Investigating Pluto's Troposphere Using a Radiative-conductive-convective Model and Stellar Occultation Data

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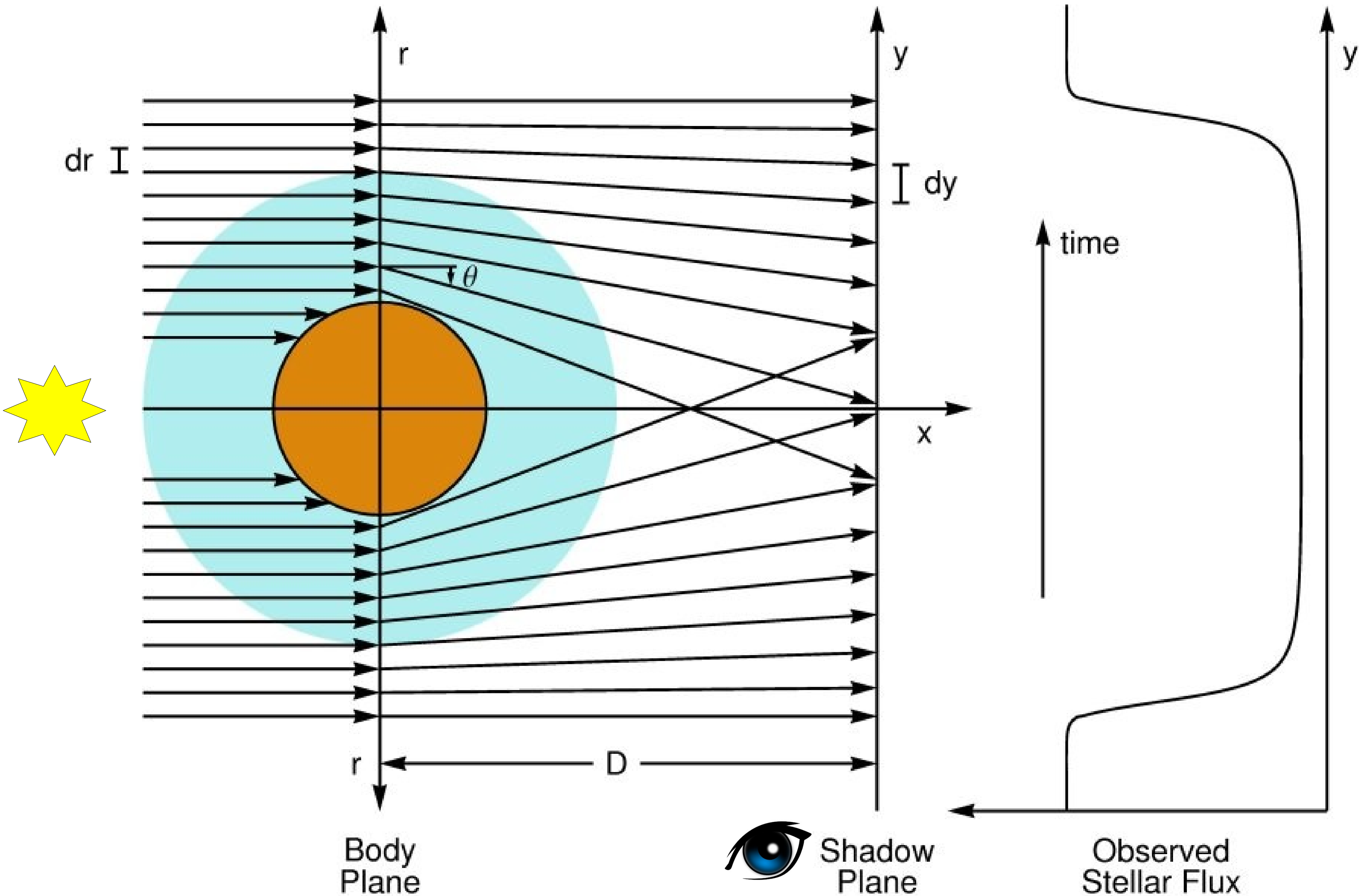
Motivation

- Stellar occultations are a useful tool for probing planetary atmospheres.
- Pluto's atmospheric composition, surface pressure, and in turn temperature structure are not yet well constrained.
- The radiative-conductive model of Strobel et al. 1996 (Icarus 120, 266–289), now with the effects of CH_4 moist convection, is used to calculate temperature profiles and model light curves.
- The model is compared with data from 1988, 2002, and 2006 to determine surface pressure, possible troposphere depth, and surface radius, which is also unknown to within tens of km.
- This study improves upon previous ones (Stansberry 1994, Icarus 111, 503–513; Lellouch 2009, Astron Astrophys. 495, L17–L21), which used idealized temperature profiles and did not explicitly consider heat balance in the atmosphere.

What is a Stellar Occultation?



A stellar occultation occurs when a body moves in front of a star. As starlight passes through the atmosphere, it is refracted. By measuring the intensity of light as a function of time, an observer in the shadow plane can determine the atmospheric structure.

Strobel et al. (1996) Radiative-conductive-convective Model for Pluto's Atmosphere

Atmospheric composition

Primary constituent N_2

Trace amount of CH_4

(heating at 2.3 and 3.3 μm, cooling at 7.6 μm)

Trace amount of CO

(cooling in 25 spectral lines)

Input parameters

surface radius (r_s)

surface temperature

surface pressure (p_s)

CH_4 mixing ratio

CO mixing ratio

troposphere critical height* (h_c)

$$c_p \rho \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 K \frac{\partial T}{\partial r} \right) + R_{net} + c_p \rho \frac{\partial}{\partial r} \left(K_T \frac{\partial T}{\partial r} \right) + C$$

Solve T(r) in steady state

Conduction

Radiative heating and cooling

Eddy diffusion of temperature

Eddy diffusion of equivalent potential temperature, i.e.

$$\frac{\partial \theta_e}{\partial t} = \frac{\partial}{\partial r} \left(K_C \frac{\partial \theta_e}{\partial r} \right)$$

*troposphere critical height is the level at which eddy diffusion turns off

Procedure for obtaining light curves from numerical model

Solve for T on a grid of surface pressure, surface radius, and tropopause critical height

↓

Use ideal gas law and hydrostatic balance to obtain refractivity first and second derivatives with r at each grid point

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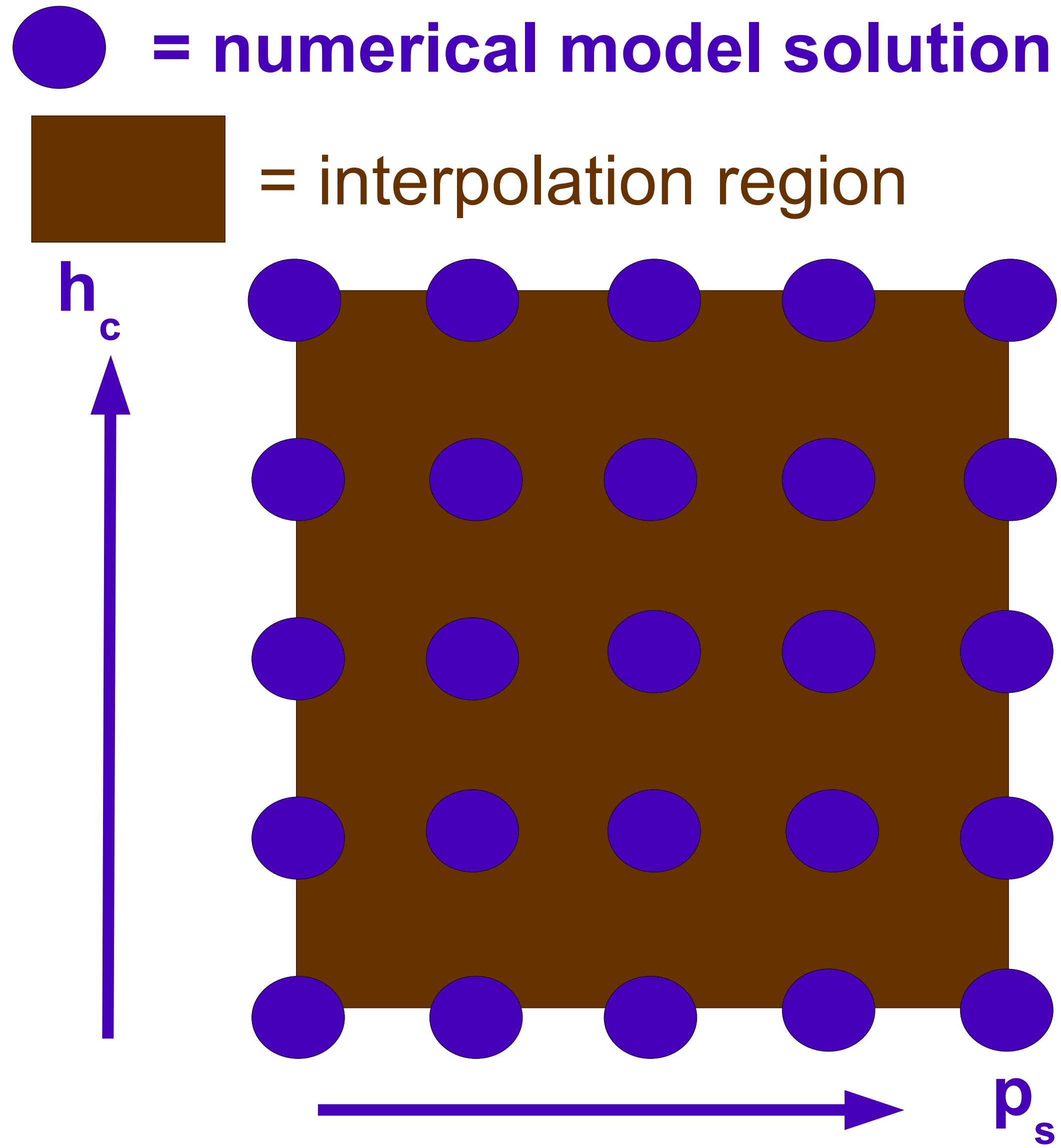
Interpolate refractivity first and second derivatives in surface pressure, surface radius, and tropopause critical height

↓

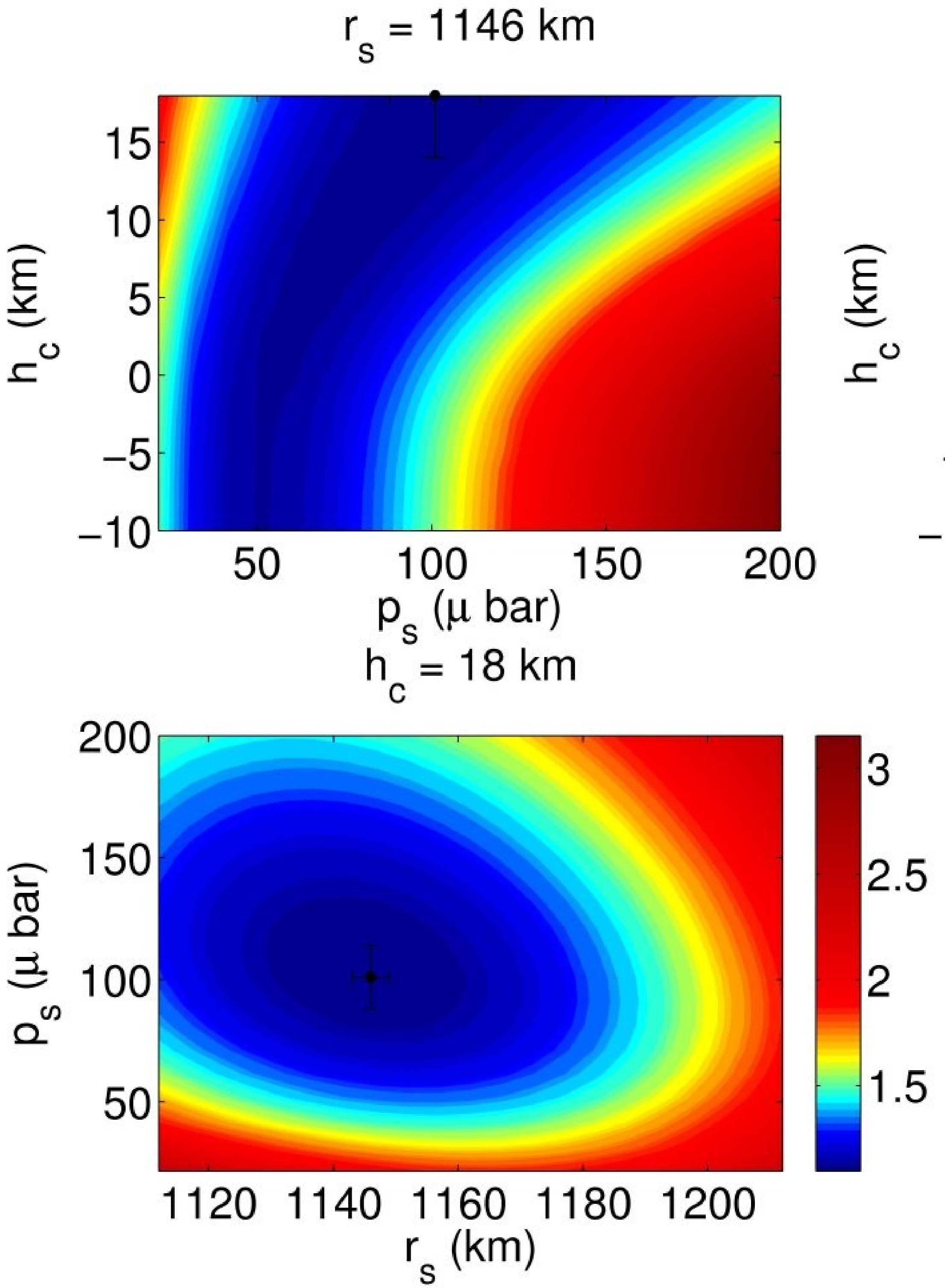
Calculate light curve for any point in interpolation region assuming a clear atmosphere (no absorption or scattering)



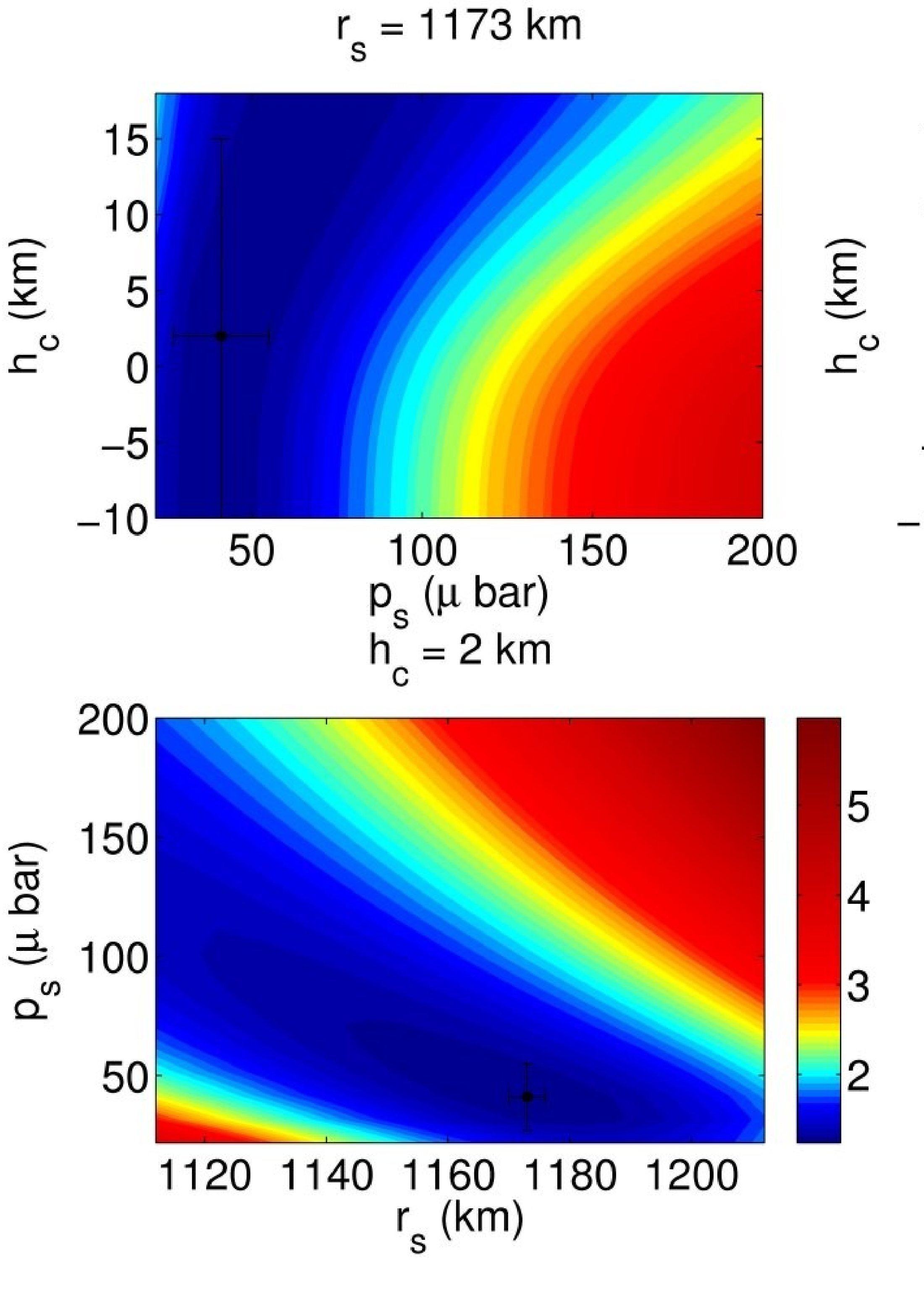
Light curve model is least sensitive to CH_4 and CO mixing ratios, these are held constant at 0.9% and 0.05%

Comparison Between Model and Data

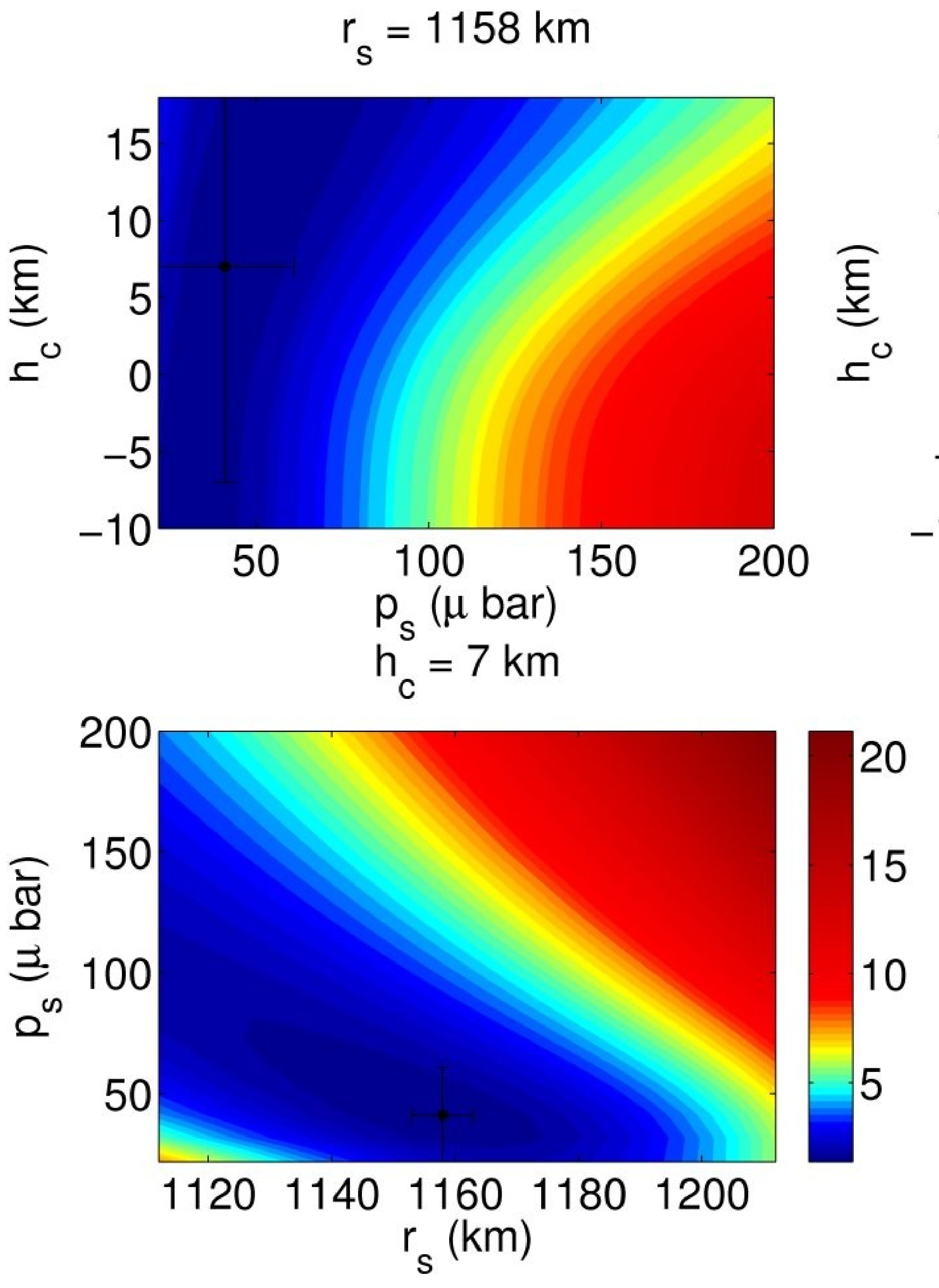
- Even though occultation data do not probe the surface, a change in surface properties affects the entire temperature profile and hence the light curve.
- We determine best-fit parameters by finding minimum chi^2 between model and data.
- Least-squares fitting, which explores chi^2 space in a deliberate manner, does not converge on a solution because surface pressure and tropopause critical height are highly correlated.
- Instead, we calculate chi^2 within a large domain to find minima.



Plots of reduced chi^2 for the 12 June 2006 Siding Spring occultation (Elliot et al. 2007, Astron J. 134, 1–13). Cross sections of p_s, r_s, h_c parameter space for the minimum reduced chi^2 are shown.



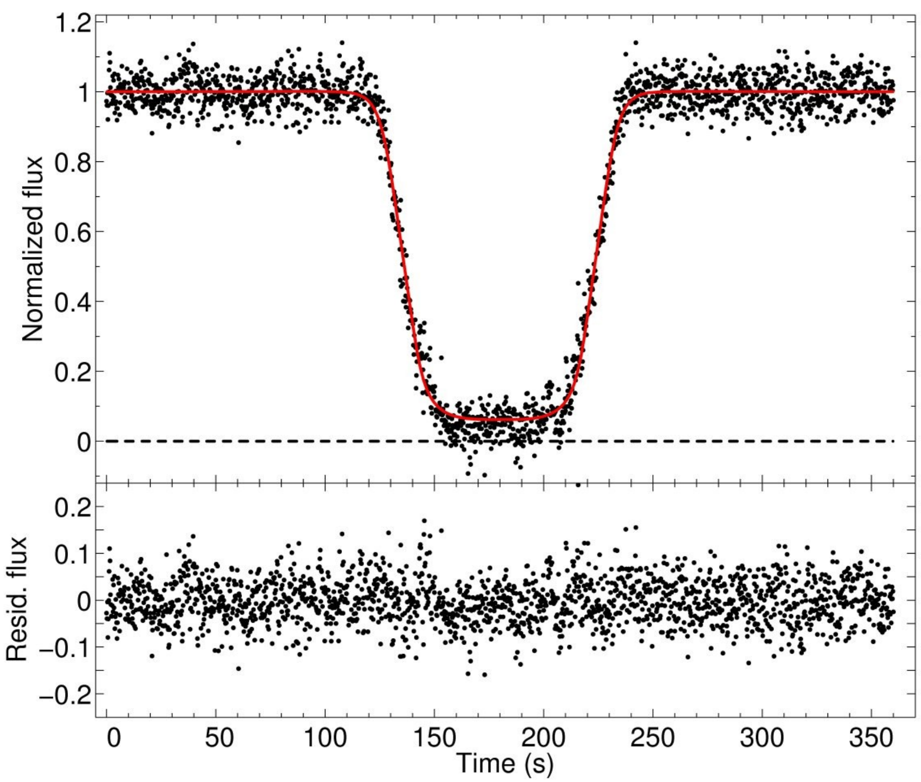
Plots of reduced chi[2] for the 21 August 2002 University of Hawaii 2.2m occultation (Elliot et al. 2003, Nature 424, 165–168). Cross sections of p_s, r_s, h_c parameter space for the minimum reduced chi[2] are shown. Only the top 60% of the light curve is used due to extinction effects in the lower portion.



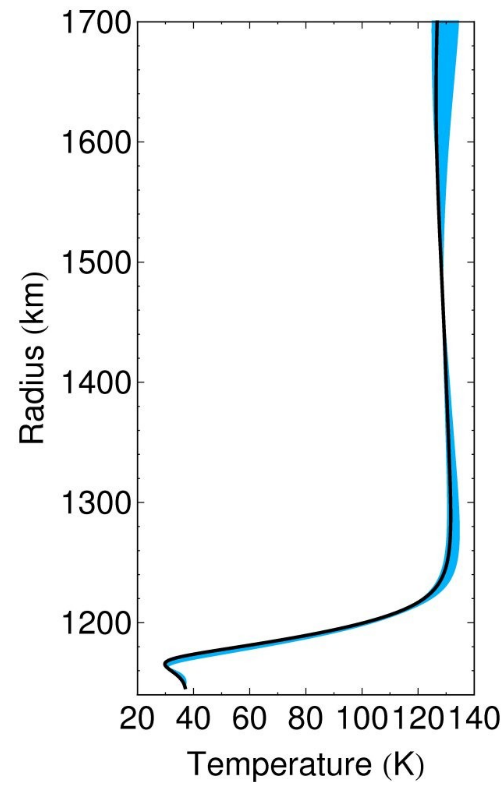
Plots of reduced chi^2 for the 9 June 1988 Kuiper Airborne Observatory occultation (Elliot et al. 1989, Icarus 77, 148–170). Cross sections of p_s, r_s, h_c parameter space for the minimum reduced chi^2 are shown. Only the top 60% of the light curve is used due to extinction effects in the lower portion.

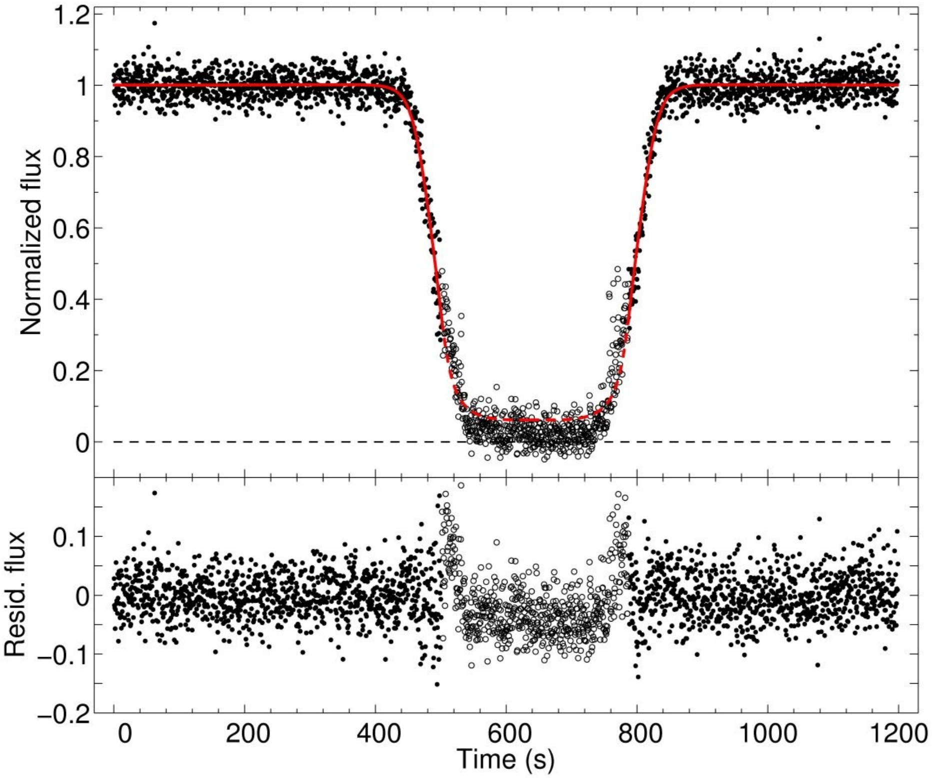
Table of Results

Event	p_s (µbar)	r_s (km)	h_c (km)	Troposphere depth for best-fit solution (km)
2006 Siding Spring	101±13	1146±3	18±4	19
2002 UH 2.2m	41±14	1173±3	2±13	6
1988 KAO	41±20	1158±5	7±14	10

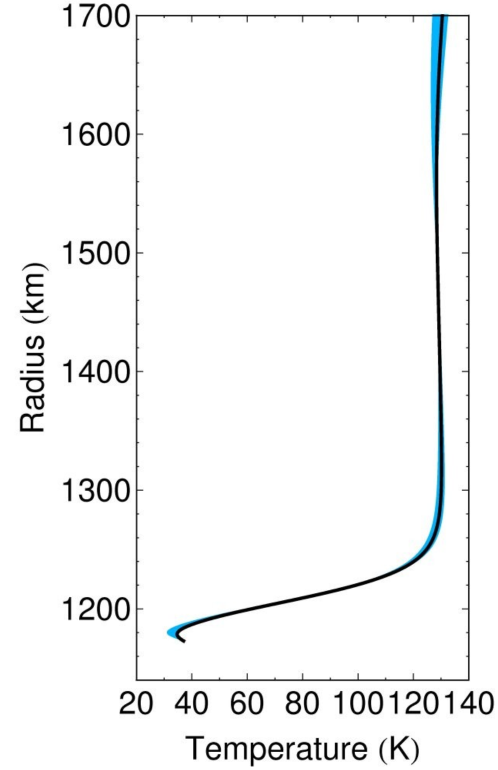


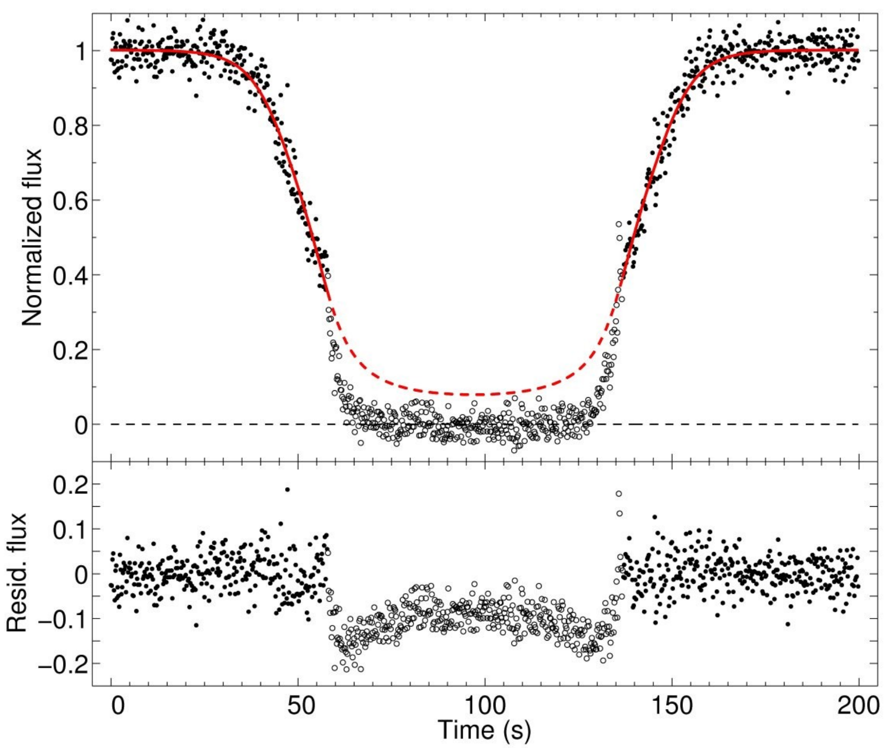
Left: 2006 Siding Spring light curve data (points) and best-fit model (red line).
Right: Temperature profile corresponding to the best-fit light curve. The 1-σ errors are shaded.



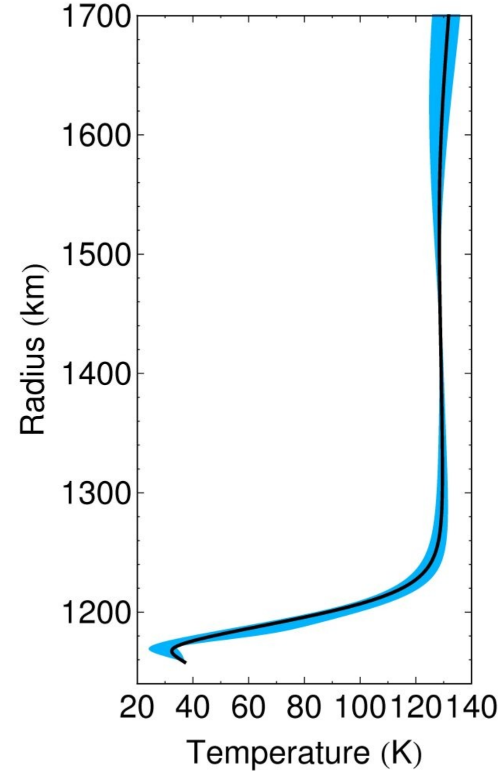


<u>Left</u>: 2002 UH 2.2m light curve data (filled points) and best-fit model (solid red line). The data not used in the chi[2] calculation are shown as open circles, and the corresponding model curve is dashed.
<u>Right</u>: Temperature profile for the best-fit light curve. The 1-σ errors are shaded.





<u>Left</u>: 1988 KAO light curve data (filled points) and best-fit model (solid red line). The data not used in the chi[2] calculation are shown as open circles, and the corresponding model curve is dashed.
<u>Right</u>: Temperature profile for the best-fit light curve. The 1-σ errors are shaded.



Discussion

- p_s increases between the years 2002 and 2006, but is constant between 1988 and 2002. This behavior is opposite of Elliot et al. 2007 (Astron J. 134, 1–13), in which pressure increased from 1988 to 2002 and was constant from 2002 to 2006.
- No apparent trend in h_c with time is seen. Differences may be accounted for by latitudinal variations, or departures from head balance (such as from atmospheric circulation).
- p_s results are higher than upper limit of 24 μbar given by Lellouch et al. 2009 (Astron. Astropys. 495, L17–L21). Tropopause depth is less than or approximately equal to their upper bound of 17 km.
- The formal error bars on r_s are small, and the measurements do not overlap with each other. As in no-tropopause fits of Zalucha et al. 2010 (submitted to Icarus), error on r_s is probably about 10 to 20 km.

Future Work

- Compare the troposphere solution with the not troposphere solution, as both obtain viable best-fit curves.
- Combine the Strobel et al. 1996 model with a Pluto general circulation model to quantify the affects of atmospheric circulation

Acknowledgments

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