Project Report: Delivery of Organic Materials to Planets

Jet Propulsion Laboratory 2
Executive Summary
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The discovery of more and more planets in orbits around extrasolar stars holds out the promise that life exists and can ultimately be identified elsewhere in the Universe. Data gleaned from terrestrial planets in our Solar System, (Mercury, Venus, Mars) are now being used to create computer models that can simulate essential life−supporting characteristics of extrasolar planets and to assess the probability that a given set of atmospheric, thermal, and other conditions constitutes a habitable environment.

The Virtual Planetary Laboratory: Towards Characterization of Extrasolar Terrestrial Planets

Motivated by the recent discoveries of over a hundred extrasolar Jovian−size planets, NASA has initiated a series of mission designs for space−based observatories that will detect, characterize, and search for life on extrasolar earthlike planets. These missions will address one of astrobiology s fundamental questions, Are we alone? To optimize the designs and search strategies for these NASA missions, and to ultimately interpret the remote−sensing observations that they return, we must have the capability to recognize worlds that might have habitable conditions, and to discriminate between planets with and without life.

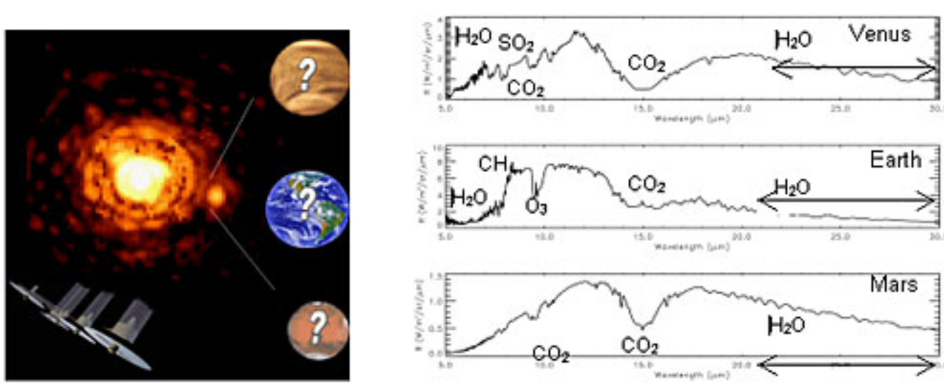

Figure 1: Terrestrial Planet Finder (TPF) and the characterization of extrasolar earthlike planets.
Future space−based missions such as Terrestrial Planet Finder (TPF) will be able to directly detect and characterize extrasolar earthlike planets by using spectroscopic information. Mid−infrared spectra for planets in our own Solar

System showing examples of spectral features we may encounter in observations of extrasolar terrestrial planets.

The characterization of earthlike planets in our own Solar System is a field with a relatively long history in the planetary and Earth−observing sciences. Many of the techniques used by these disciplines could be adapted for use in the characterization of earthlike planets around other stars. Included in these techniques are time−resolved whole−disk photometry, spectroscopic remote sensing for the detection and retrieval of atmospheric and surface composition and physical parameters, and time−resolved spectroscopy of spectral features to look for diurnal or seasonal variations in surface albedo or atmospheric composition.

The nascent field of extrasolar planet characterization is necessarily theory−based, given that existing observational techniques are not yet sensitive enough to directly detect and gather information on Earth−sized planets around other stars. To improve our understanding of the potential range of characteristics for earthlike planets in our galaxy, and the spectroscopic signatures that we are likely to encounter, our team is developing a suite of innovative modeling tools to simulate the environments and spectra of extrasolar planets and of the early Earth. These modeling tools constitute a Virtual Planetary Laboratory (VPL), which will provide the first models to couple the radiative fluxes, climate, geology, and biology of an earthlike planet in order to produce a self−consistent state for a broad range of candidate planetary environments.

The core of the VPL is a coupled−radiative−transfer/climate/ chemistry model, which will be assembled from existing models that have been validated individually to address many key scientific problems in the planetary and Earth sciences. This coupled−climate−chemistry model will be augmented by interchangeable modules currently under development. These modules will characterize fluxes at the upper and lower boundaries of a planetary atmosphere, and so will consist of geological, exogenic, atmospheric escape, and life processes. The VPL will be validated using data derived from the terrestrial planets in our own Solar System. It will then be used to explore the plausible range of atmospheric compositions and thermal structures, and to generate disk−averaged spectra for extrasolar planets and for early Earth. These models will be run with and without biological processes in an effort to improve our understanding of the effects of life on a planet's atmospheric composition and spectrum. These models will also be used to create a spectral catalog that can be used as a statistical sample space to explore the optimum wavelength range, spectral resolution, and instrument sensitivity required to characterize extrasolar earthlike planets.

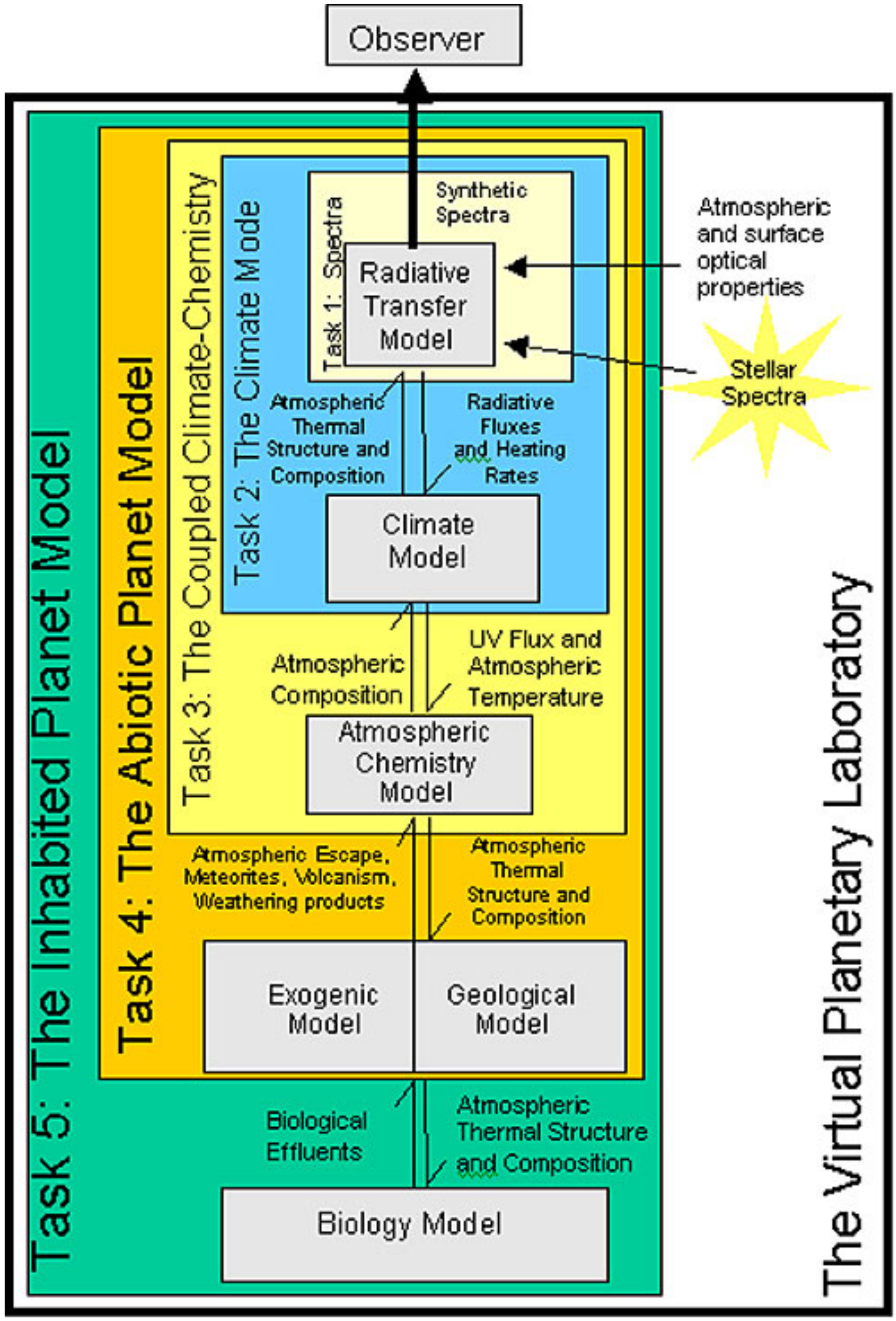

Figure 2: The Virtual Planetary Laboratory. The suite of radiative−transfer, climate, chemical, geological, and biological component models are shown as boxes, and their interactions with each other are shown as arrows. The information transferred between these component models is labeled at each interface. The order in which these component models are coupled to each other during the course of building the VPL is specified by the Task number. The radiative−transfer, climate, and atmospheric chemistry models already exist, and the remaining models are under development by our team. At each task development stage the model can be used to generate synthetic spectra to derive required capabilities for astronomical instrumentation.

This was the first year for this NAI group, and our initial efforts were directed toward acquiring necessary equipment and new personnel. We purchased and installed a 32−CPU (central processing unit) Beowulf cluster and a 64−CPU Beowulf cluster that will be used to develop and test the VPL; recently we welcomed two postdoctoral scholars to our team. The preliminary development work focused on model architecture, operability, and speed. We also worked to get the existing individual models running efficiently on the new parallel−processing machines. We have analyzed the input requirements for the three core models and are currently working on defining the optimum interface algorithm to run the coupled model. As input to the coupled model, important molecules for this work have been identified. Spectroscopic information needed for the radiative− transfer model has been assembled from existing spectral databases, and new spectroscopic parameters for sulfur−bearing molecules significant for both life and geological processes is being collected.

To support our efforts to model biosignatures for earthlike planets around stars of different spectral types, we are collecting and collating stellar spectra and understanding the specific requirements of the chemistry model for different input stellar types. In addition, work has been started on the geological and biological modeling efforts. We are continuing to examine the circumstances under which earthlike planets can be expected to possess geodynamos, for a planetary global magnetic field can strongly affect planetary habitability.

Work on the life−model component is currently concerned with three main areas: estimating the probable extreme environmental constraints for a habitable planet, predicting the microbial communities most likely to remain active on a planet across a significant fraction of the planet s lifespan, and developing statistical methods for detecting spectral signatures resulting from the activity of these communities. Addressing these topics requires modeling, laboratory experimentation, and fieldwork, which we have undertaken through collaborations with Ames Research Center (ARC) and JPL Biosignatures (JPL1) teams.

Modeling efforts have included work on principal−component analysis of near−infrared spectral signatures, studies of the photosynthetic limits of the continuously habitable zone, and a first attempt to describe the feedback loops that may have contributed to stabilization of the Archean biosphere on Earth. Laboratory and field work have focused on attempts to determine whether a biosphere can develop in basalt or ultramafic rocks. This is of interest because if microbial communities can make a living in such primordial environments without prior chemical weathering, biogeochemical interaction may appear quite early in the life history of a terrestrial planet. Field studies in this area are also aimed at isolating and characterizing new organisms and their gas fluxes and other observable interactions with their environment. We have also collaborated with the Ames NAI group in efforts to understand the signal detection limits for cyanobacterial mat gas fluxes across Earth s history.

Highlights in these areas include a collaborative effort with JPL1 and Oregon State University, which provided the first evidence for microbial life in vesicular basalt 1.3 kilometers below the surface of Mauna Kea on the island of Hawaii.

As a proof of concept for the analysis of spectra generated by the VPL, we have undertaken a principal−component analysis of spectra of planets in our own Solar System, which indicates clear spectral discrimination between planetary atmosphere and surface types with as few as five bands.

In addition to initiating the assembly of the VPL itself, our team has also worked on two related projects, both of which use component models of the VPL to explore the detectability of biosignatures by means of remote−sensing techniques.

In the first such project, the VPL s radiative transfer model produces spatially resolved spectral models of Earth, Mars, Venus and Titan (Saturn s largest satellite). The three−dimensional (3−D) datacube of synthetic spectra, which is generated for each planet, is being used to determine the effects of spatial and spectral averaging and temporal variability on the detectability of biosignatures, and on other spectral features that provide important constraints on a planet s physical and chemical state, and its potential for habitability. These models are also being created as a validation standard to test progressive development of the larger VPL model.

To start this project, we have worked to get our radiative−transfer model running on the VPL s new parallel−processing computers. We have started model construction with Mars, which has large spatial variations in temperature, and readily available surface and atmospheric data. Mars surface albedos have been derived from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES), and the atmospheric thermal structure and surface pressure have been derived from the Ames Mars General Circulation Model (MGCM) simulations. With considerable student participation, we have completed coding of the geometrical components of the model, including manipulation of viewing geometry and solar illumination, and are working on interpolation of synthetic spectra, as we generate the database of synthetic spectra for this Mars model. This first model, once completed, will provide the basic structure for the subsequent Earth, Venus, and Titan models.

As an experimental validation component for these models, our collaborators have acquired high−resolution full−disk spectra of Mars using the Fourier Transform Spectrometer on the Canada−France−Hawaii 3.6−meter telescope on Mauna Kea. In collaboration with the Australian Center for Astrobiology, we have also obtained observing time on the 3.9m Anglo−Australian Telescope, and the Australian National University 2.3−meter telescope for making simultaneous optical and infrared validation observations of Venus.

The second project using VPL component models to explore the detectability of biosignatures was worked on in collaboration with the Pennsylvania State University NAI group. In that project, an updated radiative−convective climate model with improved accuracy for the stratosphere was coupled with a chemical model to calculate the evolution of atmospheric ozone as a function of atmospheric oxygen abundance for a range of earthlike planets around stars of different spectral type. As input to this model, we obtained realistic spectra for an F2V star (hotter than the Sun) and a K2V star (cooler than the Sun) using ultraviolet (UV) spectra from the International Ultraviolet Explorer mission, and models that provide photospheric spectra for the visible through far−infrared wavelength range. Using the calculated equilibrium atmospheres from the coupled chemical−climate model, we have employed radiative−transfer tools currently under development for the VPL to generate high−resolution synthetic spectra for these atmospheres for both clear and cloudy cases. These simulations have provided significant insight into the combined effects of temperature and trace−gas distributions on the detectability of biosignatures, and have potential future uses in the interpretation of data from the planned Terrestrial Planet Finder mission.

In addition to the scientific research, scientists on the VPL team have been involved with education and public outreach. Team members have given an invited talk and been involved in education sessions at major conferences. They have also given numerous seminars and colloquia on the VPL concept and initial results at national and international venues. The team is currently working on a public website for the VPL.