Towards Understanding the Climate of Terrestrial planets – an observational perspective

David Crisp

Jet Propulsion Laboratory, California Institute of Technology

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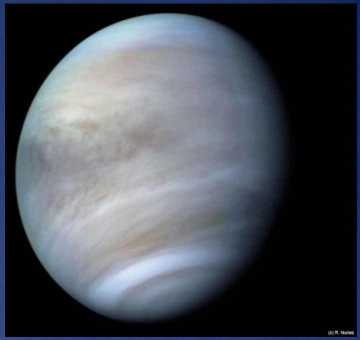
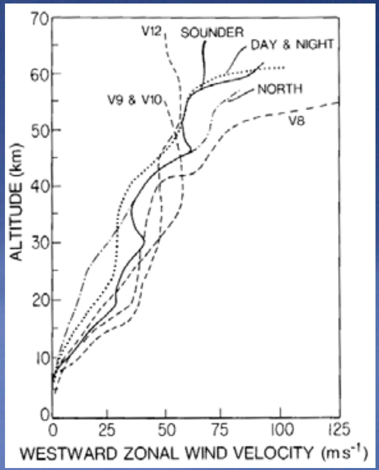
A Personal Perspective

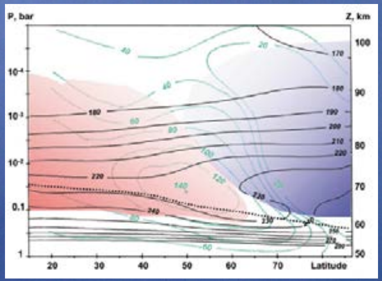
- There are several ways to illustrate the benefits of a comparative approach for observational studies of the climates of terrestrial planets.
  – I have chosen to approach this topic from a personal perspective.
- As many of you know, my formal training is in theoretical atmospheric physics and radiative transfer.
- However, I have spent as much of my career designing and building hardware to observe the climates of terrestrial planets as I have building and using numerical models to analyze those measurements.
  – These tools have been used to deign and test in situ and remote sensing instruments for Earth science, planetary atmospheres, and astrophysics.
- Here, I will summarize the insights gained from a synergistic investigation of:
  – The atmospheres of Venus, Mars, Jupiter, and Neptune;
  – The Earth's stratospheric ozone hole and greenhouse gas distribution;
  – Extrasolar planets

The Early Years: the First Golden Age of Planetary Exploration – the 1970's

- It all started with an investigation of the Venus super-rotation:
  - Why do the cloud tops rotate 60 times as fast as the surface?
  - Why do the winds decrease rapidly with height above the clouds?
- Initial Approach
  - Ground-based planetary astronomy – measuring Doppler shifts of spectral lines in (ultra) high resolution spectra of reflected sunlight.
  - Venera and Pioneer Venus probe measurements:
    - Doppler shifts of radio frequencies as they descended showed that the 100 m/sec cloud-top winds decreased with altitude.
  - Pioneer Venus and Venera Orbiter thermal IR observations showed that the pole was warmer than the equator above the clouds, consistent with the wind velocities decreasing with altitude there.
- These methods provided a consistent kinematic description of the winds, but provided few insights into the physical processes driving the anomalous Venus atmospheric circulation.





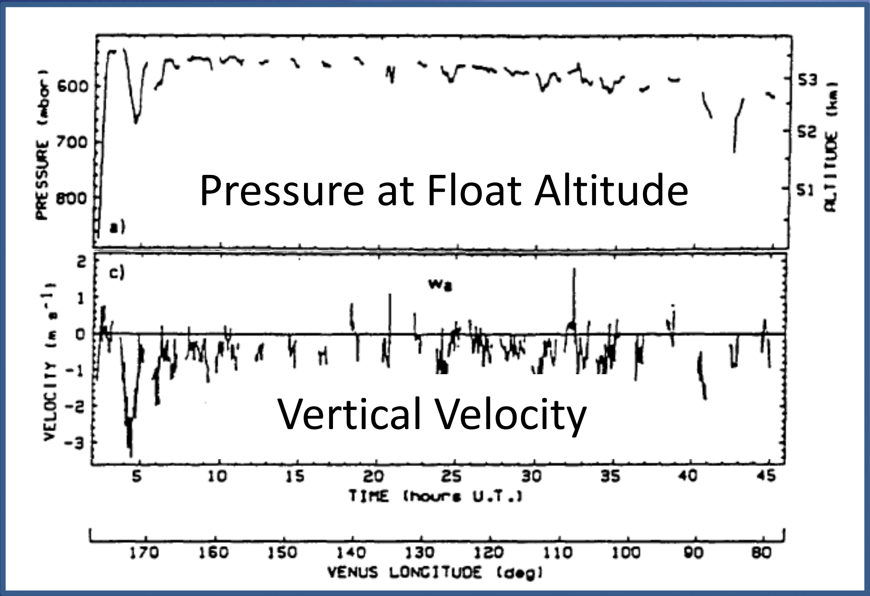


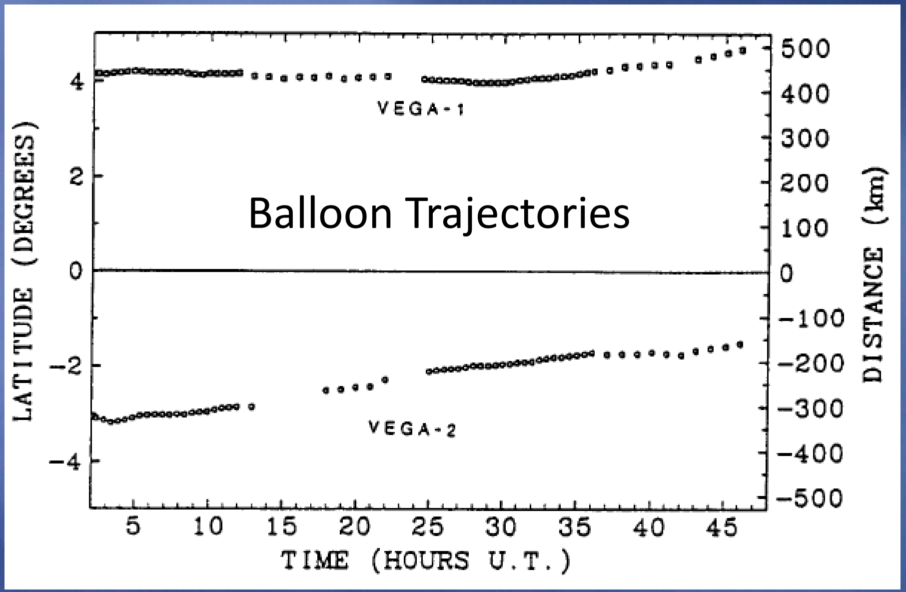
Looking for Answers in the Back of the Book: What Can we Learn about Venus from Earth Atmospheric Science?

- I turned to the Earth Climate Modeling community, pursuing a PhD at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL):
  - I converted a state-of-the-art Earth general circulation model to simulate Venus, but found that I could not reproduce the observed super-rotation at the equator.
  - My advisor, Steve Fels suggested that this was partially due to inadequacies in the input radiative forcing – the solar heating and thermal cooling of the atmosphere.
  - I found that the radiative transfer models used in Earth climate models did not include most of the physical processes needed to simulate the massive, optically thick, scattering, absorbing, emitting atmosphere of Venus due to:
    - Fundamental shortcomings in radiative transfer methods; and
    - Limitations in the available laboratory measurements of gas absorption.
- For my thesis, I developed more physically rigorous methods to:
  - Describe the radiative energy distribution within and above the clouds,
  - Explain the dynamical processes responsible for reversed pole-to-equator temperature structure above the clouds.

Peering Beneath the Cloud Tops: Flying Balloons in the Venus Atmosphere

- As the first Golden age came to an end, we had one last chance to study the Venus atmosphere in situ --- with the Soviet/French/US VEGA Balloon mission.
  - Two balloons floated in the middle cloud (~53 km) for 48 hours each
  - Working with colleagues IKI in the Soviet Union and at CNES and NASA AMES, we analyzed their in situ measurements and VLBI tracking data.

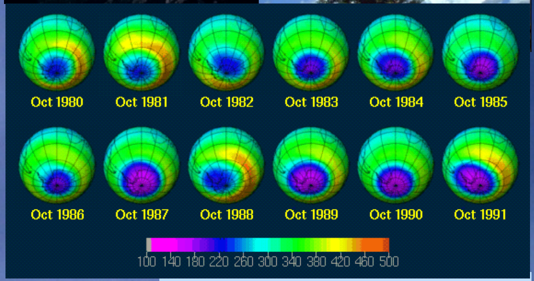


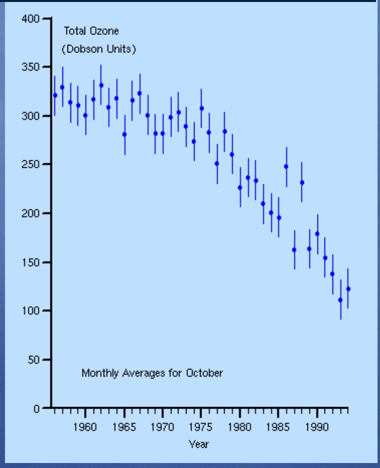


- That was the last Venus in situ mission, but not the end of the story.

Meanwhile, back at the Ranch …
Volcanic Eruptions and the Ozone Hole

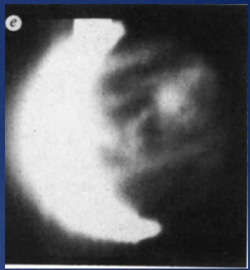
- Explosive eruptions of the Mount Saint Helens (1980), El Chichon (1982), and Pinatubo (1991) volcanos added progressively larger amounts of ash and sulfuric acid to the stratosphere, raising concerns about their impact on the climate and the ozone layer.
  - Methods pioneered for studying sulfuric acid clouds on Venus and airborne dust in the Martian atmosphere were pressed into service (c.f. Gerstell et al. 1995).
- In the 1970's NASA funded extensive studies of chlorine photochemistry in the Venus atmosphere to understand its role in stabilizing the CO_2 atmosphere.
  - The discovery of the role of CFC's in the destruction of ozone is often credited to this NASA-funded research
- And then the Ozone hole was discovered …
  - The Venus radiative transfer models and mesospheric 2D dynamics codes upgraded to study its origin.

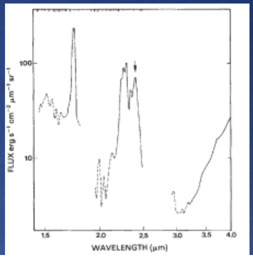


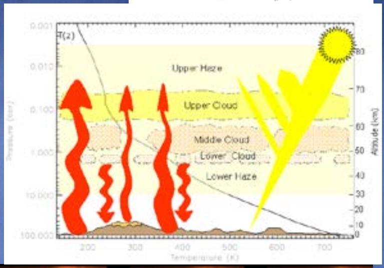


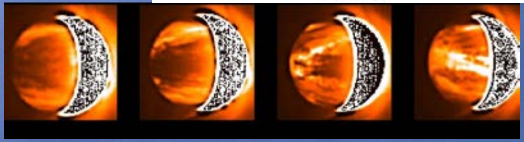
Peering Beneath the Cloud Tops: Near Infrared Images and Spectra of the Venus Night Side

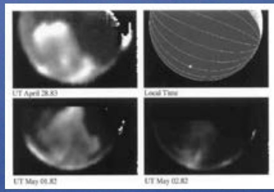
- The pioneering ground-based infrared astronomer, David Allen, discovered intense, variable emission from the Venus night side at 1.74 and 2.3 microns while testing a near infrared spectrometer.
  - He concluded that this emission originated from the deep atmosphere, and that the contrasts were caused by variations in the opacity of the middle and lower clouds.
  - This provided a new way to probe the Venus atmosphere using remote sensing techniques, eventually revolutionizing our understanding of:
    - The dynamics middle and lower cloud decks,
    - Trace gas concentrations in the sub-cloud atmosphere, and
    - O_2 airglow from the Venus Mesosphere
- To fully exploit this spectral range, we needed:
  - New laboratory measurements of gas absorption,
  - More accurate radiative transfer and retrieval techniques for absorbing, emitting, scattering atmospheres.





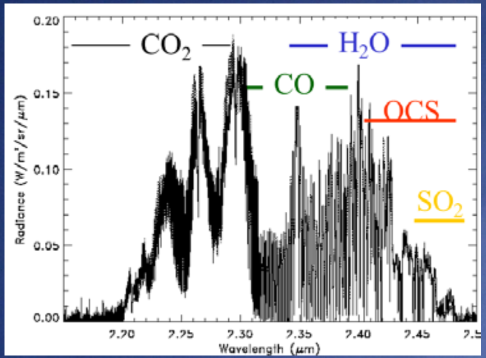


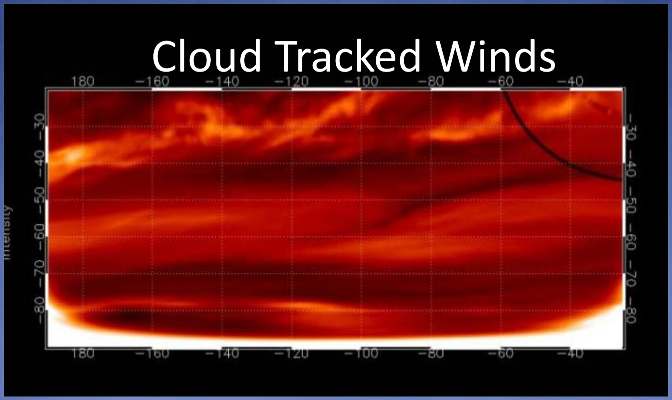


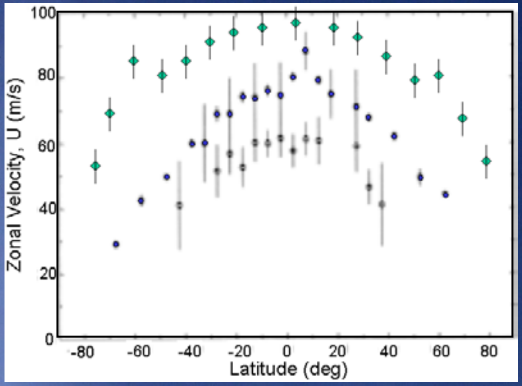


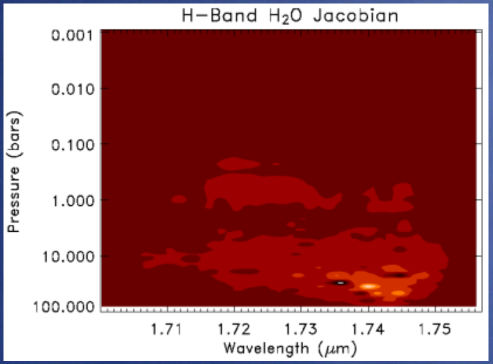
Early Products of Venus Night Side Observations

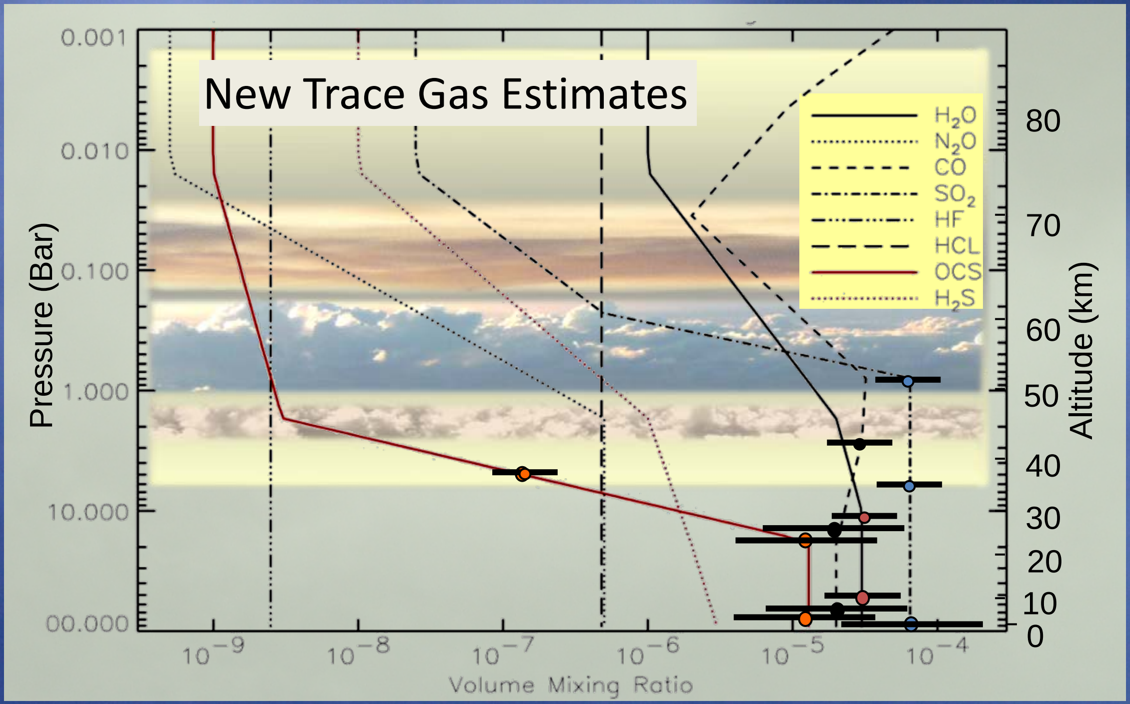
New Retrieval Methods

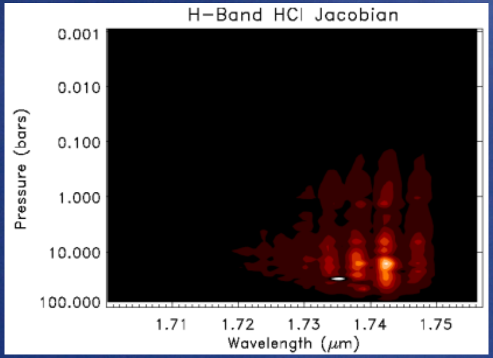




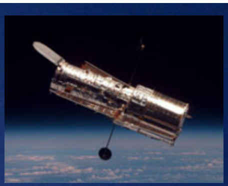






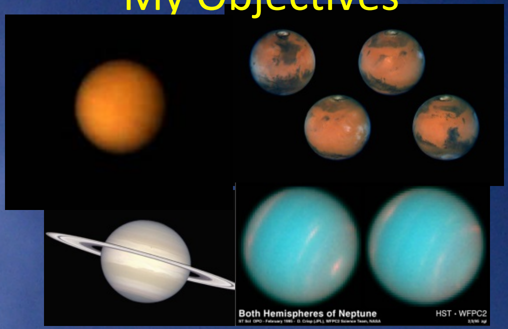


A First Career in Astrophysics – HST WFPC-2



- I was hired at JPL to work on HST WFPC-2, because I understood optics (from planetary astronomy) and computers (from GFDL).
  - I became the science team member responsible for the design, procurement, and testing of the 48 spectral filters and the calibration system for WFPC-2.
- My primary objective was to use HST WFPC-2 as a high resolution planetary imager – and I eventually did that.
- Along the way, I contributed to a few astrophysics problems , including:
  - Resetting the distance scale and age of the universe;
  - Analyzing SN 1987A and other dying stars;
  - Characterizing stellar nurseries and proto solar systems.
- I also learned a vast amount about optics, detectors, calibration systems, and flight instruments, in general.

My Objectives

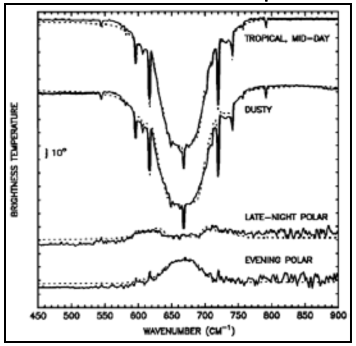


Our Products

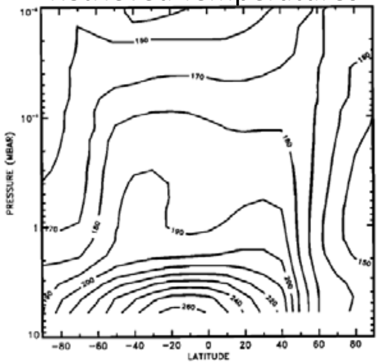
And then On To Mars

- Michelle Santee, a grad student at Caltech, was looking for a thesis topic. I suggested that she take another look a the Mariner 9 IRIS observations collected in 1971.
  - We adapted the radiative transfer methods developed for Ozone hole studies into our first, true remote sensing retrieval code and retrieved temperature and dust amounts.
  - An updated version of the 2-D Eulerian-mean residual circulation model developed for Ozone Hole studies was used to study dust transport in the Martian atmosphere.
- I was please with the results, but frustrated with our inability to learn much about near-surface atmospheric temperatures or composition from IR remote sensing data.
- Michelle went on to become a preeminent expert on the Earth's stratosphere, as a member of the UARS and then EOS Aura Microwave Limb Souder (MLS) teams.

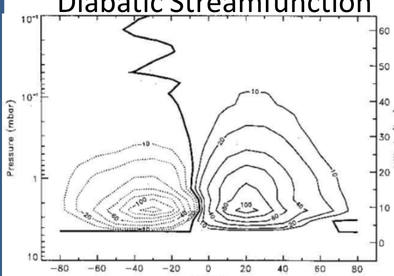
Mariner 9 IRIS Spectra



Retrieved Temperatures

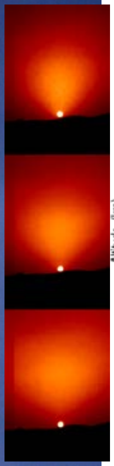


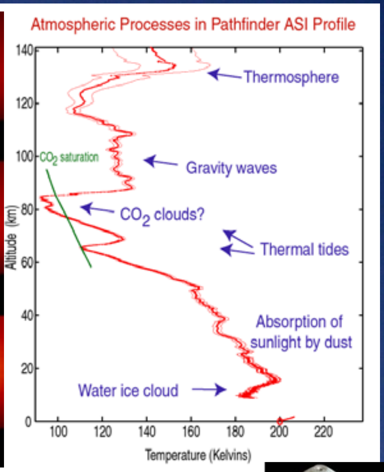
Diabatic Streamfunction

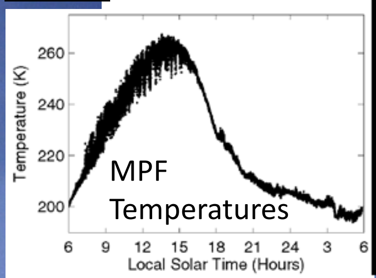


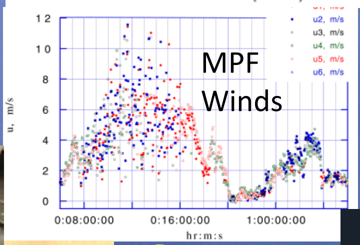
Mars Near Surface Environment

- An improved understanding of the near surface atmosphere on Mars is essential for both robotic and human exploration because this is the working environment.
- Given the background from Viking, Pioneer Venus, and VEGA Balloon measurements, we started developing in situ meteorological instruments for Mars Networks.
  - These measurements are intrinsically challenging in the thin, highly-variable Martian atmosphere
  - Technologies developed for terrestrial upper atmosphere research adapted and/or reinvented for Mars:
    - TDL Spectrometers, pressure & temperature sensors, hygrometers, airborne dust profilers.
- Products of this work eventually flew on Mars Pathfinder, Mars Polar Lander, Phoenix, and MSL.

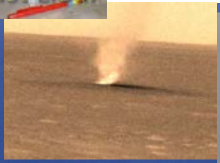


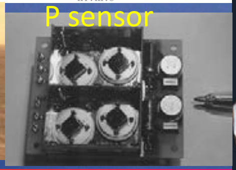






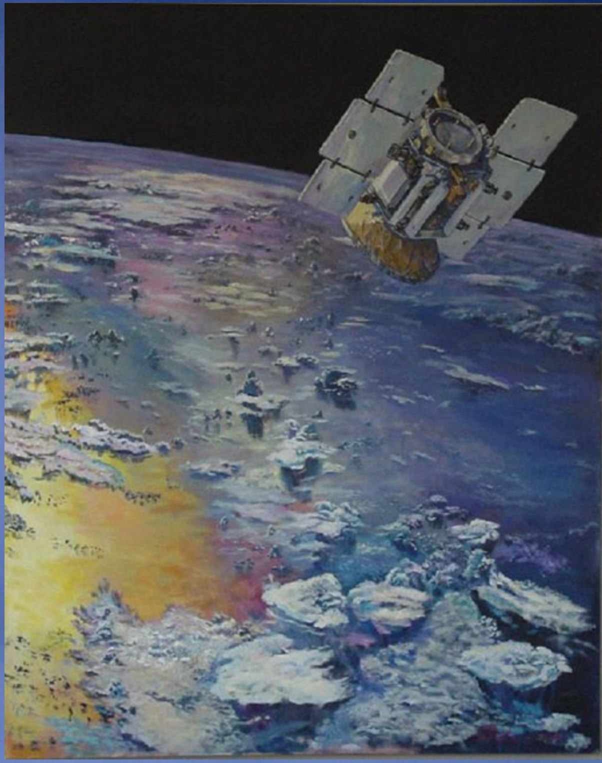
MVACS/ NetLander Wind and Temperature Sensors
- <30 grams
- <300 mW

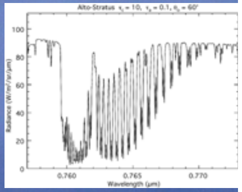


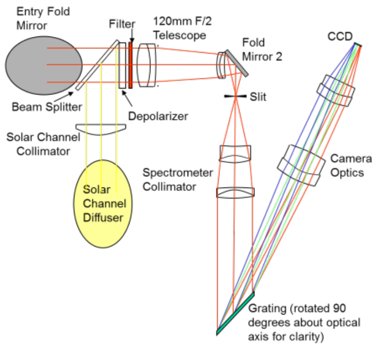


Back to Earth – The CloudSat A-Band Spectrometer

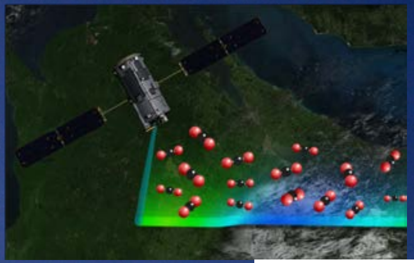
- I was drafted by Graeme Stephens to design an O_2 A-band Spectrometer the ESSP CloudSat mission.
- The objective was to design an instrument that would complement the Cloud Profiling Radar by
  - Detecting thin clouds, and cloud top pressures,
  - Quantifying the impact of clouds on solar radiation.
- I used the Venus Near-IR RT model to refine requirements for a simple, low-cost, instrument:
  - A high resolution, imaging grating spectrometer, similar to those used for the Venus Night Side observations.
- The A-band spectrometer was eventually descoped due to cost growth in other areas, but provided additional insight into Earth science measurements needs and flight instrument design requirements.



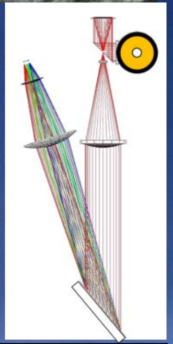




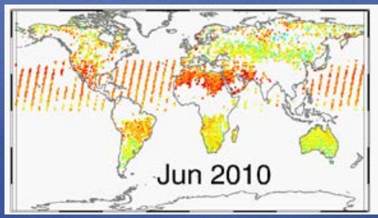
Measuring CO_2 in the Earth's Atmosphere – The Ongoing Saga of OCO



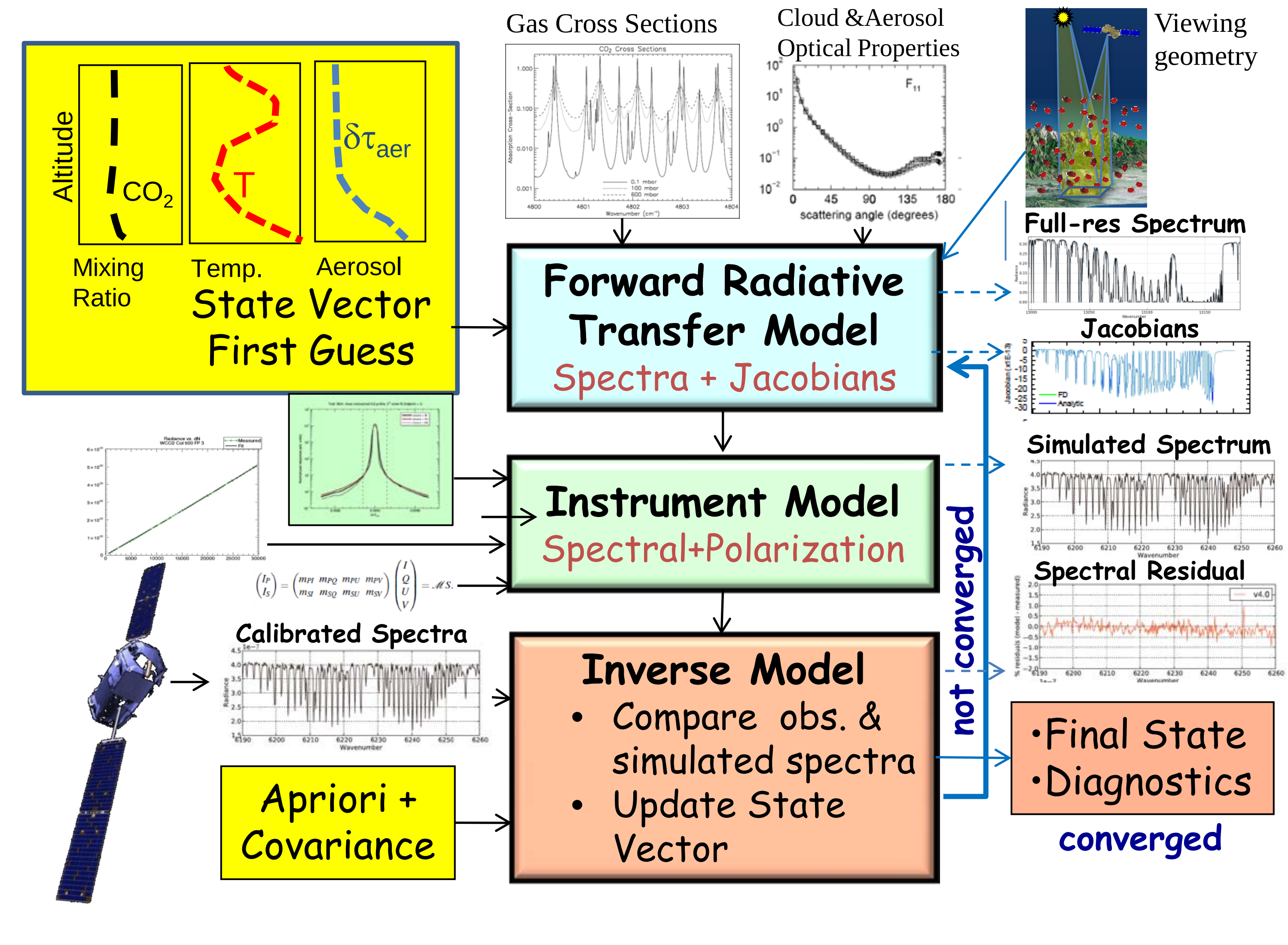
- Growing concerns about climate change demanded precise measurements of greenhouse gas sources and sinks
- I lead a team that proposed the Orbiting Carbon Observatory (OCO) to the NASA Earth System Science Pathfinder Program.
  - OCO was to be the first NASA mission to measure atmospheric CO2 with the accuracy, coverage, and resolution needed to quantify CO2 fluxes on regional scales over the globe.
  - Combined Venus RT models with instrument technologies derived from the CloudSat A-band spectrometer and the ground-based telescope instruments being used to study Venus.



- OCO was completed and delivered, but was lost when its launch vehicle malfunctioned and failed to reach orbit.
  - NASA authorized a replacement for OCO, called OCO-2, which under development for a late 2014 launch.
  - The OCO-2 team is working closely with the Japanese GOSAT team to validate their retrieval, calibration and validation methods.



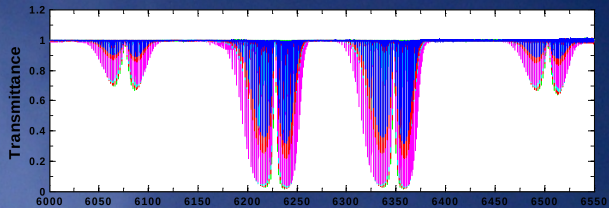
The OCO-2 "Full Physics" X_{CO2} Retrieval Algorithm



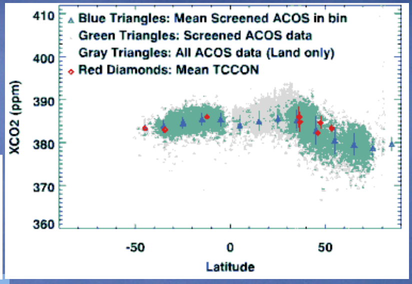
State Vector
CO_2 profile
H_2O profile (scale factor)
Temperature profile (offset)
Aerosol Profiles
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift
Zero Level Offset

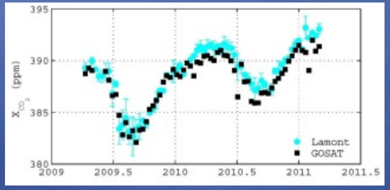
Spin-offs of OCO/GOSAT/OCO-2

- To meet its objectives, OCO-2 must measure the column-averaged CO_2 dry air mole fraction to an accuracy of ~0.3%.
- This high accuracy is driving the development of new capabilities across a wide range of fields, including:
  - Laboratory measurements of absorption by CO_2, O_2, H_2O, CH_4, and other trace gases,
  - New, high precision trace gas remote sensing techniques, designed to yield << 1% errors in the presence of aerosol scattering and other uncertainties,
  - Instrument design and calibration strategies that return measurements with unprecedented accuracies, and
  - New ground-based and space-based measurement validation methods.
- These developments are expected contribute to planetary and exoplanet remote sensing methods.



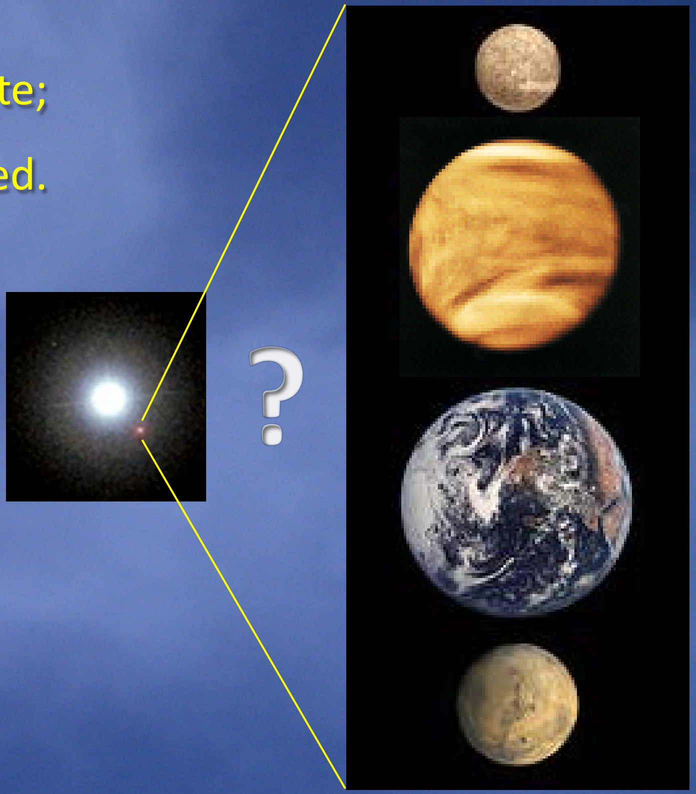
TCCON
total carbon column observing network





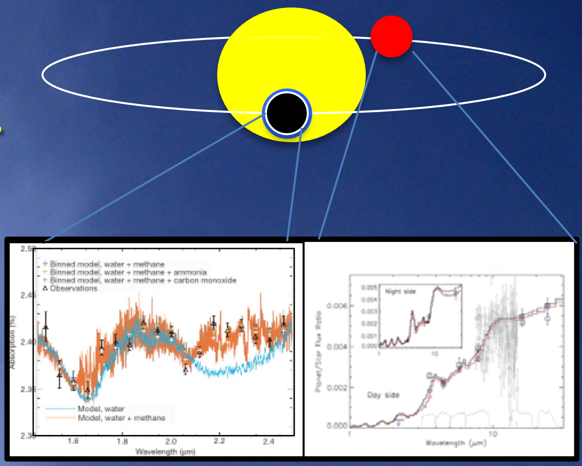
And On to Extrasolar Planets

- Can we optimize planned space based telescopes to characterize the environmental factors that affect the habitability of a terrestrial exoplanet?
- Global Energy Balance:
  - Stellar Type - luminosity, spectrum;
  - Orbital distance, eccentricity, obliquity, rotation rate;
  - Bolometric albedo – fraction of stellar flux absorbed.
- Presence of an atmosphere:
  - Surface pressure
  - Bulk atmospheric composition
  - Trace gases/greenhouse gases
  - Clouds/aerosols
- Surface properties:
  - Presence of liquid water on the surface?

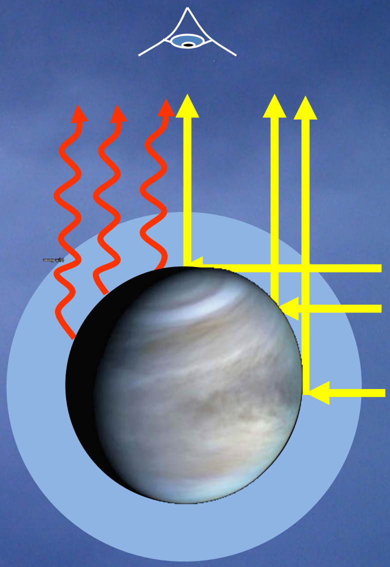


Remote Sensing of ExoPlanets – Baby Steps

- Methods developed for studies of terrestrial planets in our solar system are being refined for us on exoplanets.
  - Occultations yield insight into planetary size (transit), albedo (secondary eclipse), and planetary mass (period).
  - Transit and secondary eclipse spectra provide unique constraints on the mass, composition, and vertical structure of the atmosphere.

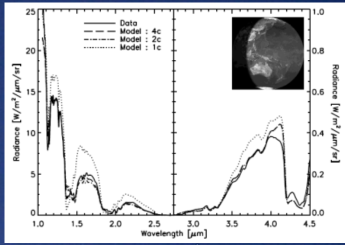


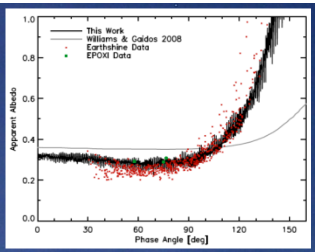
- Exoplanets pose special challenges for conventional remote sensing methods:
  - Full-disk observations sample a range of optical path lengths, complicating the retrieval of trace gas amounts.
  - There is generally no prior information about the planet to constrain the retrieval.
    - This is a requirement of the "optimal estimation" methods used for Earth and planetary retrievals.



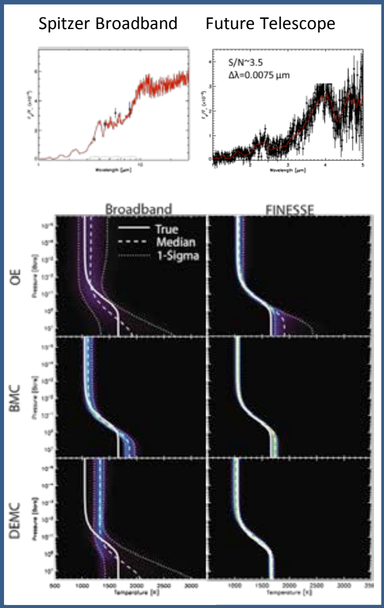
Some VERY Preliminary Conclusions for Exoplanets

- Forward Radiative Transfer models can accurately simulate disk-integrated spectra of the only known habitable planet - Earth
  - Observations from EOS MODIS and AIRS were used to simulate the Earth's albedo, thermal structure, and cloud distribution.
  - Spatially-resolved synthetic spectra were generated, integrated over the disk for a range of viewing geometries, and validated with EPOXI data (Robinson et al., 2010; Robinson 2012).





- Three different retrieval methods were evaluated for analyzing real and synthetic transit spectra of hot Jupiters (Line et al., 2013):
  - Optimal Estimation (OE), Bootstrap Monte Carlo (BMC), and Markov Chain Monte Carlo (MCMC).
  - These three methods can yield varying results for low-quality broad-band data, like that currently available.
  - All three methods yield comparable results for higher quality data, like that expected from proposed exoplanet observatories.



A New Direction for Remote Sensing Algorithms

- As noted above, a major challenge for exoplanet remote sensing retrieval methods is the complete lack of prior information about the environment.
- Preliminary experiments show confirm that this information is most critical when the information content of the observations is relatively low (e.g. low signal to noise ratio, low spectral resolution), as it will be for terrestrial exoplanet spectra, for the foreseeable future.
- New remote sensing techniques are needed to address this shortcoming:
  – For example, can we replace the Bayesian prior constraint on the geophysical variable of interest (e.g. the temperature is between T and $T \pm \Delta t$) with a “physical constraint” like that employed in climate models (e.g. a thermal or chemical equilibrium constraint)?
  – If we can do that, such methods might be extremely valuable in Earth and planetary remote sensing models, to constrain variable for which there is typically no meaningful prior constraint–such as cloud or aerosol optical depth.
- These methods are currently being explored.

Some Conclusions

- A vigorous interaction between the Earth, Planetary, and ExoPlanet communities has yielded numerous advances and insights into:
  - The physical and chemical processes that operation in planetary environments;
  - The numerical methods needed to simulate these processes to retrieve information from remote sensing observations and climate models.
- These interactions also reveal common needs, including:
  - improved laboratory measurements of trace gases,
  - improved radiative transfer forward models,
  - remote sensing retrieval methods, that place fewer demands on prior information.
- In the past, some of these goals have been addressed by serendipitous encounters or by researchers, jumping from field to field to chase interesting problems or funding opportunities.
- Occasionally, NASA would benefit from a more direct effort to encourage interactions among these communities to solve specific problems.

Thanks for your Attention