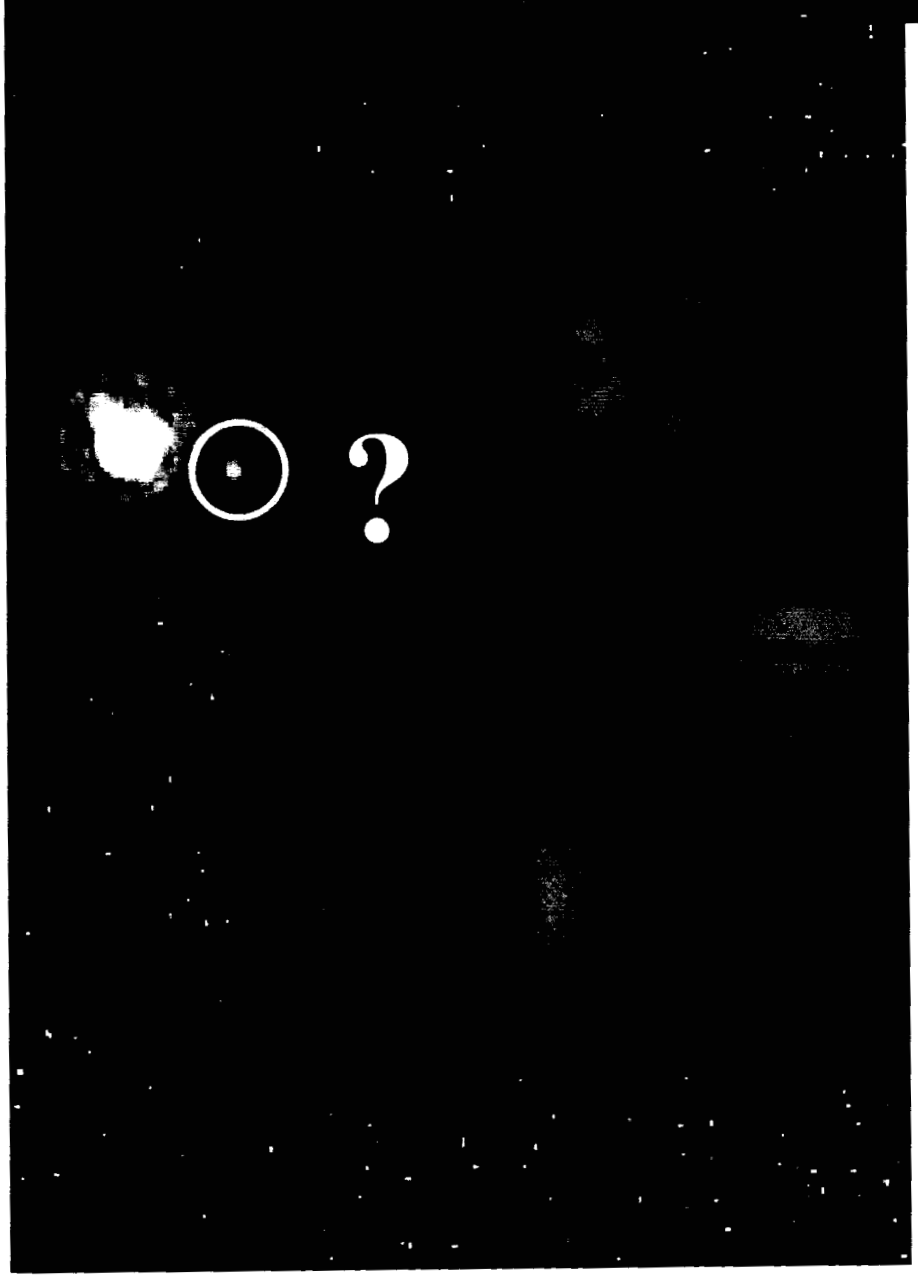
The Terrestrial Planet Finder Mission

- **Goal: Direct detection and characterization of Earth-sized planets in their habitable zones.**
  - Are there nearby Earth-like planets?
    - Search 150 stars up to 45 light years away
  - Do they have atmospheres?
  - Is there any sign of life?

Table 6.1. Time Requirements For Various Configurations of TPF to Observe Terrestrial Planets

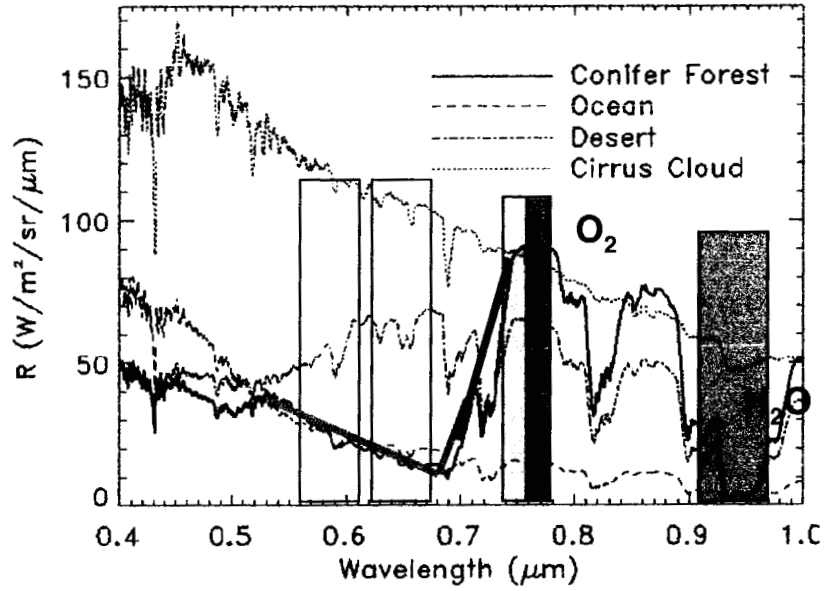
Science Goal	12 μm observation of an Earth at 10 pc	4×2 m (5 AU)	4×0.85 m (1 AU)	4×2 m (1 AU)	4×2.7 m (1 AU)	4×3.5 m (1 AU)
Detect Planet	Spectral Resolution R=3 Signal to Noise SNR=5	1.4 hr	470 hr	15.3 hr	5.1 hr	2.0 hr
Detect Atmosphere CO_2, H_2O	R=20/SNR=10	2.4 day	-	18.1 day	5.9 day	2.3 day
Habitable? Life? O_3,CH_4	R=20/SNR=25	15.0 day	-	-	-	14.7 day

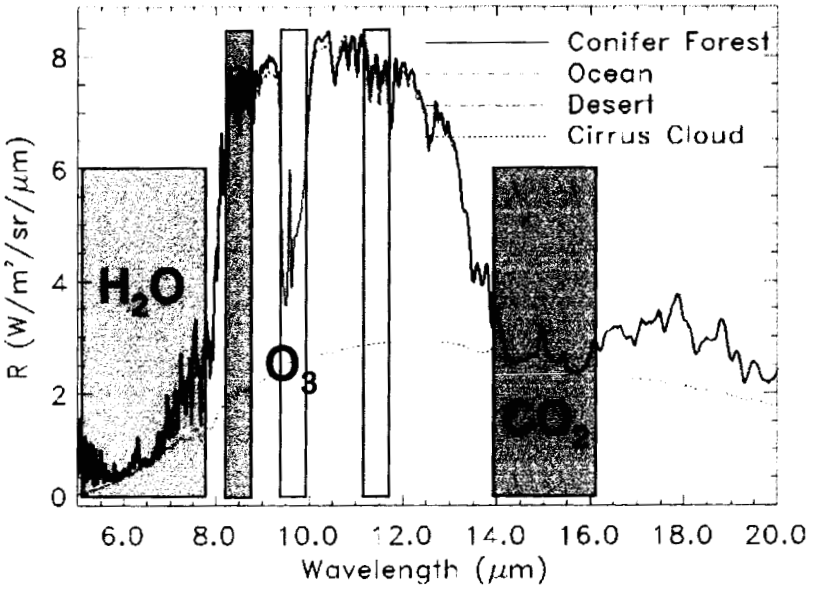
Planetary Remote Sensing



- Once an extrasolar terrestrial planet has been detected and resolved from its parent star
  - All information about its environment will arrive as photons
  - This information can be decoded using remote sensing methods
- Several remote sensing techniques have been developed for studying planets in our solar system
  - Photometry
  - Spectroscopy
- Extrasolar planets will pose special challenges
  - The planet will appear as an unresolved point source
    - No direct constraints on size
    - No spatial details
    - Limited signal-to-noise
  - No prospects for ground truth

Spectral Photometry



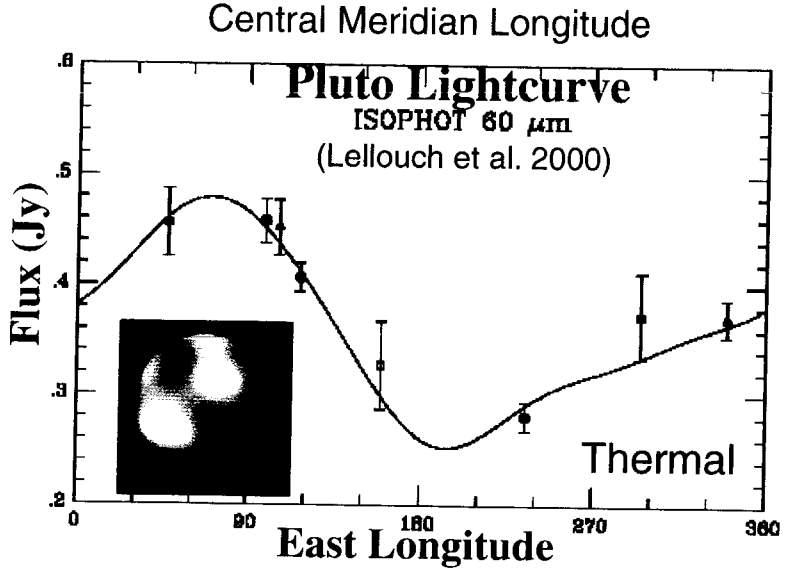


Photometric observations of an unresolved planetary disk are most useful when you know what you are looking for

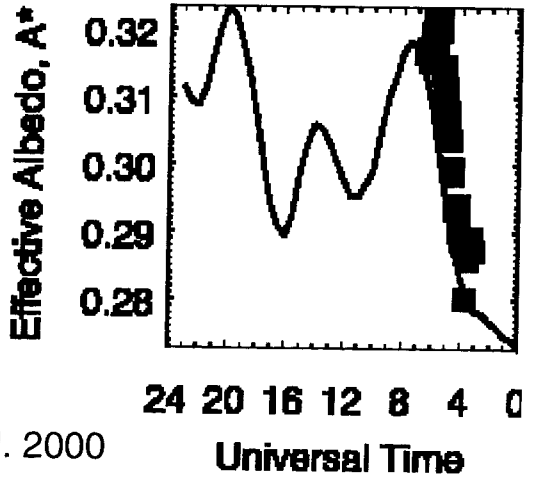
- Surface properties
  - Chlorophyll red edge
- Atmospheric constituents
  - 0.76 μm O_2 A-band
  - 0.63 μm H_2O band
  - 9.6 μm O_3 band
  - 15μm CO_2 band
- Atmospheric and surface temperature
  - 15μm CO_2 band or other well-mixed absorbing gas

CAUTION: Terrestrial planets are NOT black bodies!!

Time-Resolved Photometry



Earthshine: Goode et al. 2000



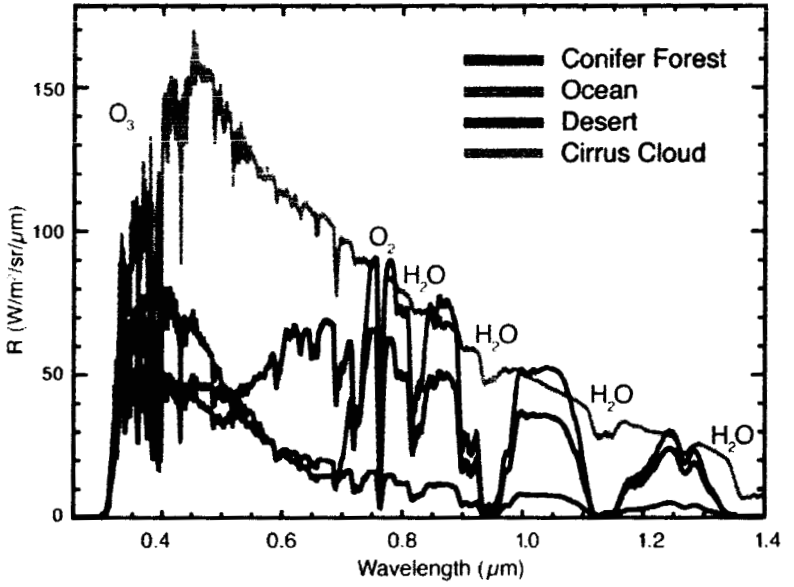
Time-resolved full-disk photometry (lightcurves) constrain:

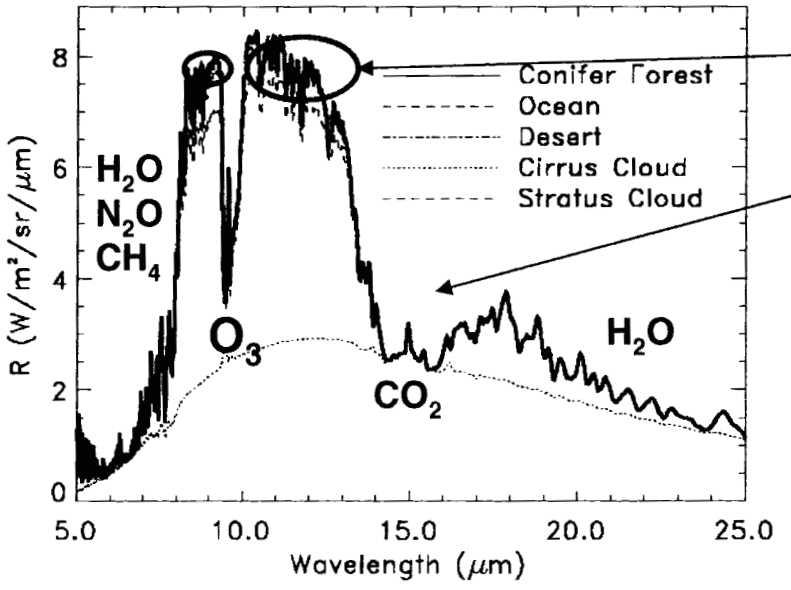
- Rotation periods
- Variations in surface physical properties
  - reflectance
  - thermal inertia
- Weather, climate and other time-variable phenomena
  - Large scale cloud systems
  - Regional/global dust storms
- Occultations by large satellites or of bright background stars would be fortuitous, but could yield constraints on the planet's size

Issues:

- Clouds will reduce the amplitude of the rotational lightcurve and mask the rotation period

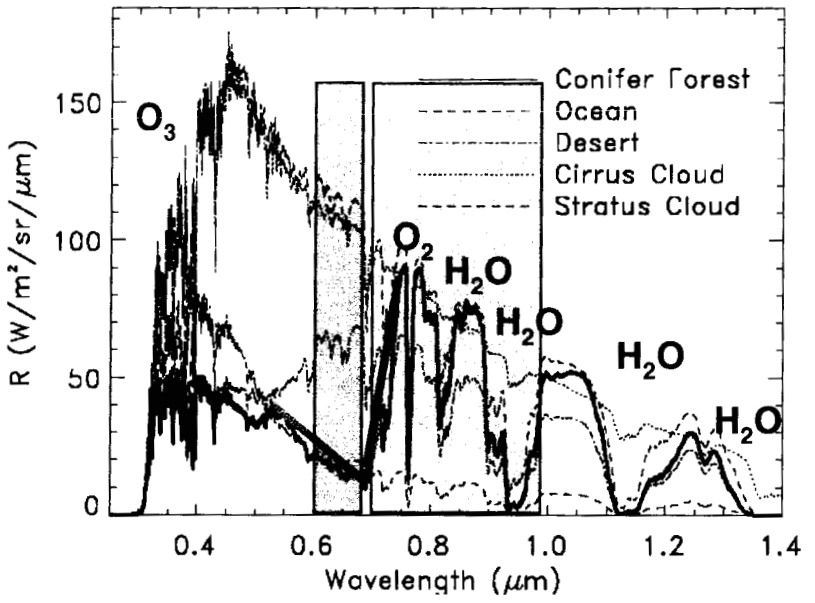
Spectral Remote Sensing





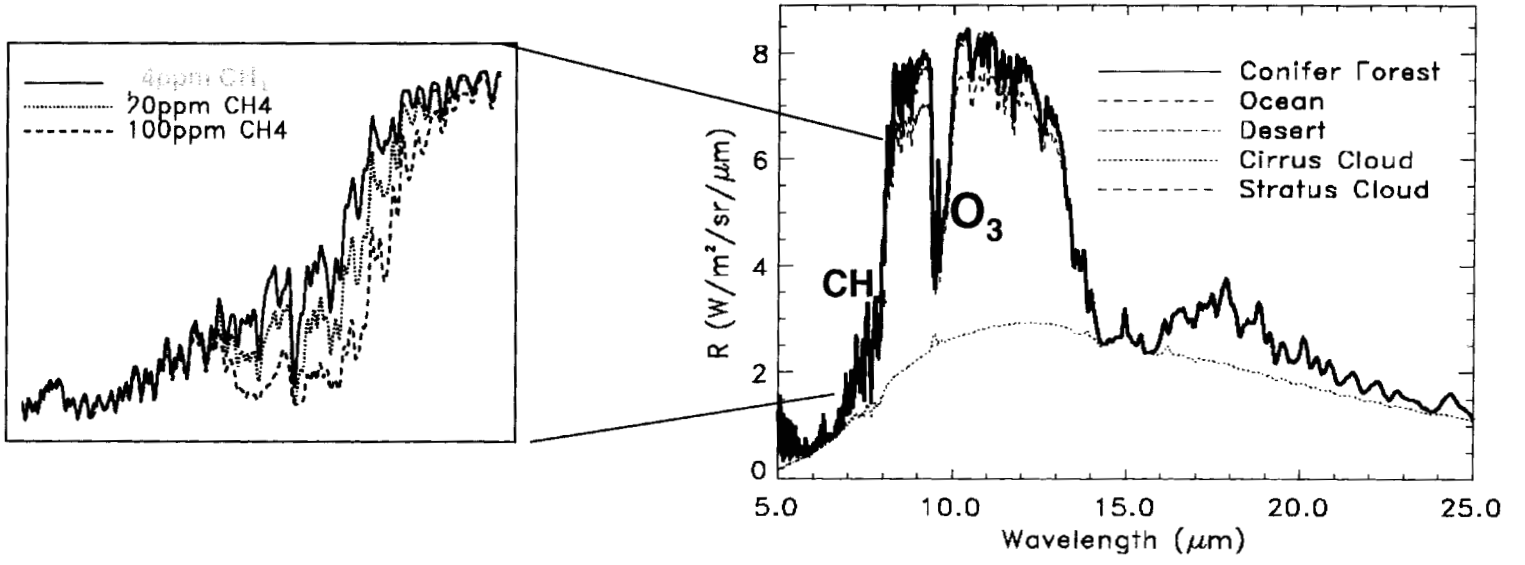
- Reflected Stellar Radiation
  - "Color" of the reflecting surface (cloud top/ground)
  - Atmospheric pressure at the reflecting surface
    - If a primary constituent absorbs at these wavelengths (O_2, CO_2)
  - Column abundance of trace gases
  - Clouds/aerosols
- Thermal Emission
  - Surface temperature
    - Window regions
  - Atmospheric thermal structure
    - CO_2 15 μm band
  - Vertical distribution of temperatures and trace gases above emitting surface
    - **H_2O, O_3, CH_4, N_2O**

Astronomical Biosignatures



Signs of Life:

- **Astronomical Biosignatures are** photometric, spectral or temporal features indicative of life
- **The visible (and NIR)**
  - O_2 (direct detection), O_3(UV), CH_4, chlorophyll and red-edge, H_2O
- **The Mid-IR**
  - O_3 (sensitive indicator of O_2), CH_4 and N_2O (H_2O - habitability)

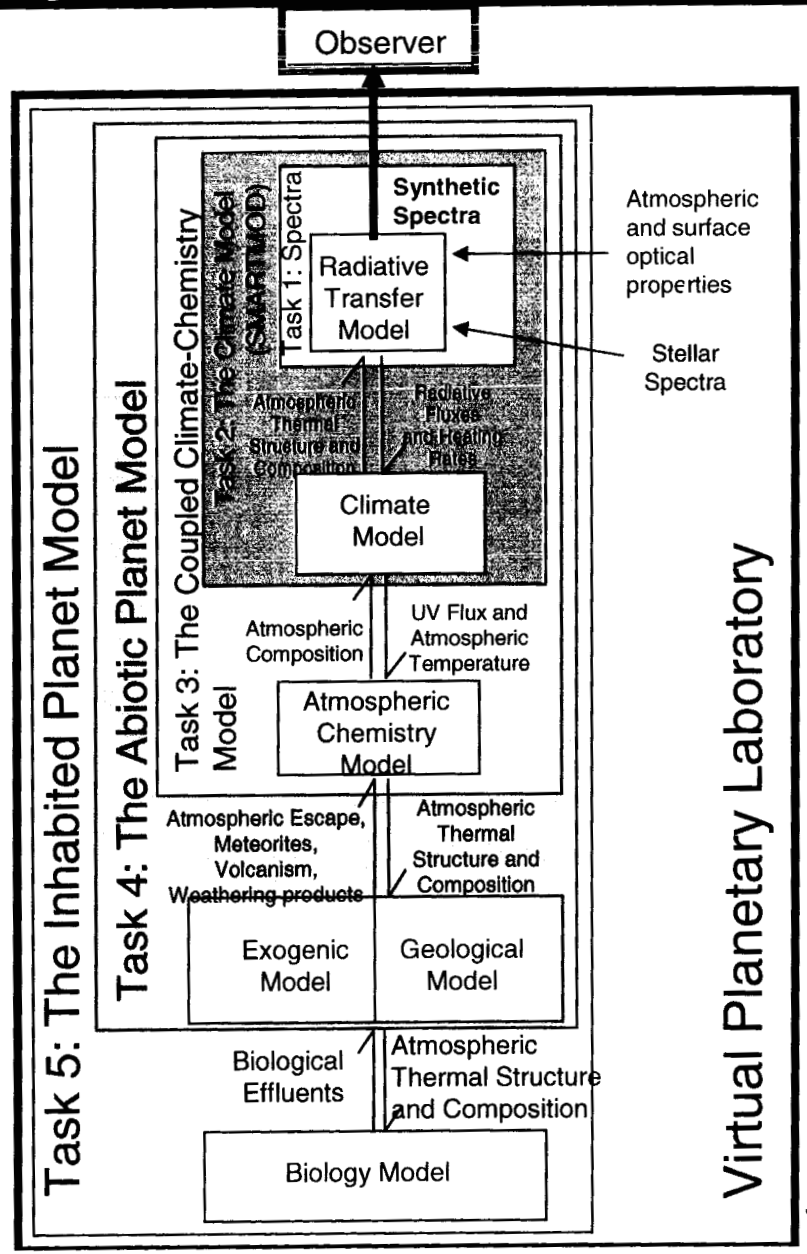


Detecting Biosignatures: The Virtual Planetary Laboratory

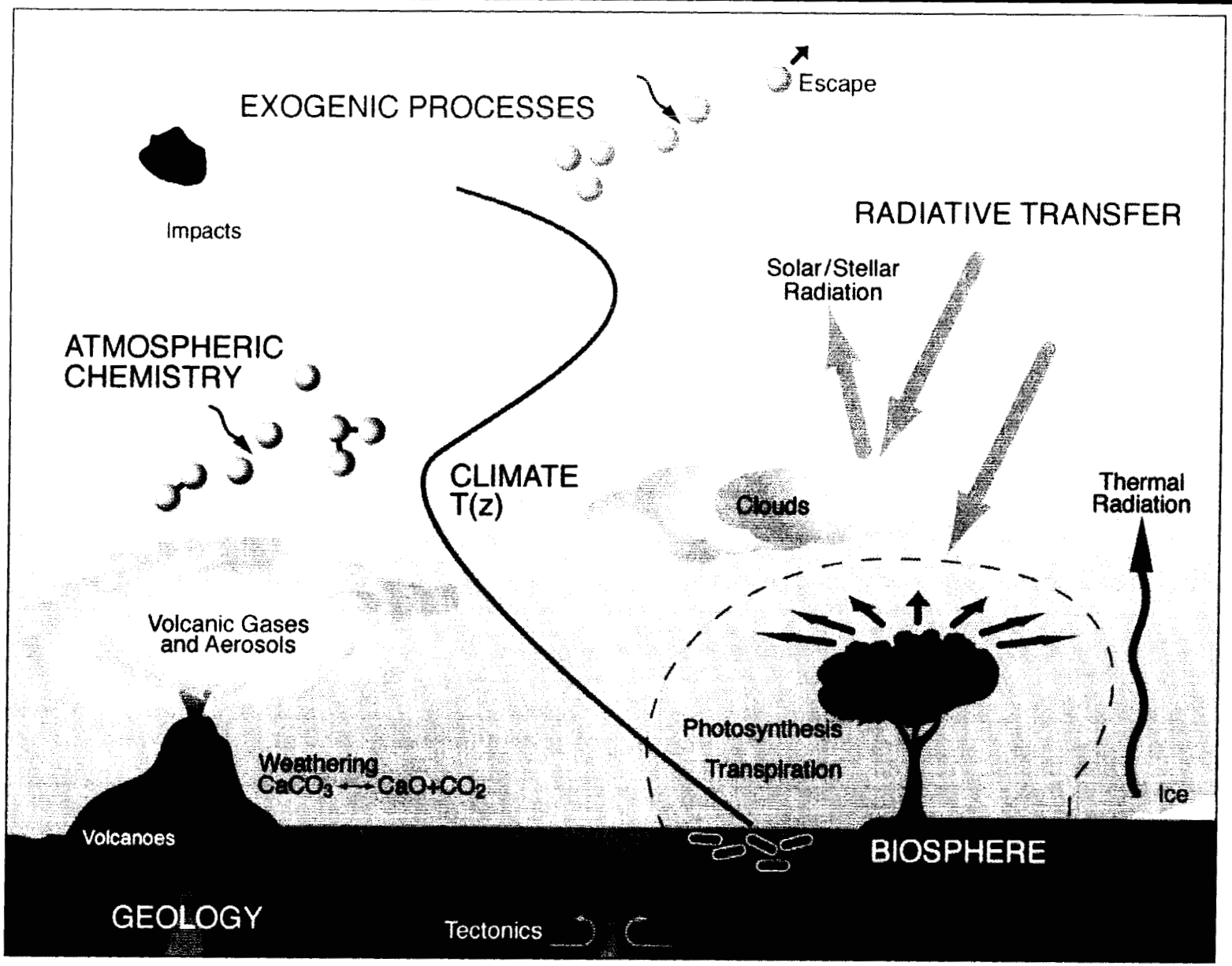
Can observatories and instruments like those currently being conceived detect biosignatures from extrasolar terrestrial planets?

The Virtual Planetary Laboratory (VPL) is a numerical model being developed to

- Simulate a broad range of planetary environments.
  - Planets other than Earth, around stars other than our Sun.
- Include abiotic and inhabited planets
  - Oxygen/non-oxygen producing life
- Generate realistic full-disk spectra that cover a broad range of wavelengths
- ultimately provide a comprehensive, ***flexible*** tool which can be used by a broader community.

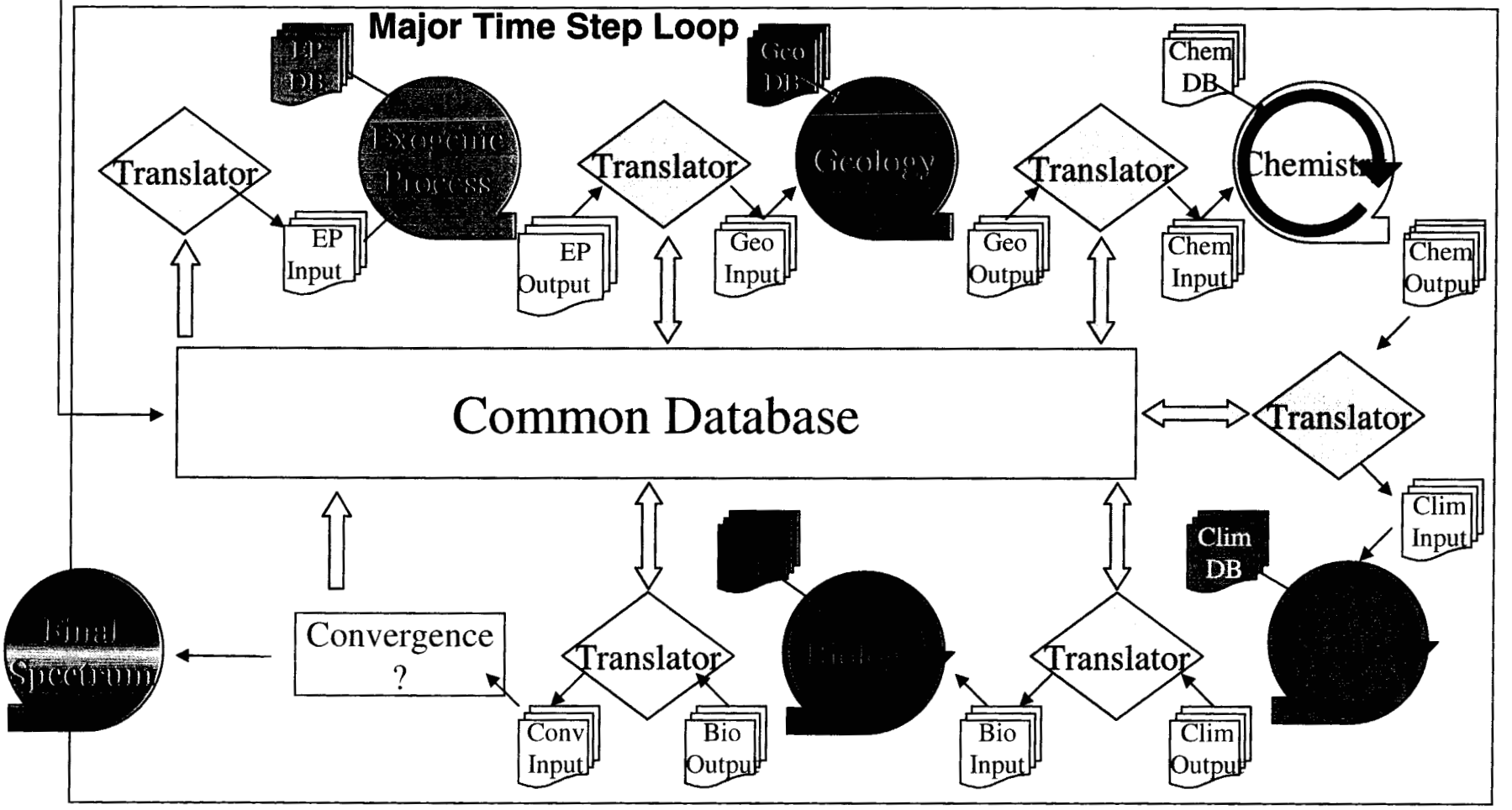


Processes Included in the VPL



VPL Architecture

The VPL simulates equilibrium planetary environments as an initial value problem by marching forward in time from an assumed initial state. It includes a series of modules that share environmental data through a common database as they progress through each time step



Thermodynamically Balanced Planets

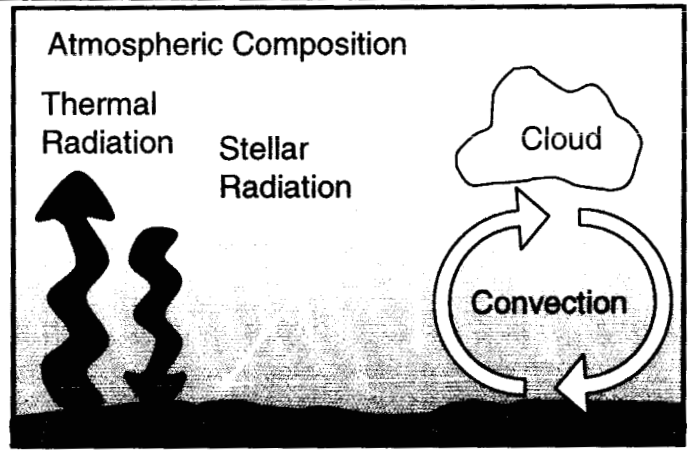
Goal: Investigate spectra of planets in thermodynamic equilibrium

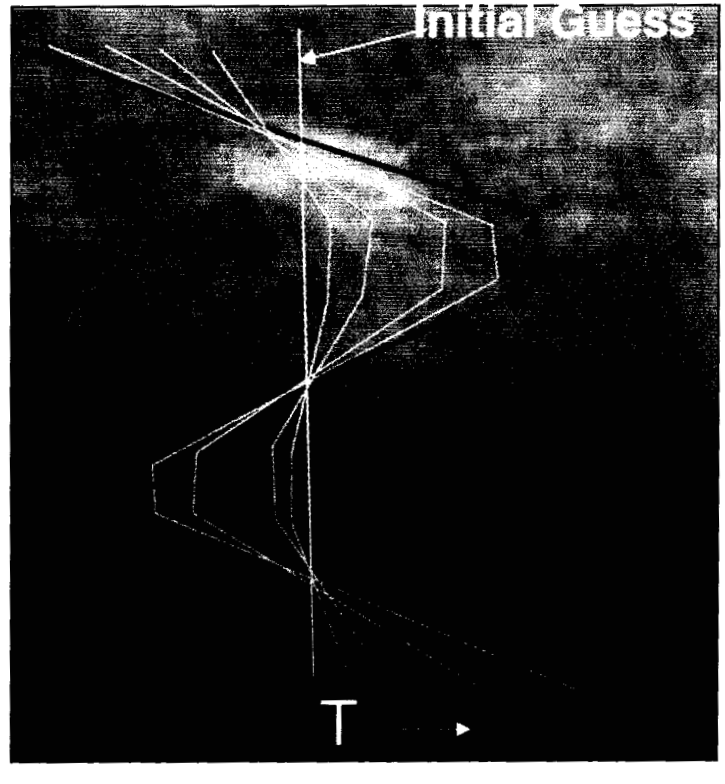
Why a climate model?

- Climate affects a planet's reflected and emitted spectrum
- Climate will change with
  - stellar type
  - orbital distance

A Simple Climate Model

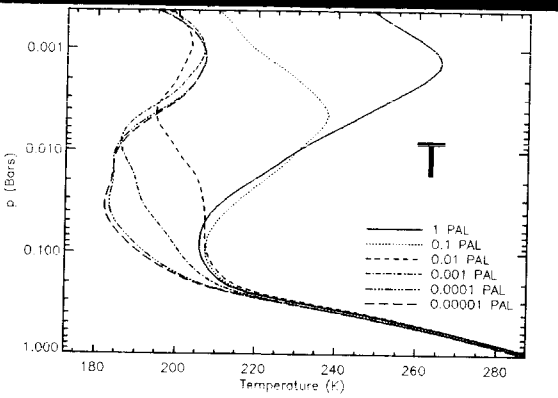
- One Dimensional (vertical)
- Three heat transport Processes
  - Radiative Transfer
    - Solar heating
    - Thermal cooling
  - Vertical Convection
  - Latent heat
    - Cloud condensation, evaporation, precipitation

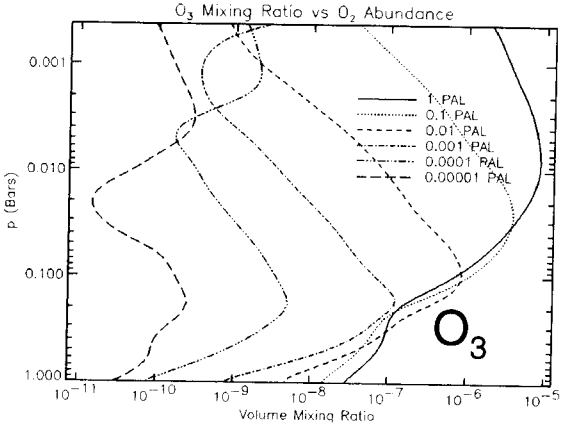


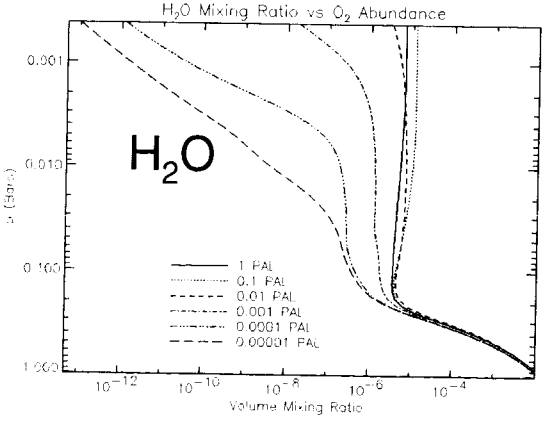


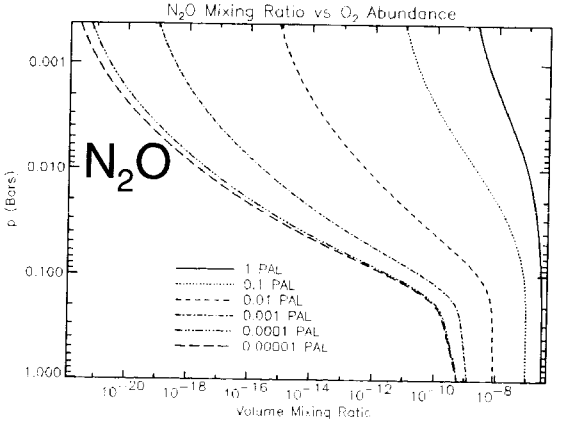
Example: Coupled Effects of Climate and Atmospheric Chemistry

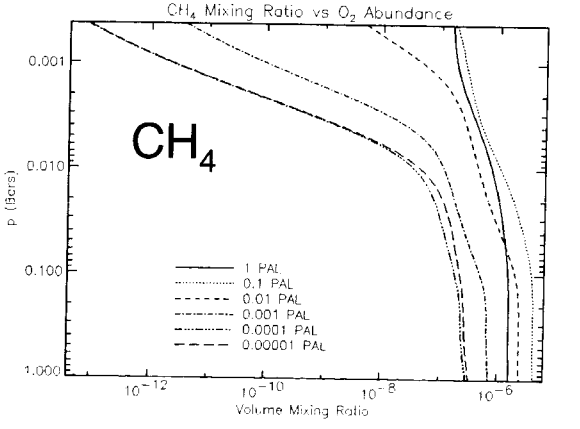
- 1-Bar "Earth-like" atmospheres
  - vary O_2 from present atmospheric levels (20.99%) to $1x10^{-5}$ of its present atmospheric level (PAL). **(Krelove and Kasting 2003)**
- Atmospheric T and composition were allowed to evolve to a near-equilibrium state at 1 AU from a solar-like (G2) star.
  - Abundance of O_3, H_2O, CH_4 and N_2O decrease with O_2 abundance
    - Particularly in the stratosphere
  - Stratospheric temperatures cooled substantially with loss of O_2 and ozone





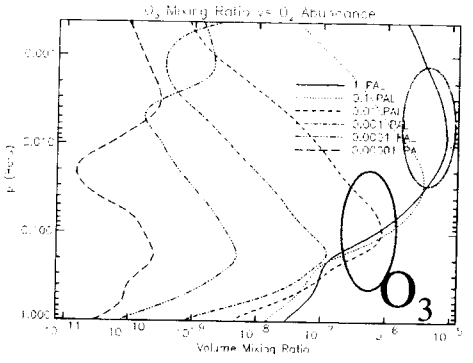


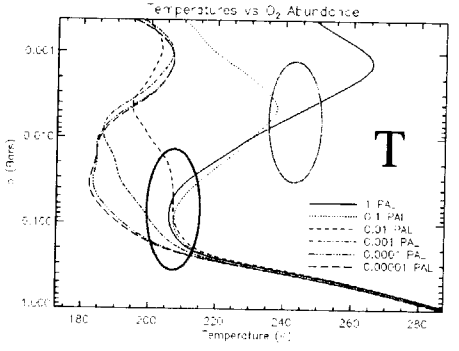


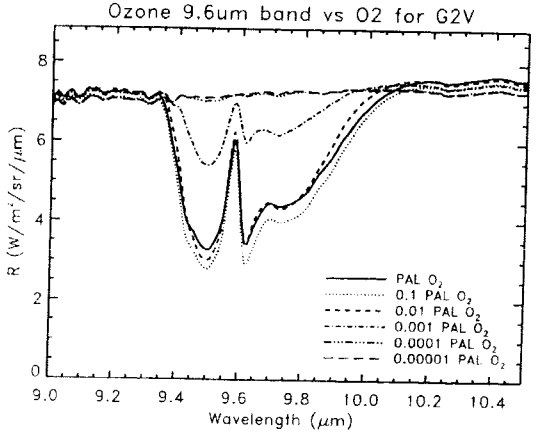


Masking and Exaggerating Biosignatures

Reduced O_2







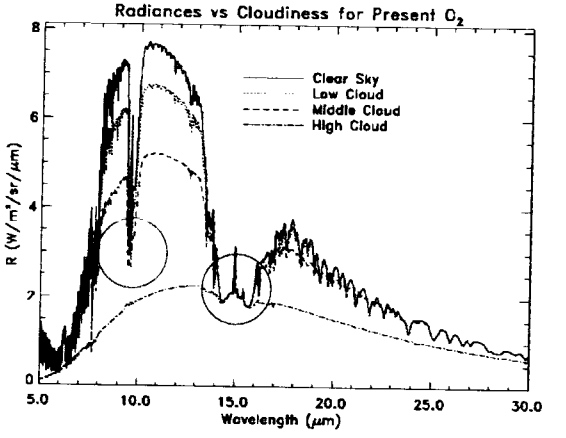
- Equilibrium environments with reduced O_2 have
  - Less stratospheric ozone
  - Lower stratospheric temperatures
    - Less ozone heating
  - A strong 9.6 μm O_3 band
    - Less stratospheric emission
    - 0.01xPAL O_2 case almost indistinguishable from 1xPAL case

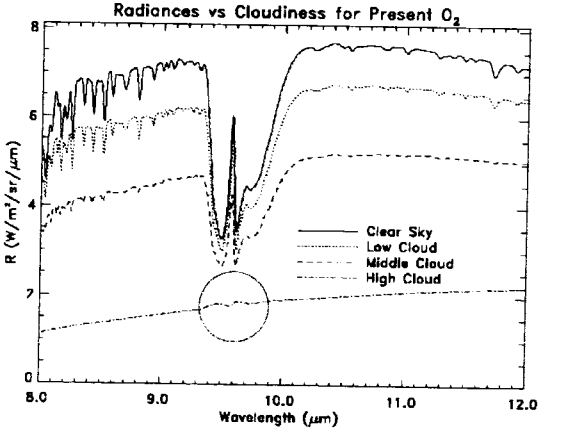
Thermal IR observations of O_3 alone will not provide quantitative constraints on O_2

- High-altitude clouds
  - Mask surface albedos and temperatures
  - Dramatically reduce the spectra strength of the ozone and CO_2 bands

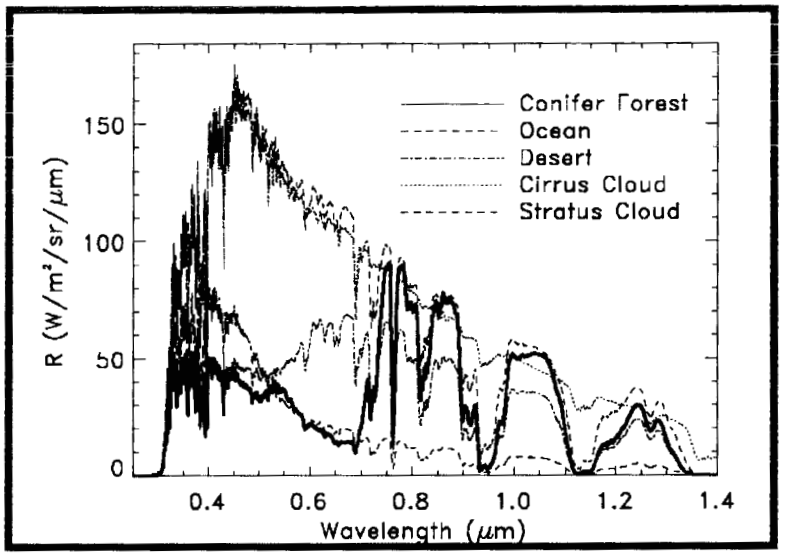
Cloudy planets hide their secrets

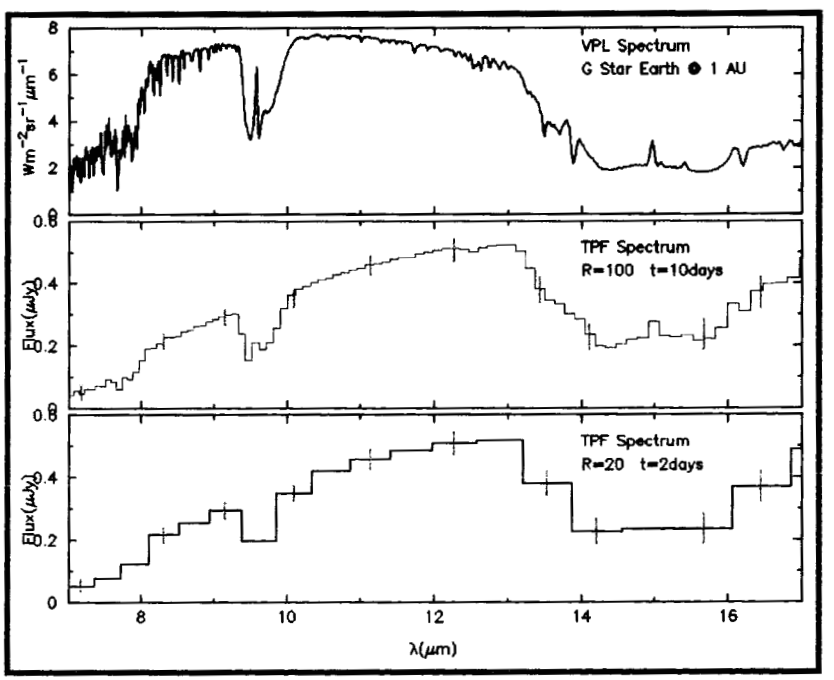
Clouds





Implications for Terrestrial Planet Finder





VIS Coronagraphs

- Most trace gas information is at UV and near-IR wavelengths
  - Currently ignored in TPF designs
- Time dependent photometric or spectroscopic data may be essential to detect/discriminate biosignatures

IR Nulling interferometers

- Atmospheric temperatures must be measured to quantify trace gas amounts from thermal radiances
  - A well mixed gas with a well known spectrum is essential for this
  - The CO_2 15 μm band is the best candidate for terrestrial planets in our solar system (Venus/Earth/Mars)
- Moderate spectral resolution and high signal-to-noise are essential for characterizing environments