Planets in Reflection

Adam Burrows (Princeton University)

The Planet/Star Flux Ratio for wide-separation extra-solar giant planets (EGPs) depends upon:

- Geometric albedo (A_g), Phase Function (Φ (α)), Keplerian elements, Epoch

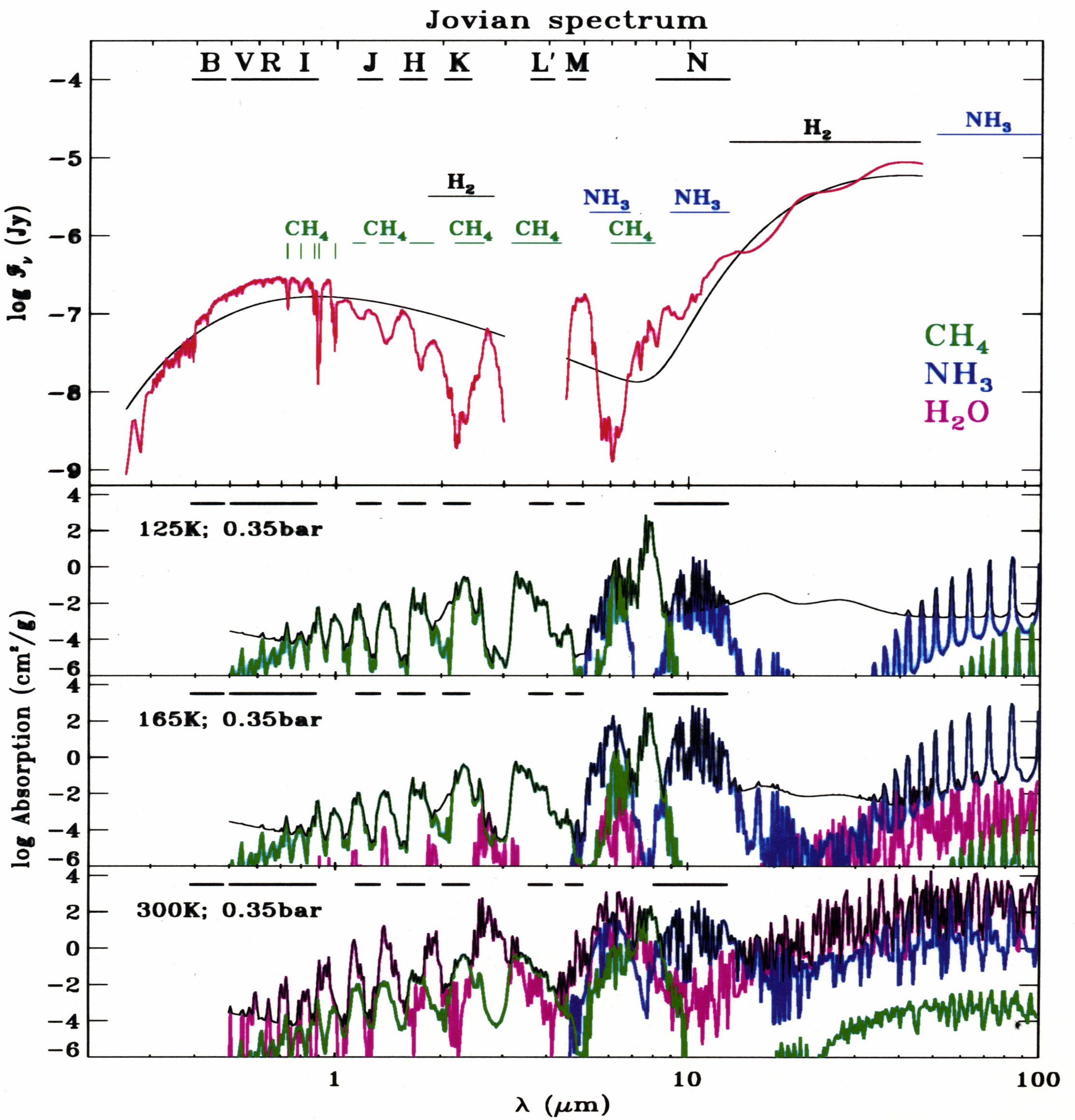
- Both A_g and Φ (α) depend upon wavelength (!) - planet color a function of phase

- Temperature-pressure-composition profiles are needed

- Clouds (NH_3 and H_2O) are crucial determinants, as are Hazes (polyacetylenes, tholins, …)
- For clouds and hazes: Need particle-size distributions, complex indices, vertical extent

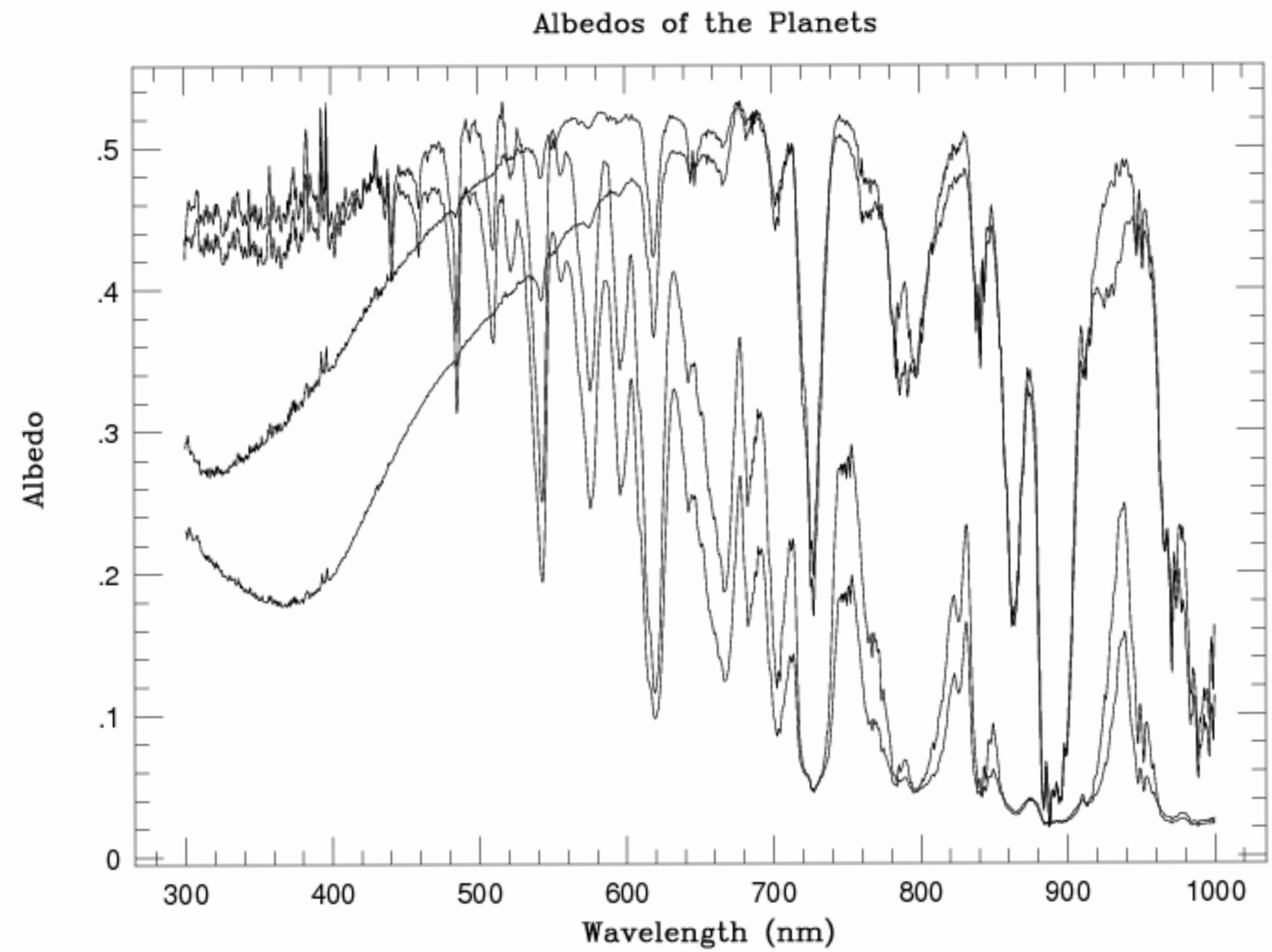
- Polarization can be a useful adjunct for physical interpretation

- Detailed models, simple models, and analytic approximations are available, but work is needed to develop analysis pipeline and reverse modeling protocols to extract physical parameters, with error bars.

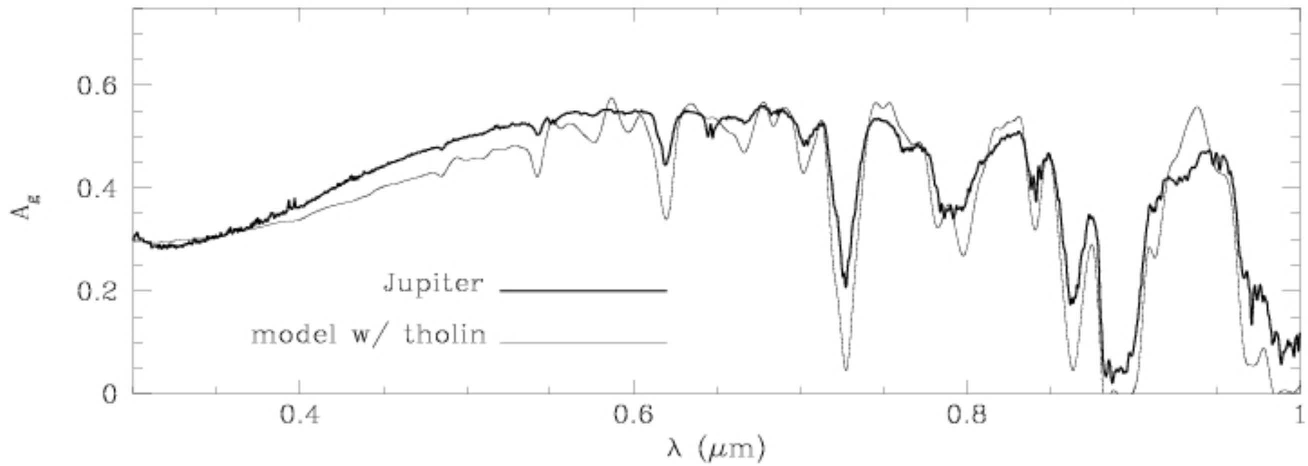


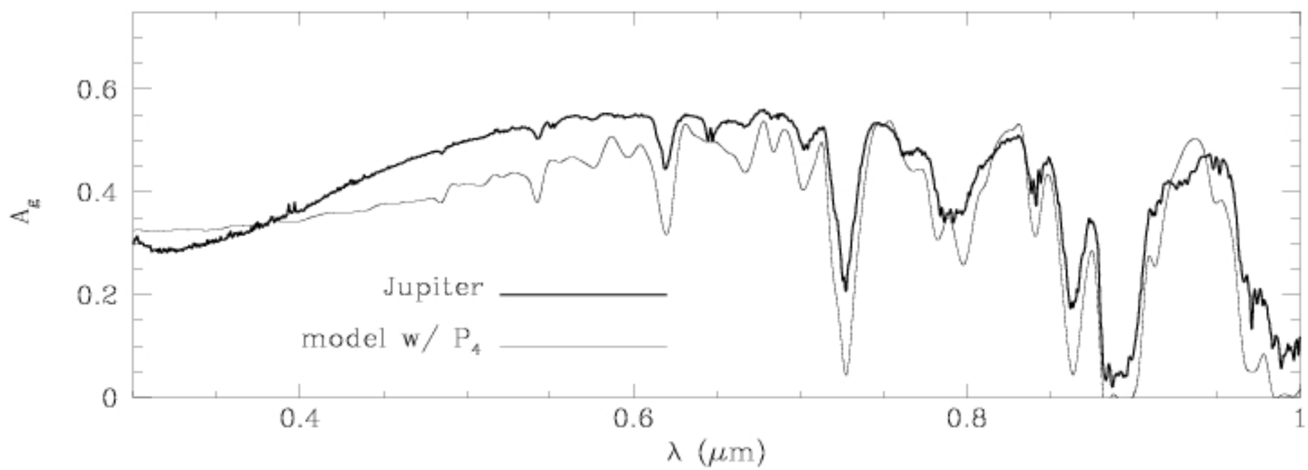
Jupiter's Spectrum

(T. Guillot)

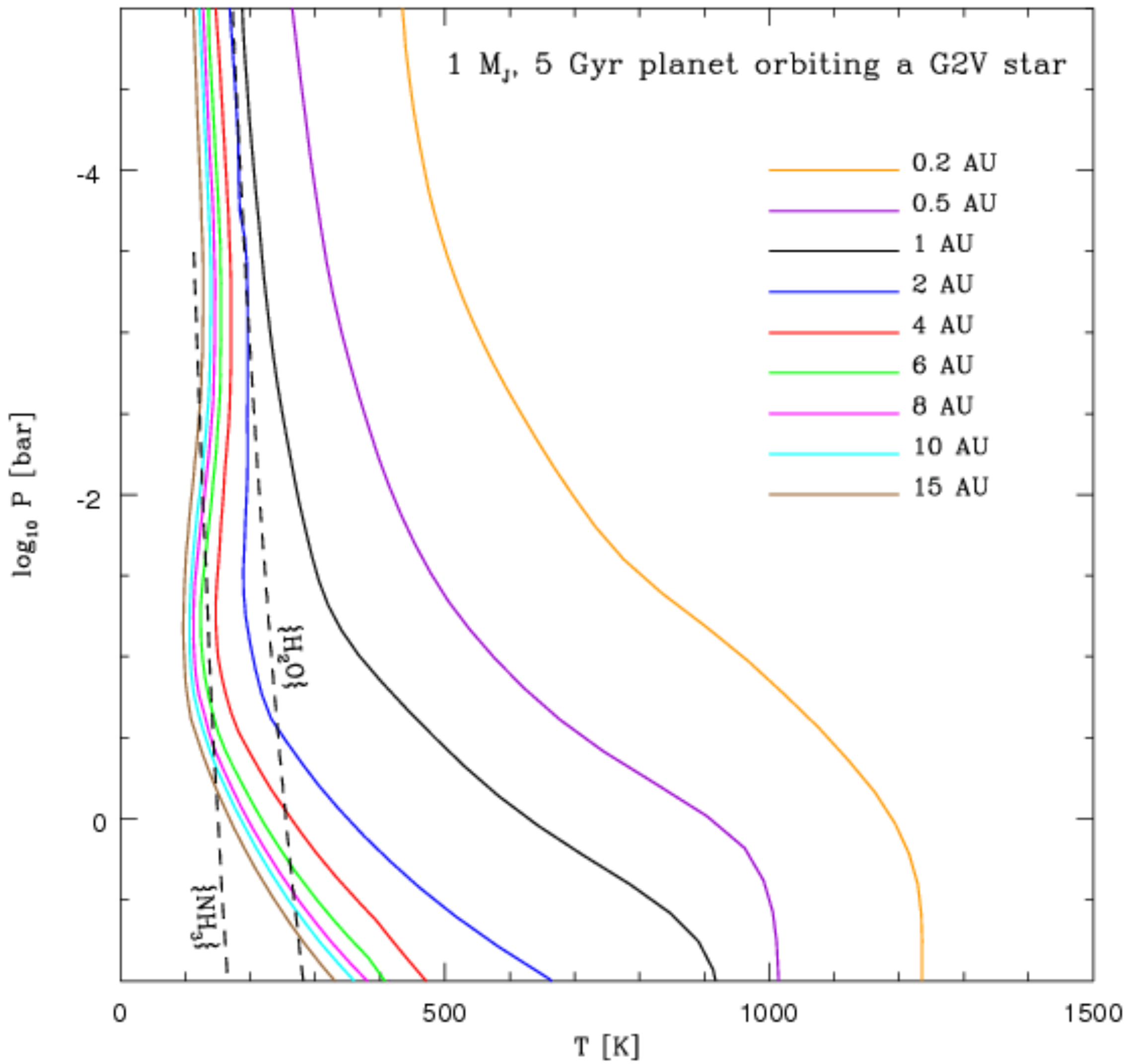


Geometric albedos of Jupiter, Saturn, Uranus, and Neptune in the optical (from Karkoscha 1994).

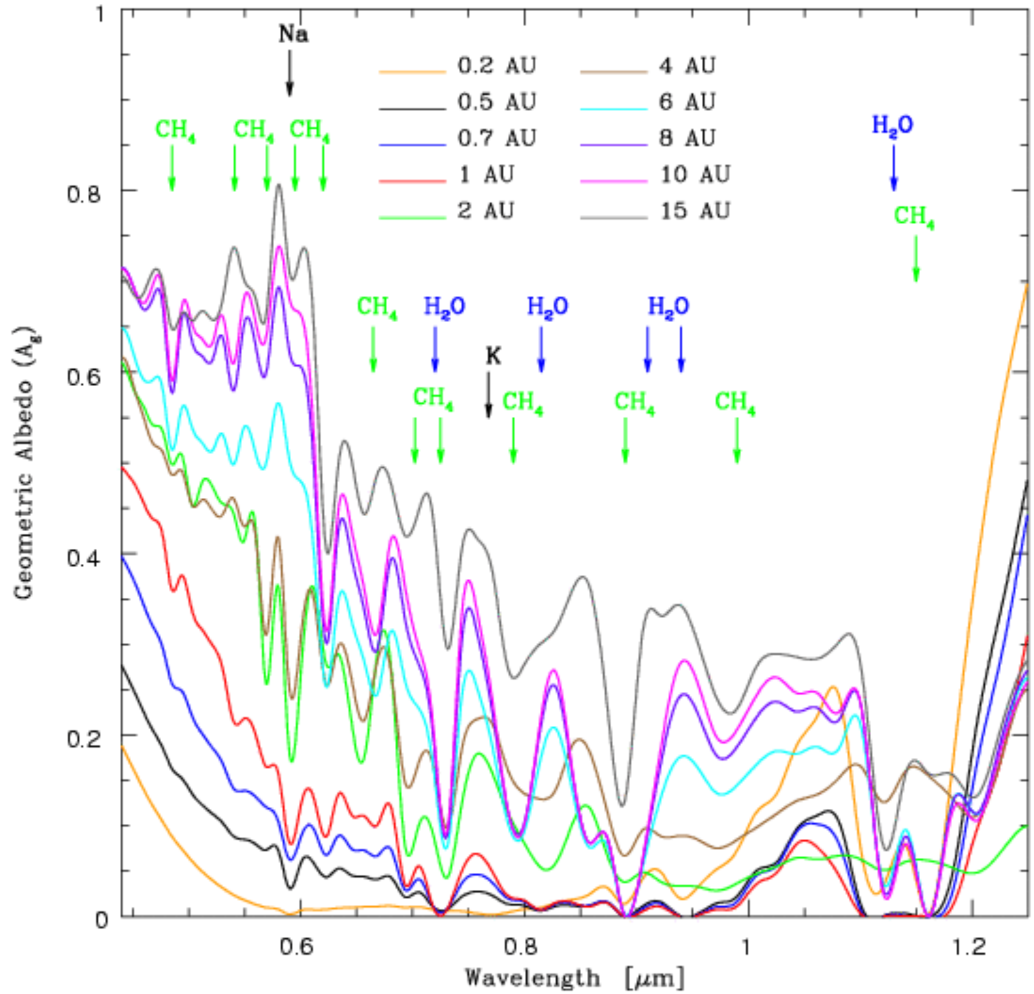




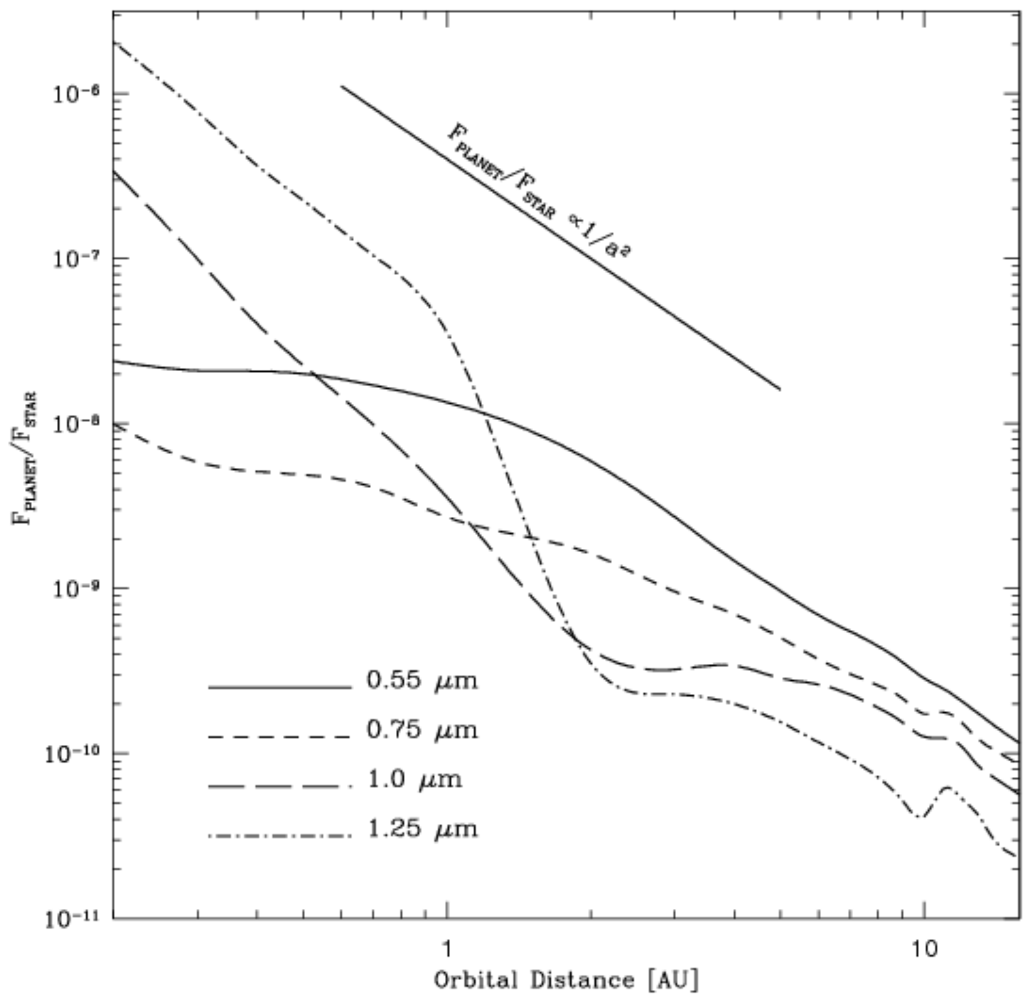
The geometric albedo spectrum of Jupiter compared with models (thin curves). The top model utilizes tholin as a chromophore, while the bottom model uses P_4.



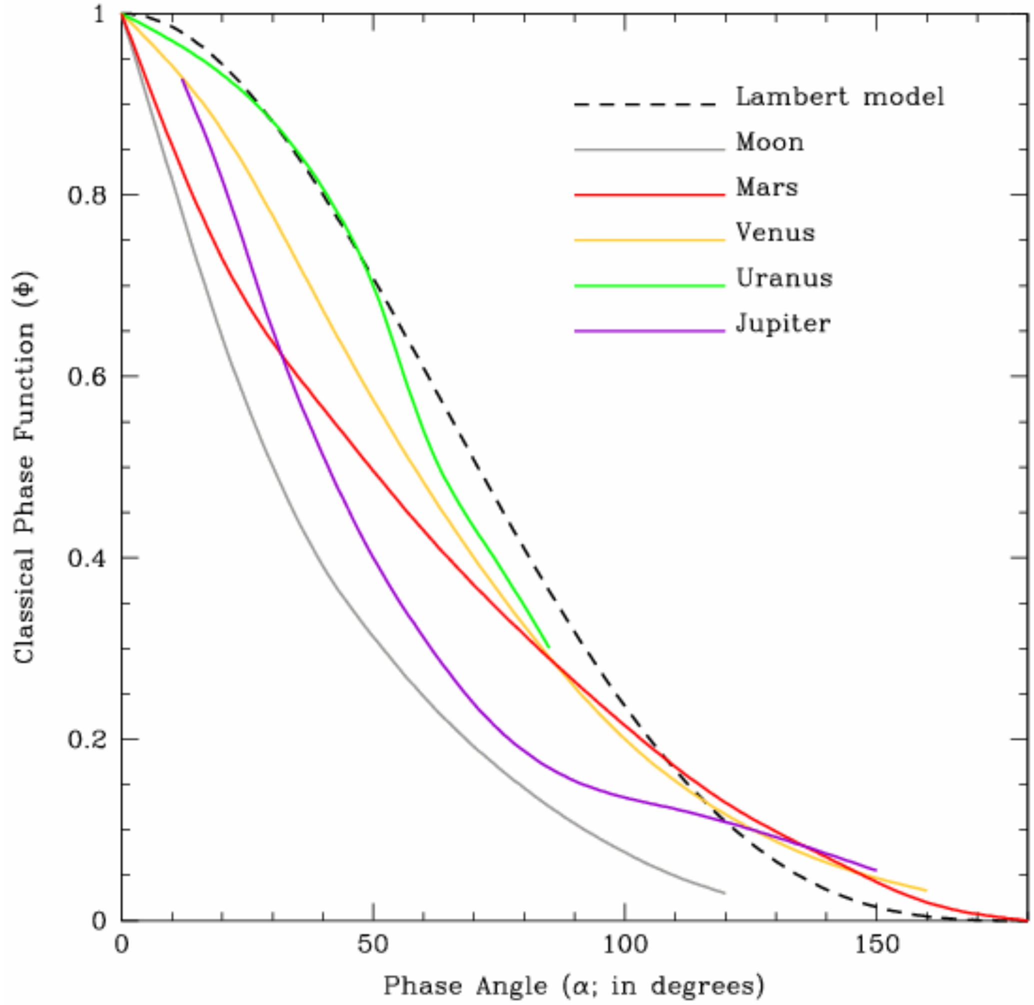
The temperature-pressure (T-P) profiles for a selection of model EGPs. Condensation curves for water and ammonia are shown.The deeper intersections of these condensation curves with the T-P profiles indicate the positions of the cloud bases.



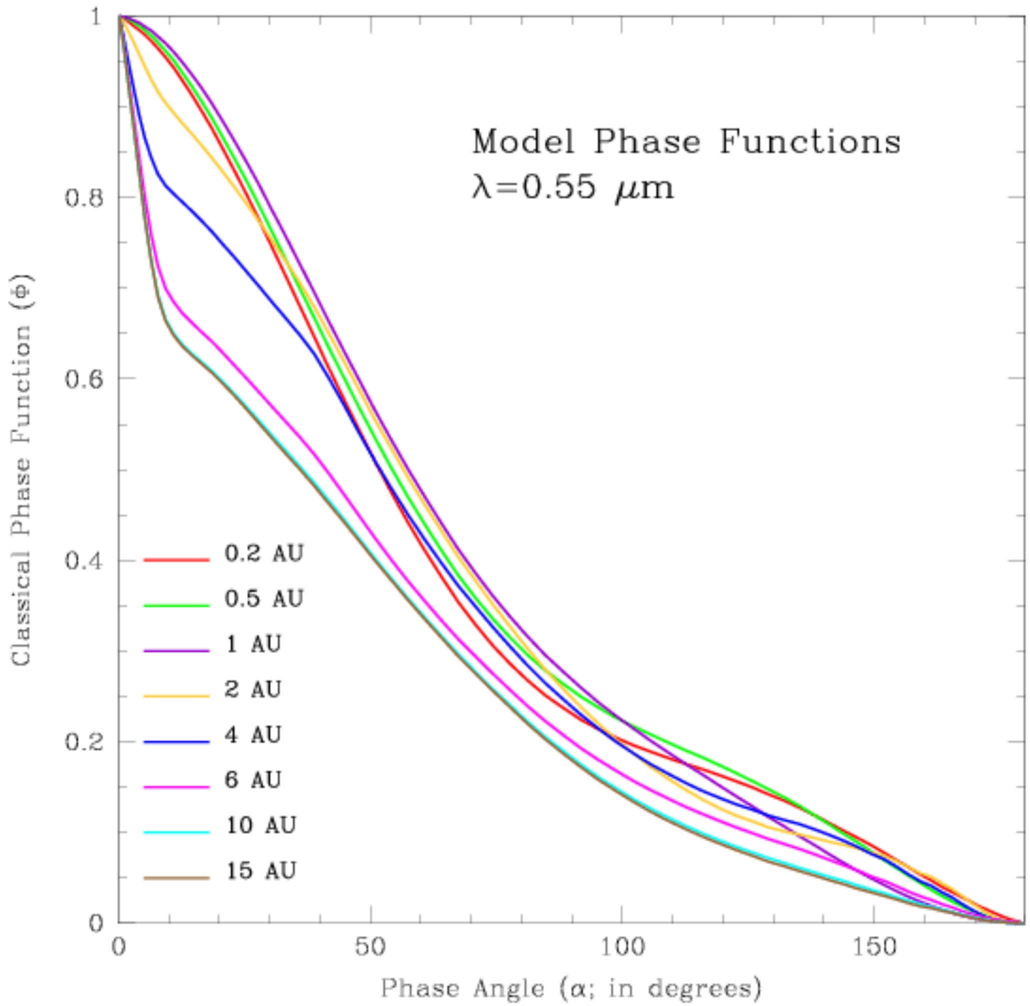
Low-resolution, wavelength-dependent geometric albedos of 1-M_J, 5 Gyr EGPs ranging in orbital distance from 0.2 AU to 15 AU about a G2V star. Cubic splines are fit to all albedo data. Reddening effects of photochemical hazes are not incorporated.



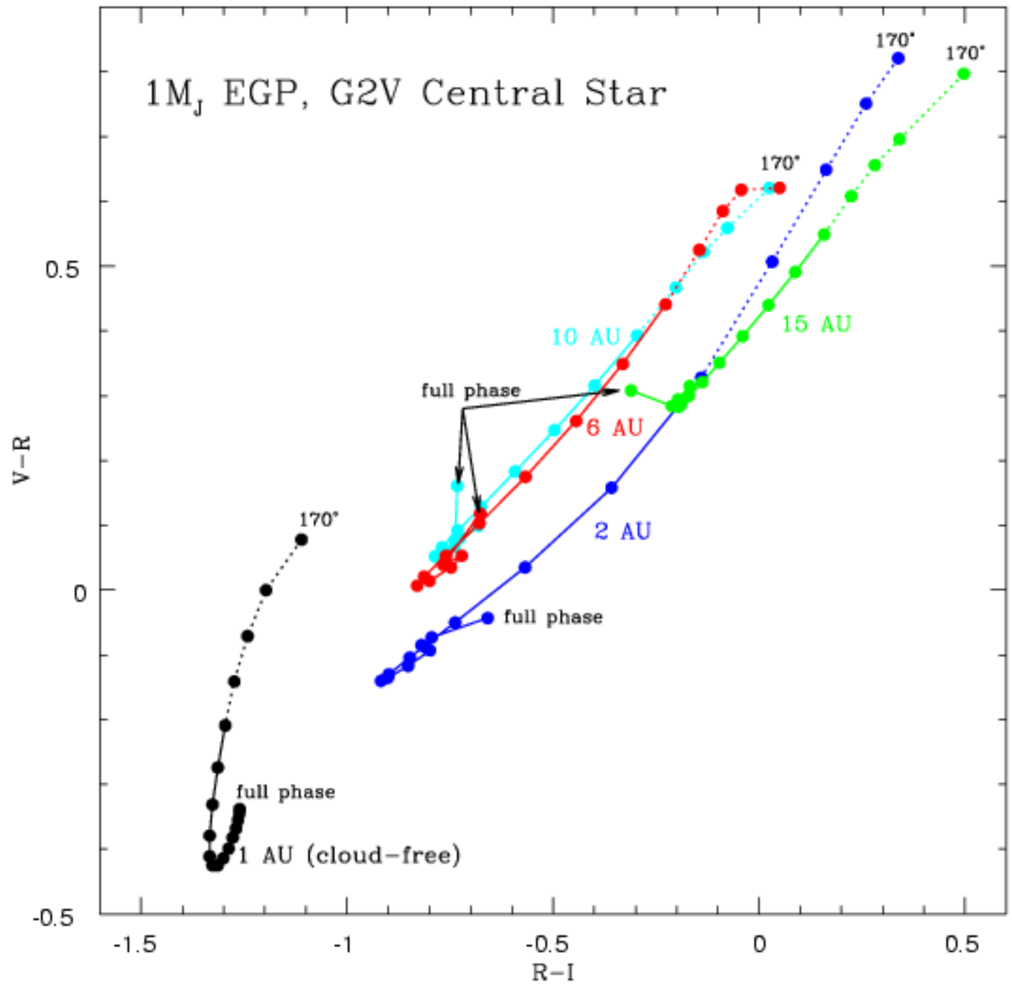
Planet/star flux ratio as a function of orbital distance at 0.55, 0.75, 1.0, and 1.25 microns assuming a G2V central star. In each case, the plotted value corresponds to a planet at greatest elongation with an orbital inclination of 80 degrees. Note that the planet/star flux ratios do not follow a simple $1/a^2$ law.



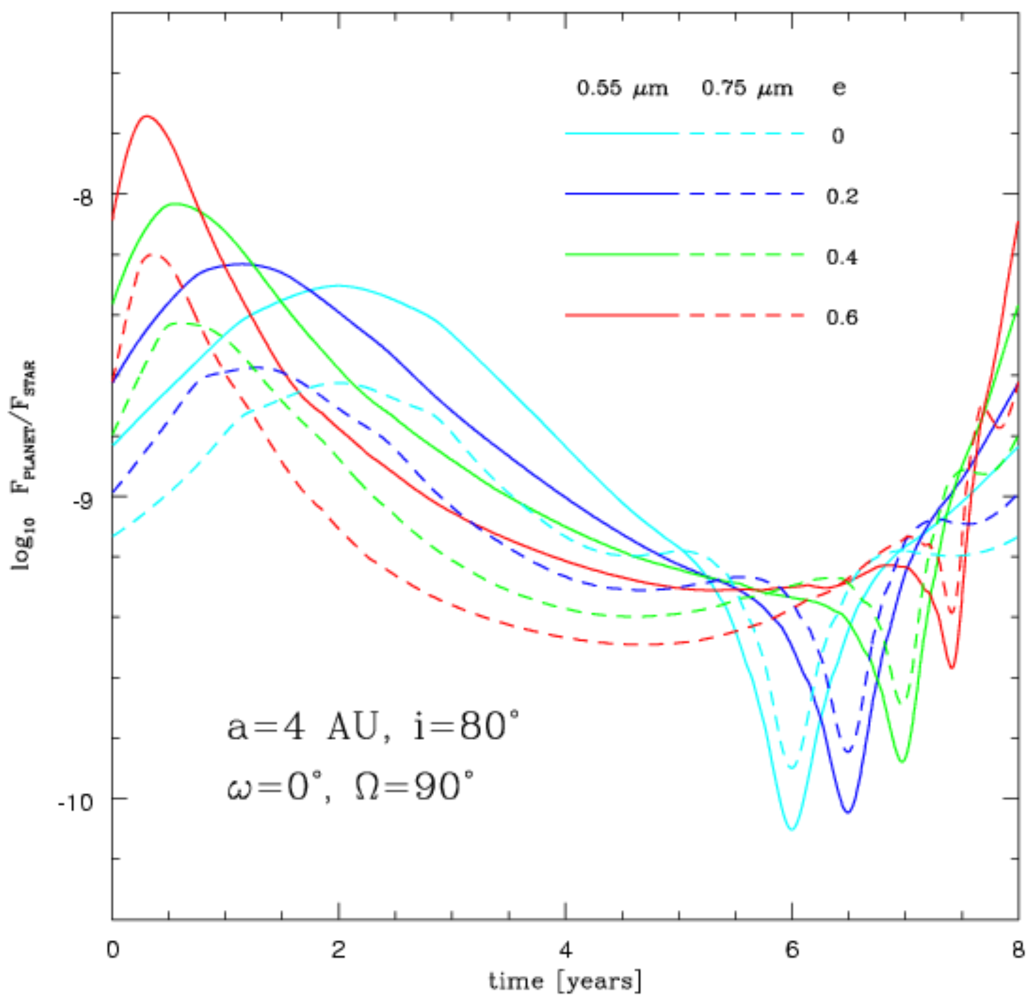
The measured visual phase functions for a selection of Solar System objects. A Lambert scattering phase curve, for which radiation is scattered isotropically off the surface regardless of its angle of incidence, is shown for comparison. The phase functions of the Moon and Mars peak near full phase (the so-called "opposition effect"). A red bandpass Jupiter phase function, taken from Dyudina et al. (2004), is also plotted.



Theoretical optical phase functions of 1-M_J, 5-Gyr EGPs ranging in orbital distance from 0.2 AU to 15 AU from a G2V star. Near full phase, the phase functions for our baseline models at larger orbital distances peak most strongly. For the cloud-free EGPs at smaller orbital distances (0.2 AU, 0.5 AU, and 1 AU), the phase functions are more rounded near full phase.



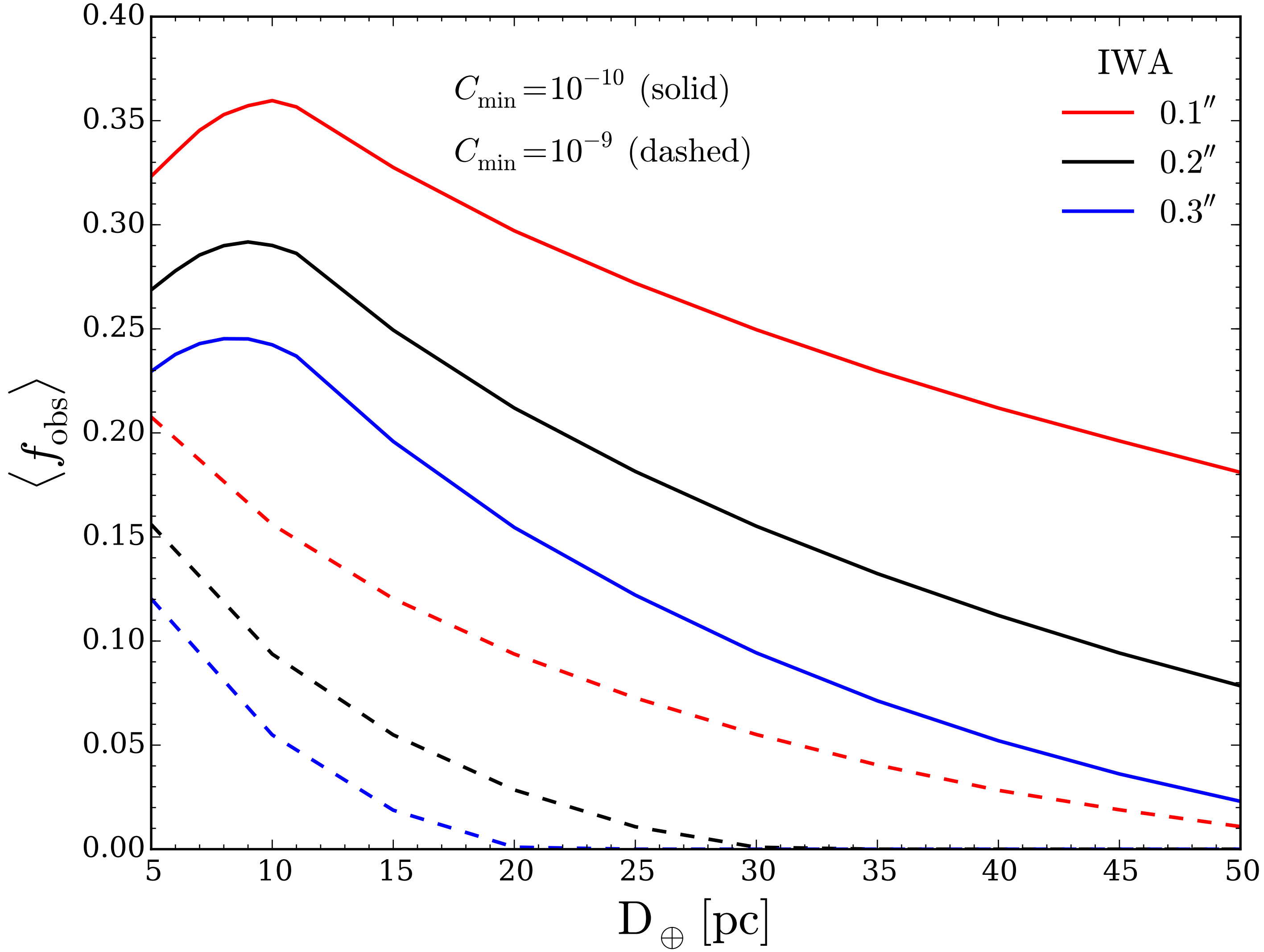
V-R vs. R-I color-color diagram detailing variations with planetary phase for a variety of orbital distances. Each of the curves depicts an orbit from full phase (0 degrees) to a thin crescent phase (170 degrees) in increments of 10 degrees (as indicated by the filled circles). Cloud-free EGPs are bluest near greatest elongation, while cloudy EGPs tend to be bluest in a gibbous phase. As full phase is approached, the colors redden somewhat. However, the crescent phases appear to be far redder, varying by as much as a full astronomical magnitude from their blue gibbous-phase colors in some cases. See text for details and a discussion of the accuracy at large phase angles (denoted by dotted lines).



The logarithm of the optical (at 0.55 microns) and far red (0.75 microns) planet/ star flux ratios as a function of eccentricity for a = 4 AU, fixing i at 80 degrees and ω is zero. The planet/star flux ratio is a factor of 2 to 3 greater at 0.55 microns than in the far red at most planetary phases.

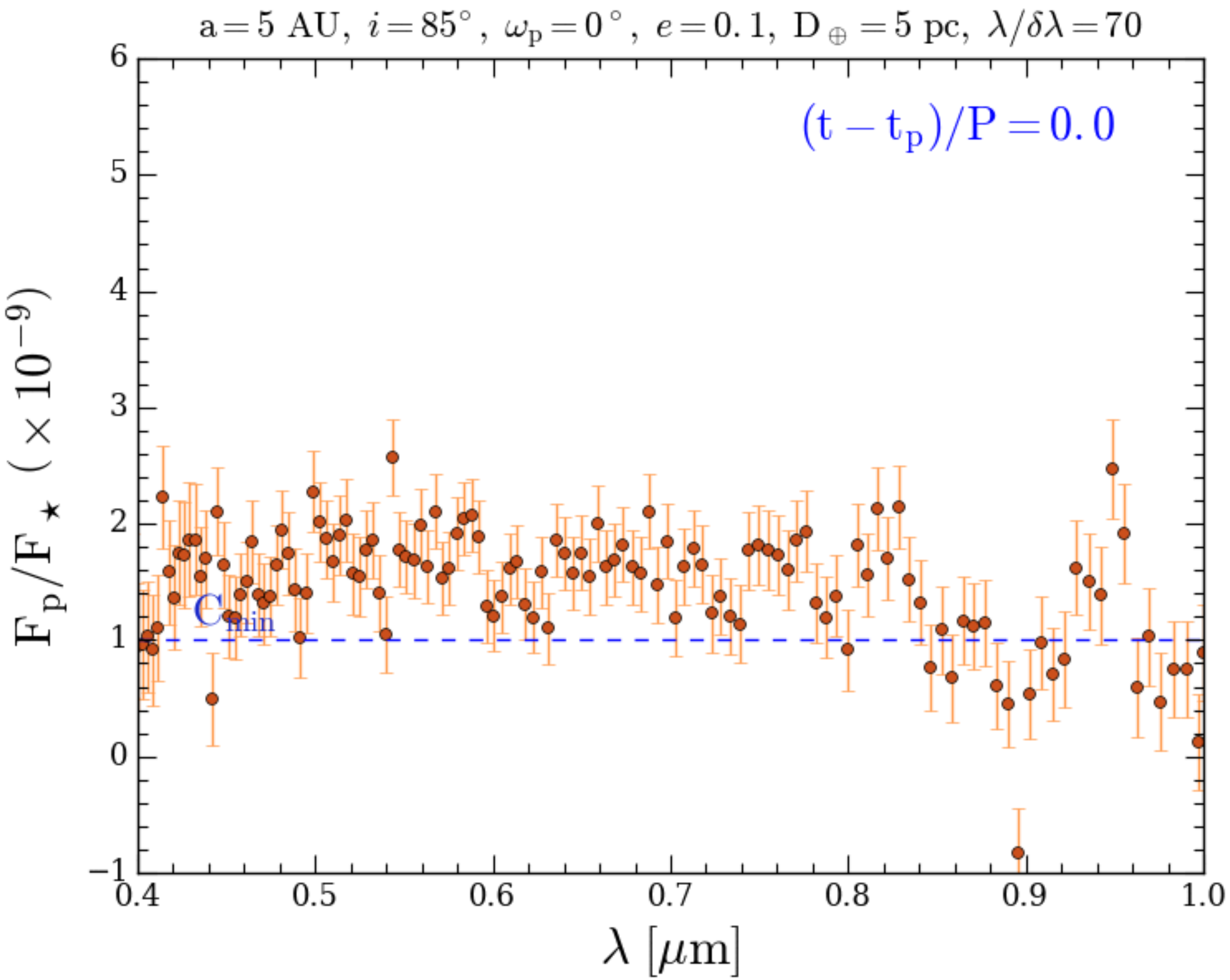
WFIRST/CGI
And Exoplanets

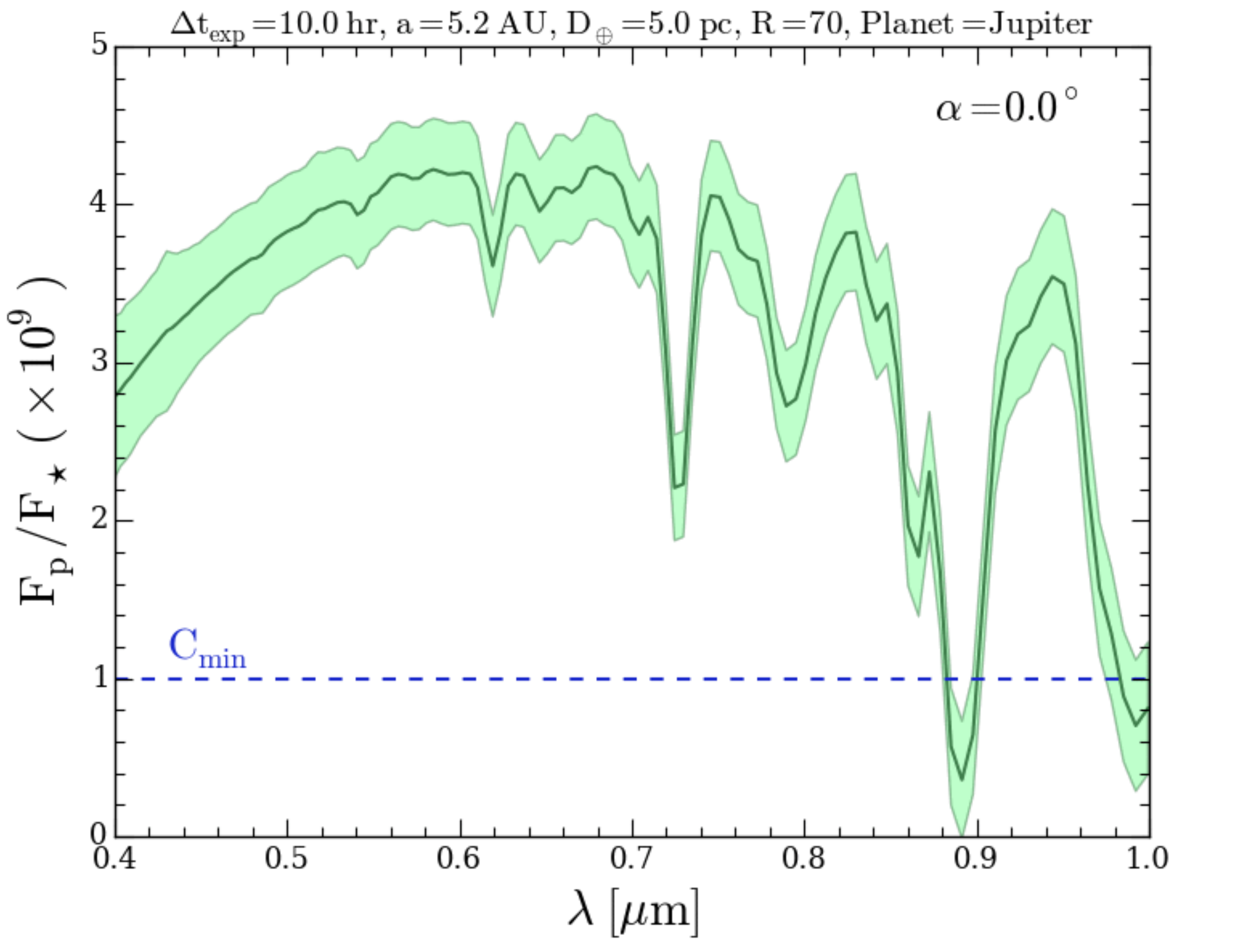
Greco & Burrows 2015



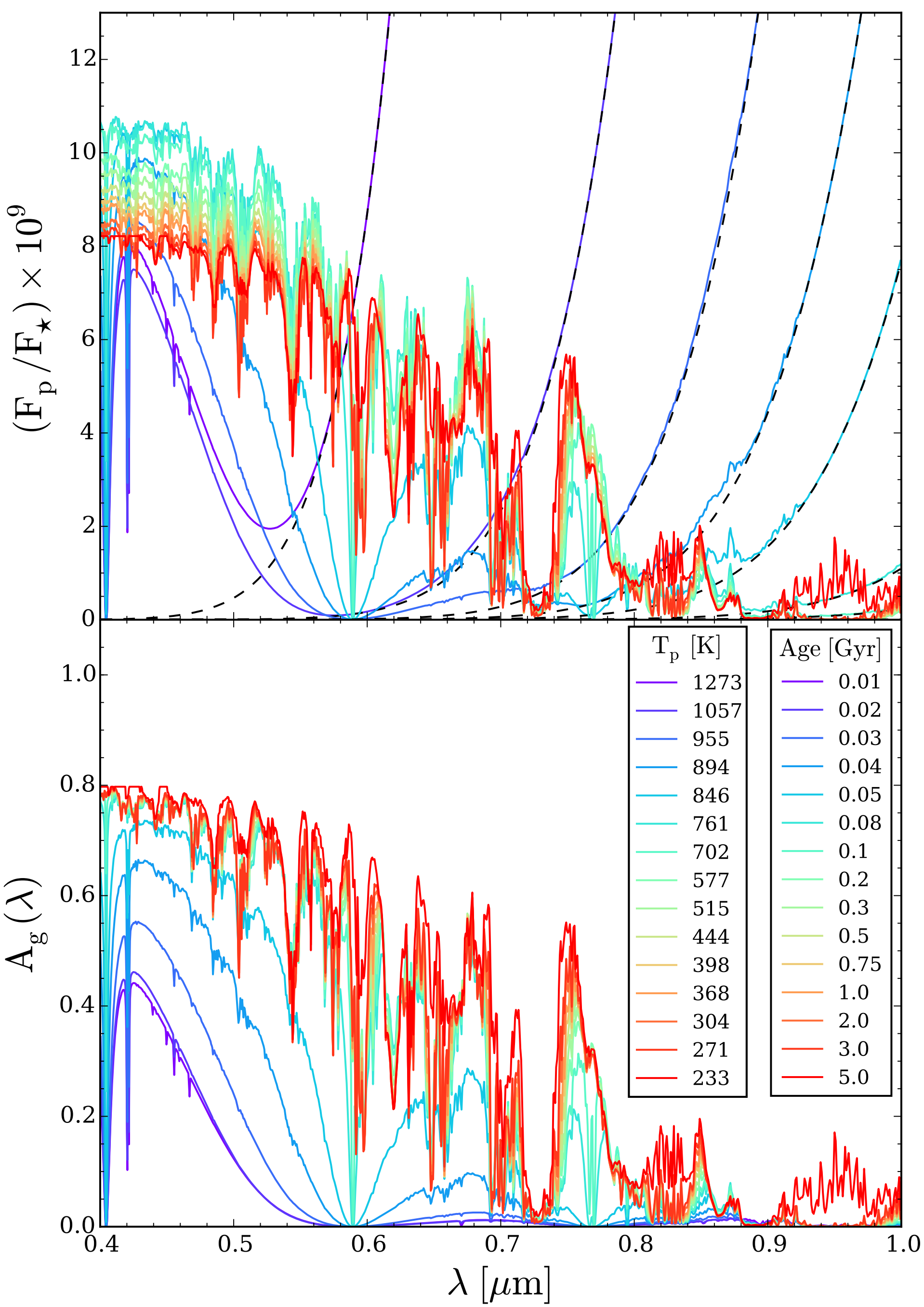
Blind Search in a volume (if there is one giant per star)

Jupiter clone Reflection Spectrum Measurement using WFIRST: “10 hr.” Exposures



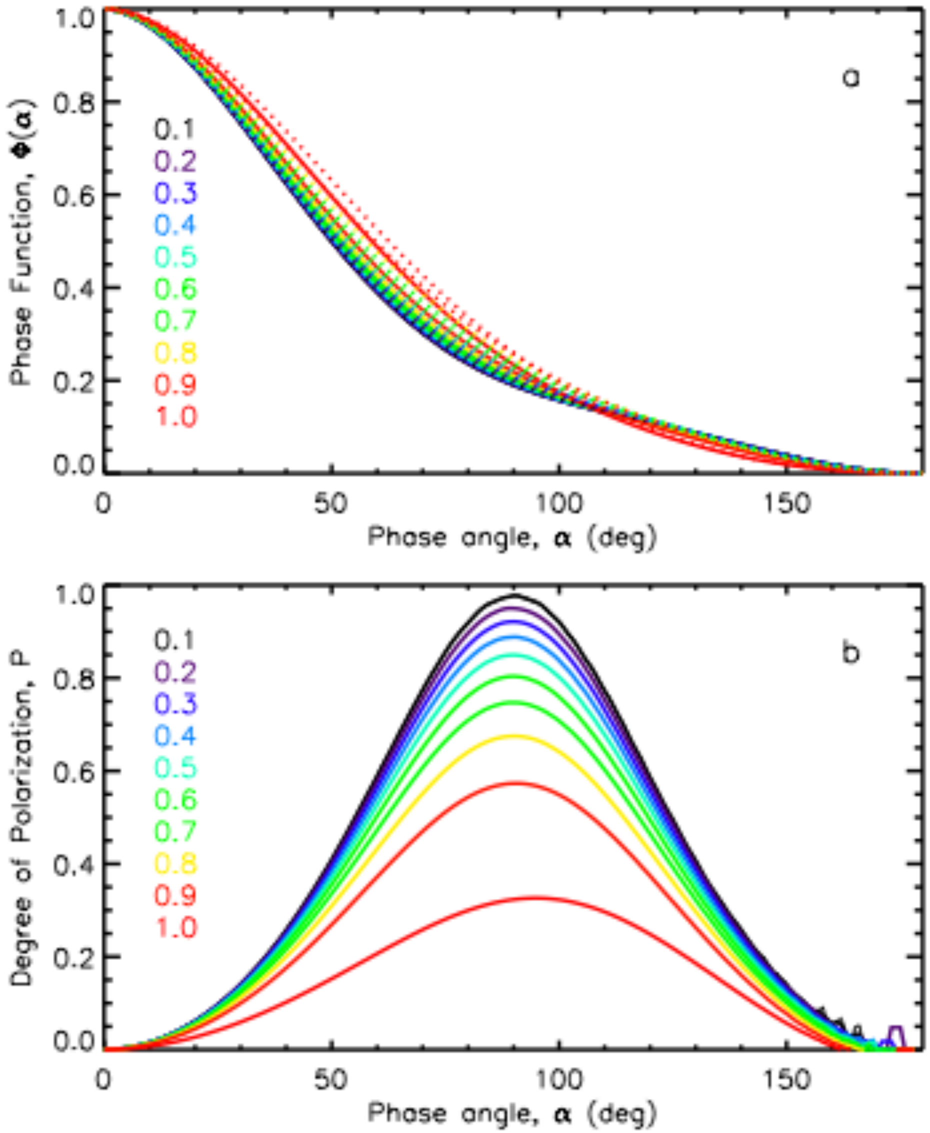


$\Delta t_{exp} = 10.0$ hr, a = 5.2 AU, $D_\oplus = 5.0$ pc, R = 70, Planet = Jupiter
$\alpha = 0.0^\circ$
C_{min}
$F_p/F_\star$ ($\times 10^9$)
λ [μm]
0
1
2
3
4
5
0.4
0.5
0.6
0.7
0.8
0.9
1.0

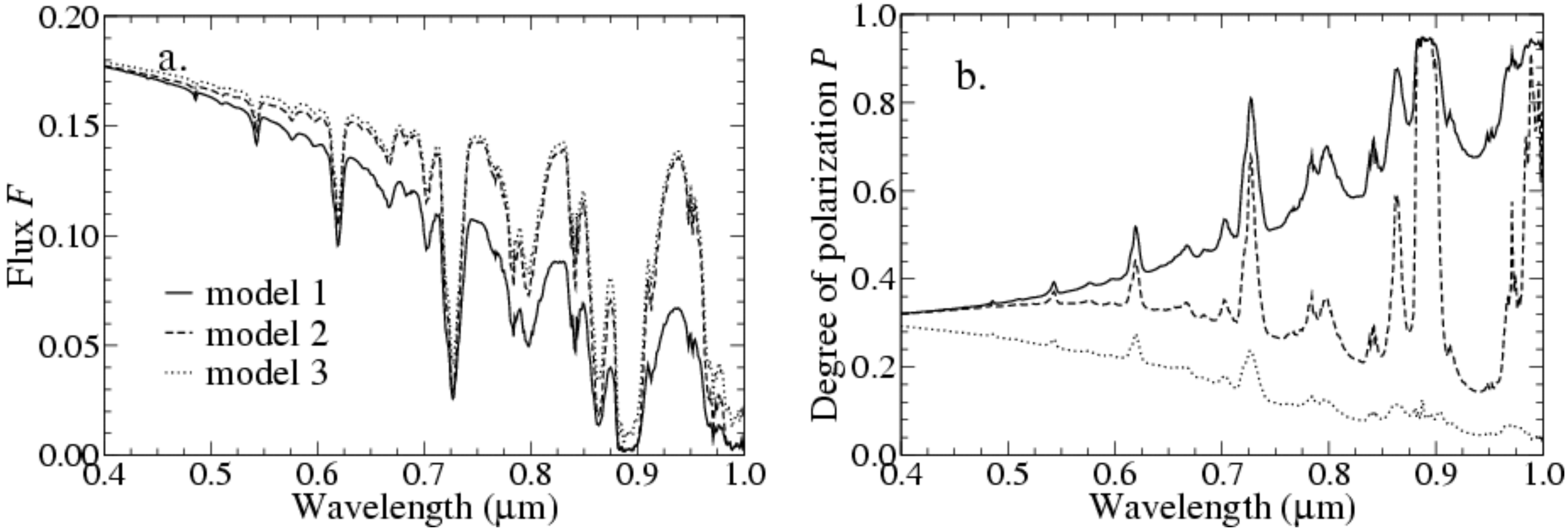


$(F_p/F_\star)\times10^9$
$A_g(\lambda)$
λ [μm]
T_p [K]
1273
1057
955
894
846
761
702
577
515
444
398
368
304
271
233
Age [Gyr]
0.01
0.02
0.03
0.04
0.05
0.08
0.1
0.2
0.3
0.5
0.75
1.0
2.0
3.0
5.0

Polarization of Giant Exoplanets



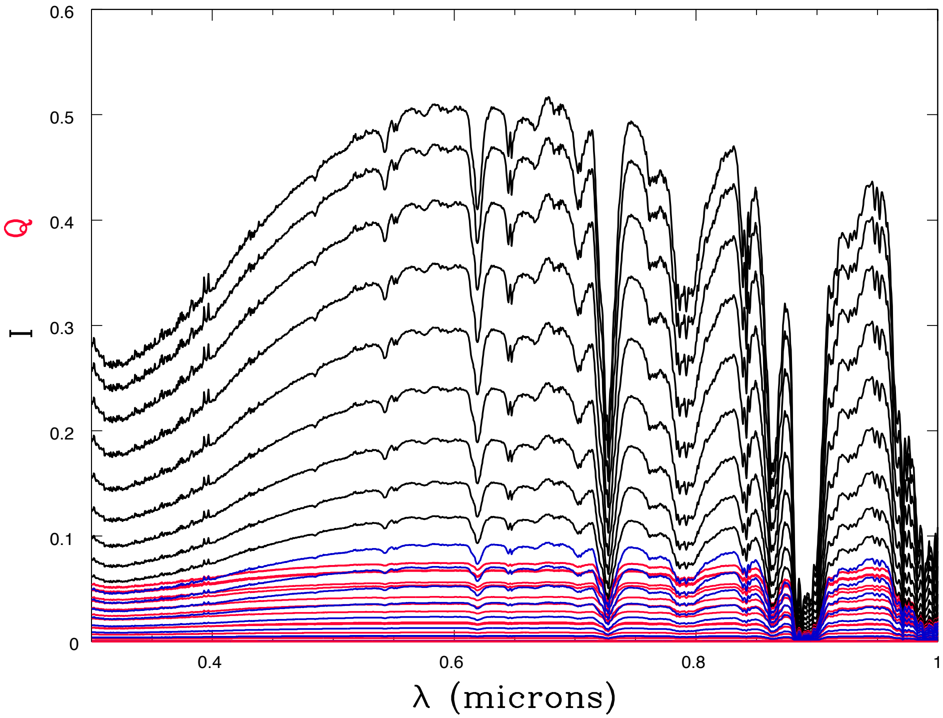
Phase curves and polarization for Rayleigh scattering. The different curves in each panel correspond to the different scattering albedos shown in the legend. In the upper panel, the solid curves show the phase curves for Rayleigh scattering using the vectorial Rayleigh phase matrix, whereas the dotted curves show those with the scalar phase function which does not incorporate polarization. The lower panel shows the degree of polarization (P), using the Rayleigh phase matrix. P is defined as $P = (Q^2 + U^2)^{1/2}/I$, where Q and U are the two Stokes parameters for linear polarization and I is the total intensity. For all the curves shown here, the orbit is assumed to be edge on (i = 90 degrees), in which case U = 0 and, hence, effectively P = Q/I.

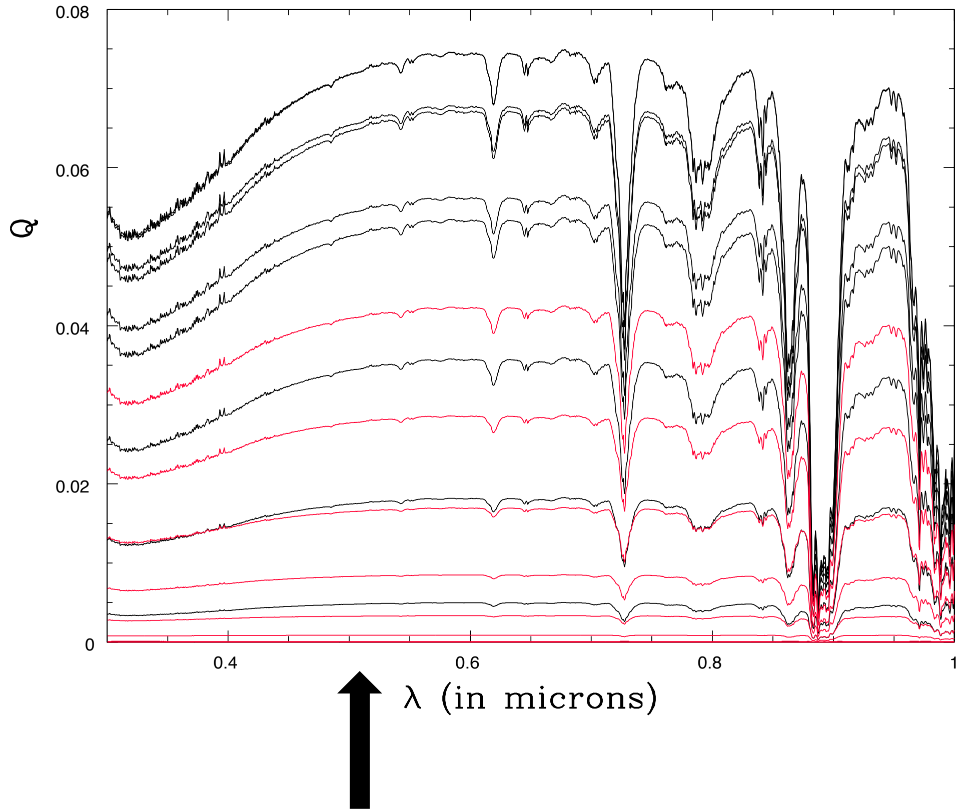


Stam et al. 2004

Polarization flux ratio (left) and polarization fraction (right)

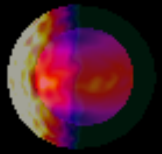
Polarization and Flux in "Albedo units" vs. Phase





Blow-up of red/blue lines

Burrows 2016



Graphic by D. Spiegel

References:

“Scientific Return of Coronagraphic Exoplanet Imaging and Spectroscopy Using WFIRST,” (A. Burrows), a Quick Study in support of the WFIRST/AFTA coronagraphic campaign, sponsored by NASA/JPL, 2014 (arXiv:1412.6097).

"Spectra and Diagnostics for the Direct Detection of Wide-Separation Extrasolar Giant Planets," (A. Burrows, D. Sudarsky, and I. Hubeny), Astrophys. J., 609, 407, 2004.

"Theoretical Spectra and Atmospheres of Extrasolar Giant Planets" (D. Sudarsky, A. Burrows, and I. Hubeny), Astrophys. J., 588, 1121, 2003.

"Phase Functions and Light Curves of Wide Separation Giant Planets,” (David Sudarsky, Adam Burrows, Ivan Hubeny, and Aigen Li), Astrophys. J. 627, 520, 2005 (astro-ph/0501109).

"Albedo and Reflection Spectra of Extrasolar Giant Planets," (D. Sudarsky, A. Burrows, and P. Pinto) Astrophys. J., 538, 885, 2000.

"The Theory of Brown Dwarfs and Extrasolar Giant Planets," (A. Burrows, W.B. Hubbard, J.I. Lunine, and J. Liebert), Rev. Mod. Phys}, 73, 719 (2001).

"Spectral and Photometric Diagnostics of Giant Planet Formation Scenarios,” (D. Spiegel & A. Burrows), Astrophys. J., 745, 174, 2012 (arXiv:1108.5172).

"Analytic Models for Albedos, Phase Curves, and Polarization of Reflected Light from Exoplanets," (N. Madhusudhan & A. Burrows), Astrophys. J., 747, 25, 2011 (arXiv:1112.4476).

“Spectra as Windows into Exoplanet Atmospheres,” (A. Burrows), PNAS, 111, pp. 12601-12609, 2014.

"A theoretical look at the direct detection of giant planets outside the Solar System," (A. Burrows) Nature 433, pp. 261 - 268, 2005 (astro-ph/0501484).