An Analysis of Pluto Occultation Light Curves Using an Atmospheric Radiative-conductive Model

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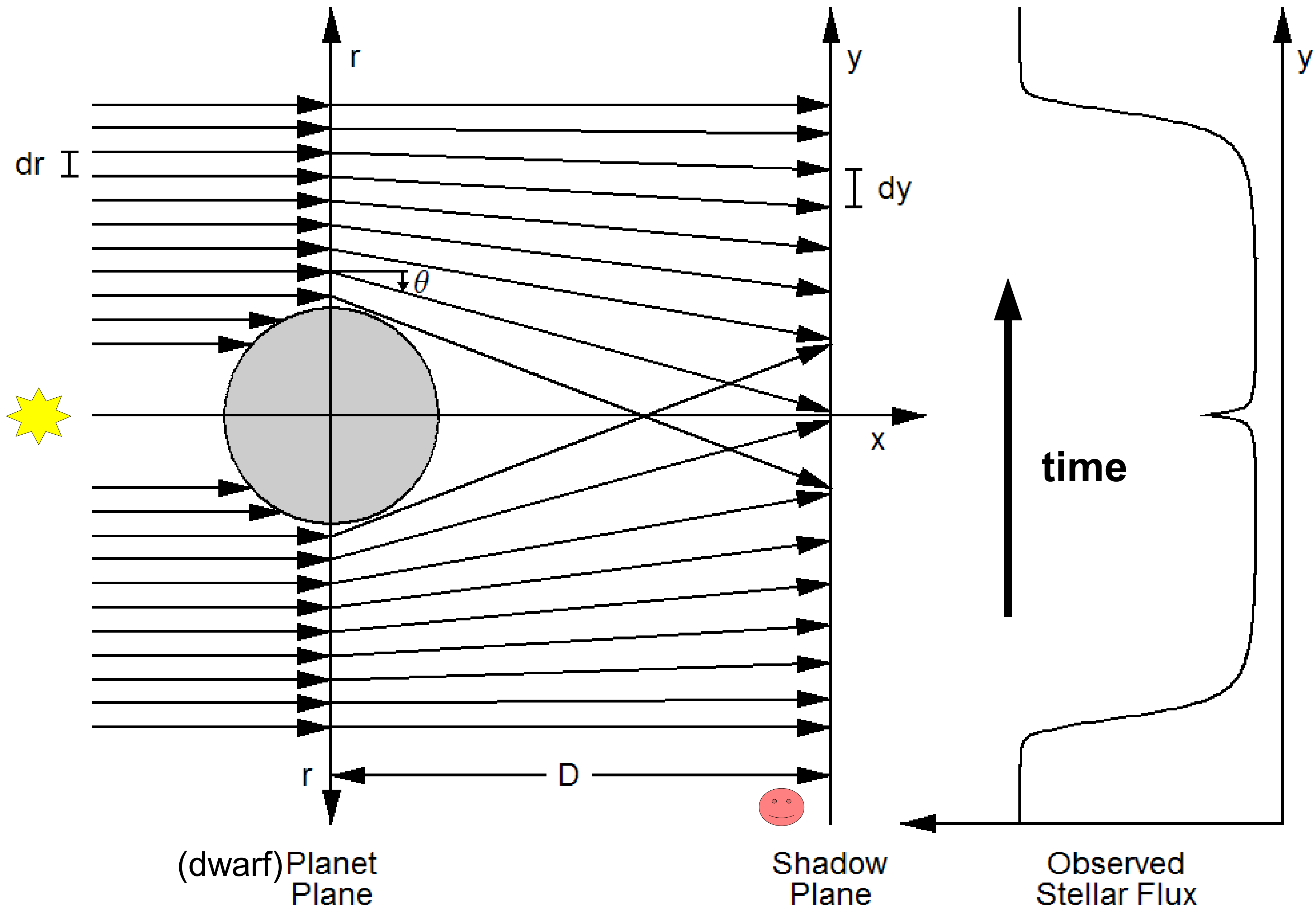

A stellar occultation occurs when a planet moves in front of a star. As starlight passes through the atmosphere, it is refracted. By measuring the intensity of light as a function of time, an observer in the shadow plane can determine the atmospheric structure.

Determining atmospheric temperature from light curves

The Elliot and Young (1992) model has used extensively to model stellar occultation light curves. Out of mathematical convenience, it assumes a power law for the dependence of temperature on radius, $T=T_h(r/r_h)^b$, which may not be accurate.

The Elliot et al. (2003) inversion method makes no such assumption in the inversion region, but requires a boundary condition at higher radii. The boundary condition that is usually used is the Elliot and Young (1992) model, which may cause systematic temperature errors in the inversion region. Zalucha et al. (2007) developed method using spikes in the light curve, but it also relies on Elliot and Young (1992) model for the upper boundary condition. In this study, we use the model of Strobel et al. (1996), which predicts atmospheric structure from the consideration of physical processes occurring in Pluto's atmosphere.

Strobel et al. (1996) radiative-conductive (convective) model for Pluto's atmosphere

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

Non-LTE heating by CH_4 3.3μm vibrational bands +

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Non-LTE cooling by CH_4 7.6μm vibrational bands +

LTE cooling by CO rotational lines

(Primary atmospheric constituent is assumed to be N_2)

Input parameters

surface radius
surface temperature
surface pressure
CH_4 mixing ratio
CO mixing ratio
troposphere depth**

Important note:

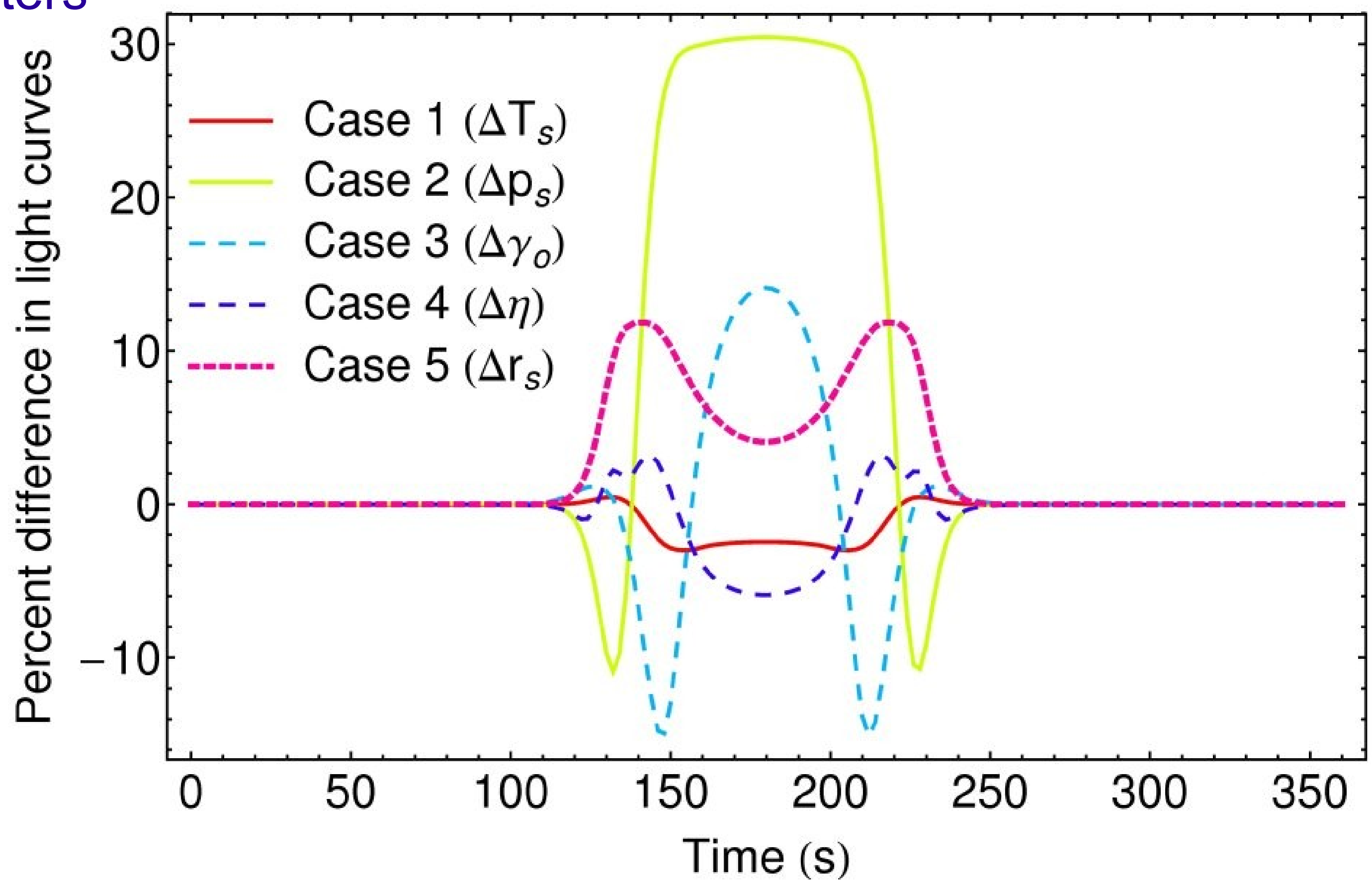
Even though occultation does not probe the surface, a change in surface properties affects the entire temperature profile and hence the light curve

Assessing the importance of each parameter

Case 1: T_s = 37 K → 42 K (constrained by surface frost)
Case 2: p_s = 18 μbar → 10 μbar (doubling of surface pressure?)
Case 3: CH_4 mixing ratio = 2 x 10^{-3} → 6 x 10^{-3} (other measurements 5-10x10^{-3})
Case 4: CO mixing ratio = 5 x 10^{-4} → 200 x 10^{-4} (insensitive to large variations)
Case 5: Surface radius = 1152 km → 1180 km (range from other measurements)

= default parameters

Calculate light curves,varying each parameter about the default.



Fix surface Temperature at 37 K, CO mixing ratio at 5 x 10^{-4} (light curve not sensitive to these parameters)

Procedure for obtaining light curves from numerical model

Solve for T on a grid of surface pressure and CH_4 mixing ratio values

↓

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 and CH4 mixing ratio

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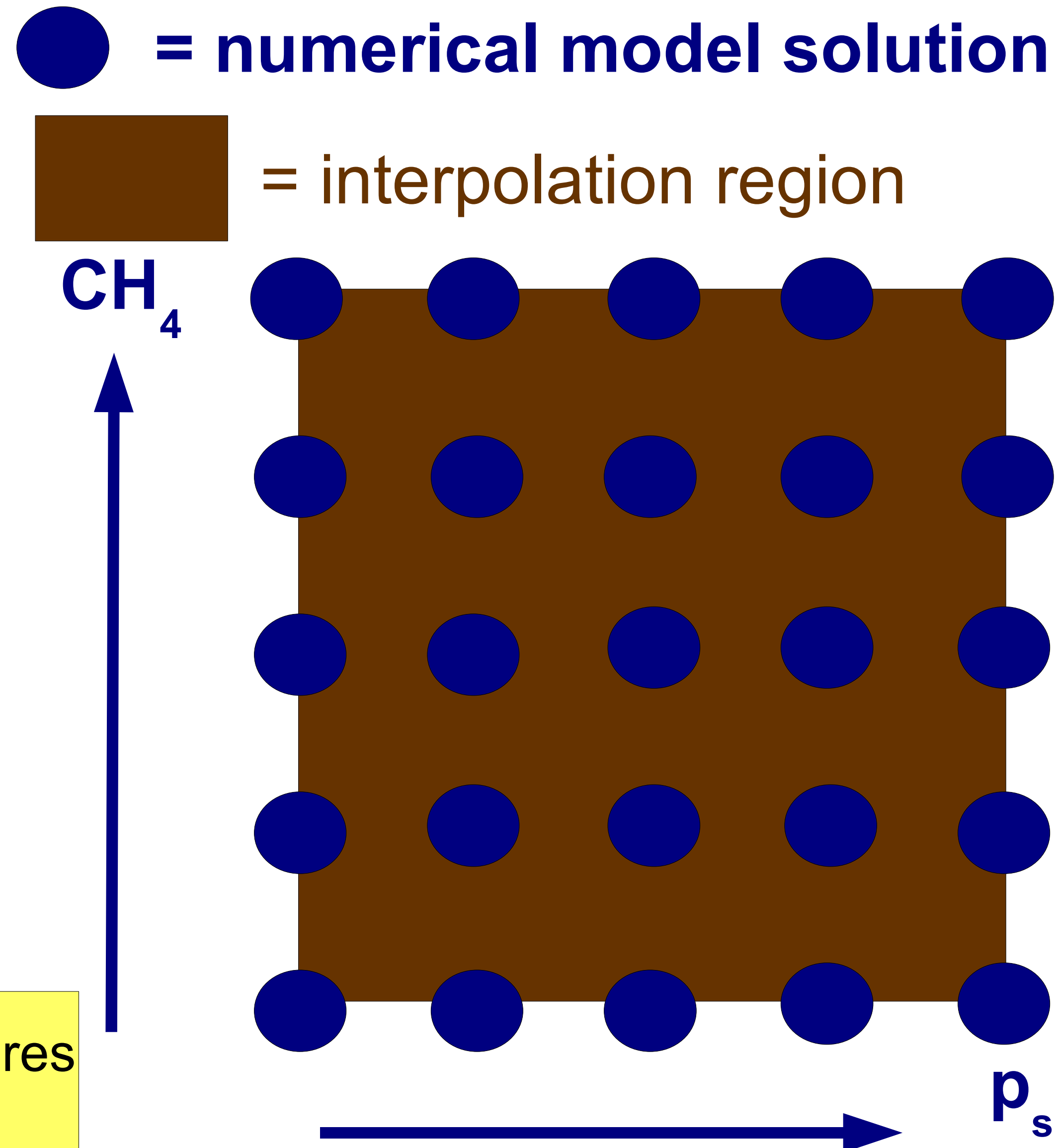
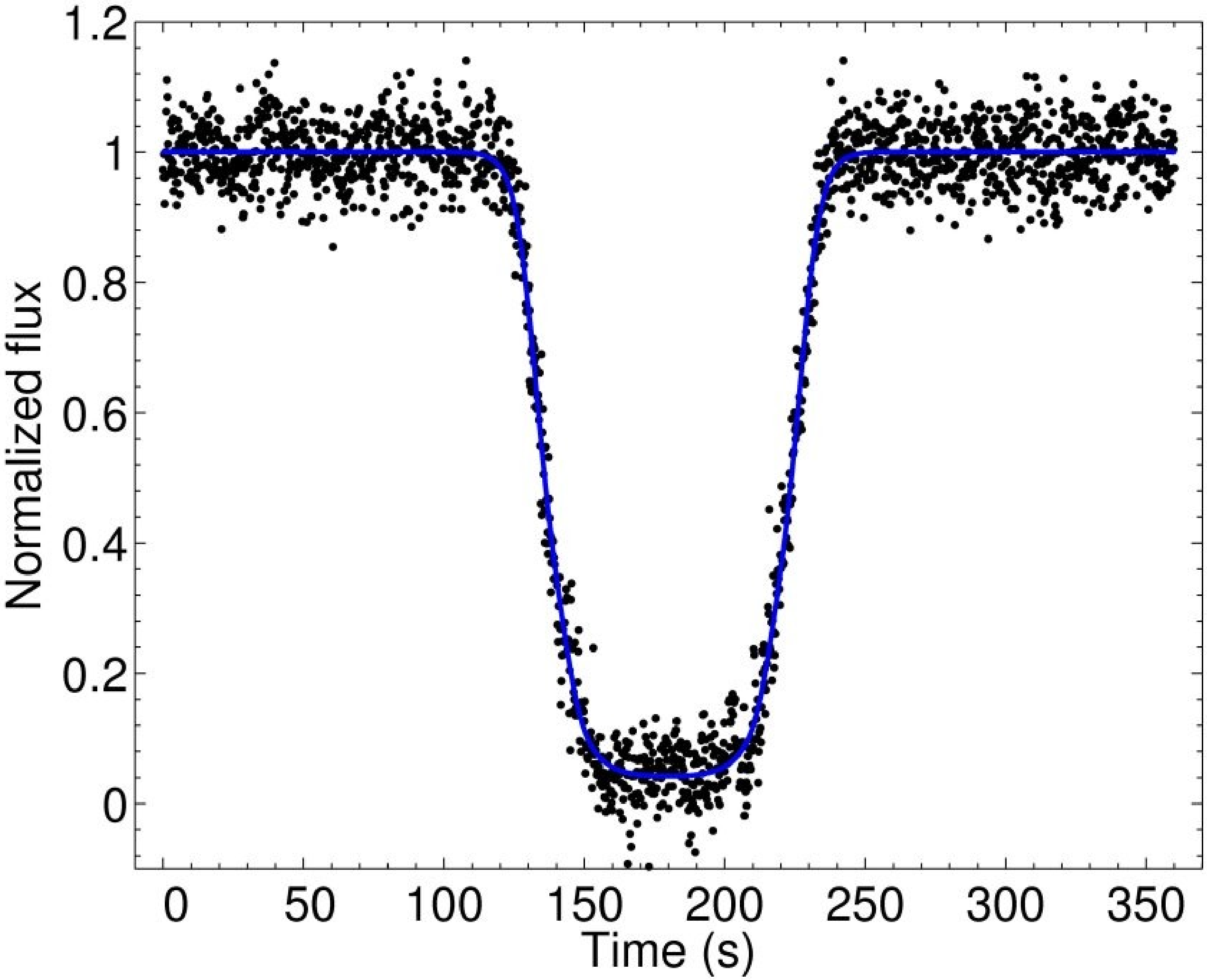
Use Chamberlain and Elliot 1997 to get light curve for any point in interpolation region

→

Least-squares fit light curve data



Least-squares fit to Siding Spring Light Curve

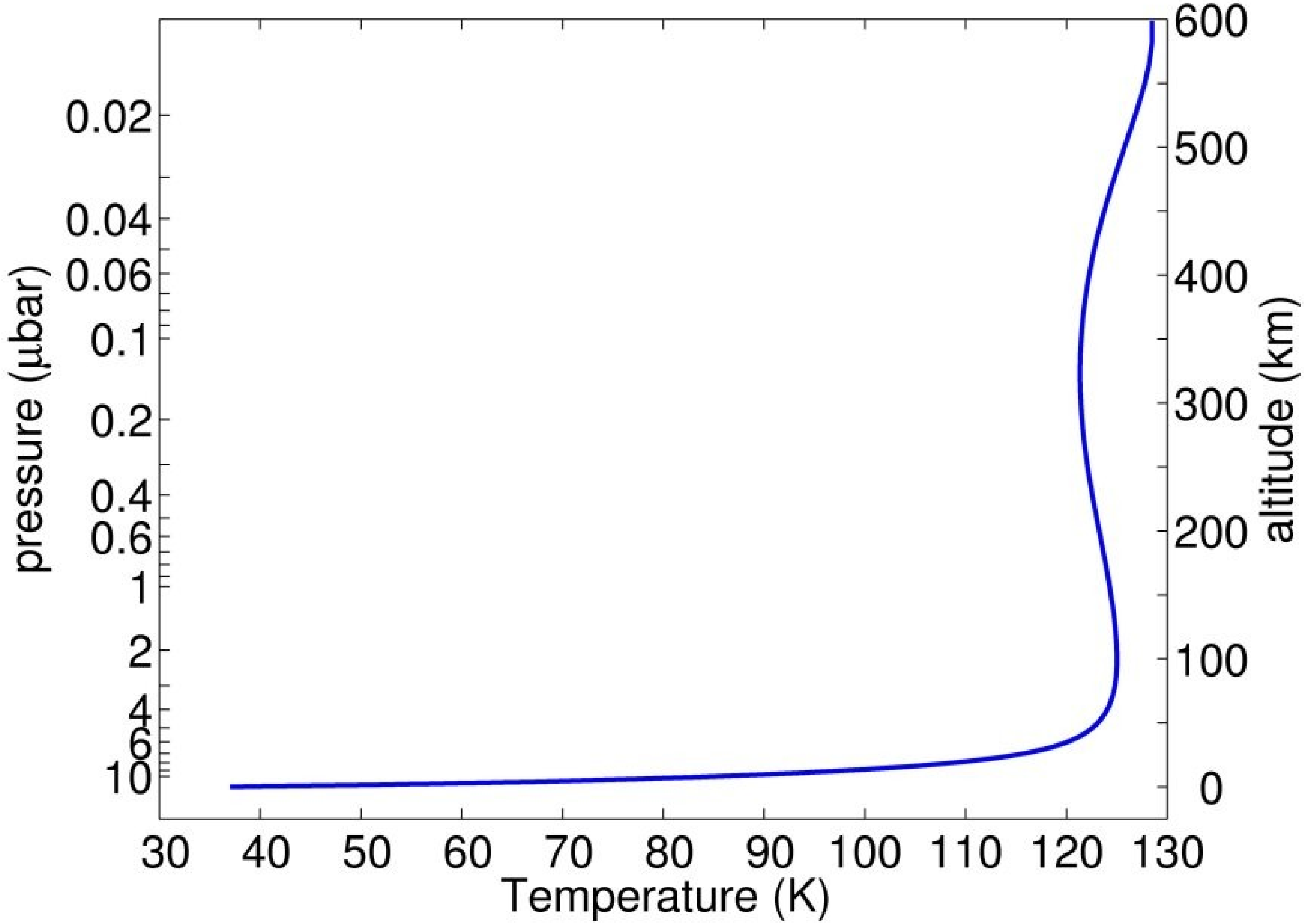


Best fit:
Surface radius = 1180 ± 2 km
Surface pressure = 13.2 μbar
CH_4 mixing ratio = $(9.4 \pm 2.7) \times 10^{-3}$

Lellouch et al. 2009: stellar occultations (21 August 2002) and methane spectroscopy (1 August 2008)
surface pressure = 6.5–24 μbar
CH_4 mixing ratio = $(5.0 \pm 0.1) \times 10^{-3}$
Tropospheric depth at most 17 km, though not required

The Siding Spring light curve (black points) was measured on 12 June 2006 at the Australian National University 2.3m telescope at Siding Spring, Australia (Elliot et al. 2007). The blue curve is the least-squares fit using the Strobel et al. (1996) model.

Temperature profile corresponding to best-fit light curve



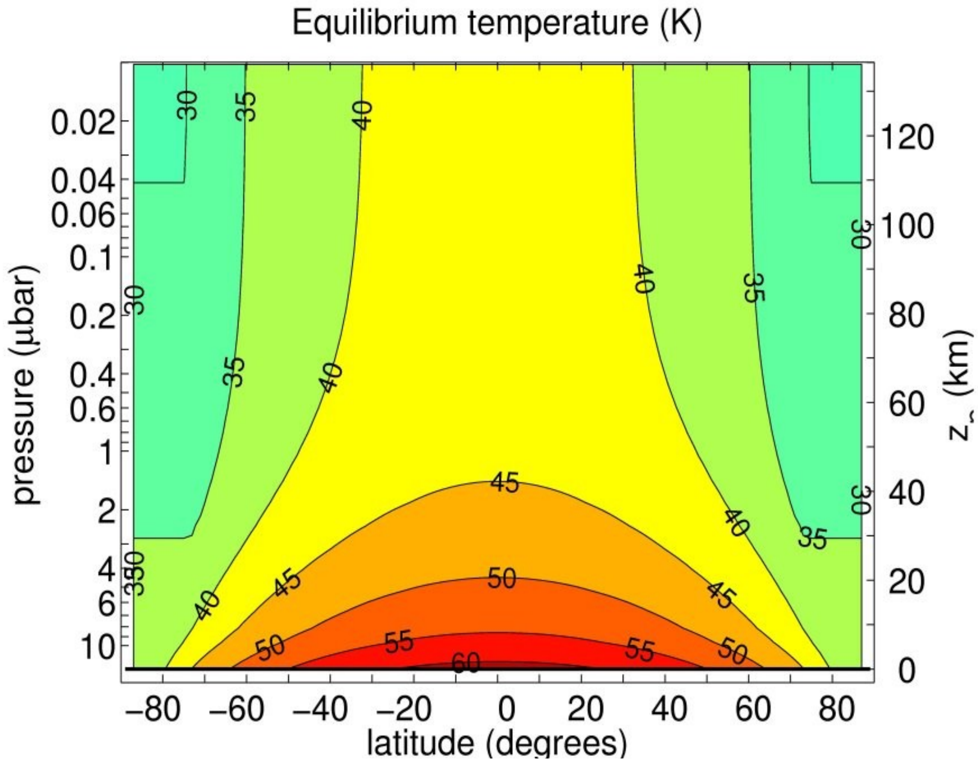
The next step: a Pluto GCM

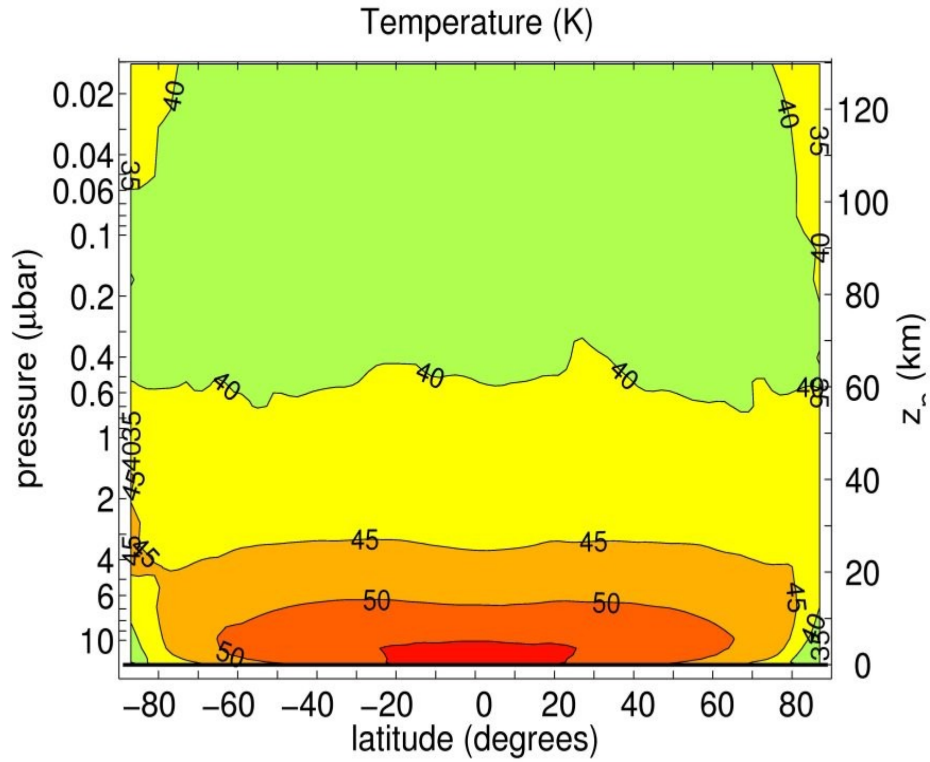
The temperature profiles from the Strobel et al. (1996) model are in radiative equilibrium, which means they do not incorporate any heat transport by dynamical processes in the atmosphere. As Pluto has a relatively slow rotation rate of approximately six Earth days, the circulation pattern is expected to be dominated by an equator to pole Hadley cell in each hemisphere around time of the equinox season (the current season on Pluto). Heat is transported by the Hadley circulation from the equator to the poles, resulting in a true atmospheric temperature not in radiative equilibrium.

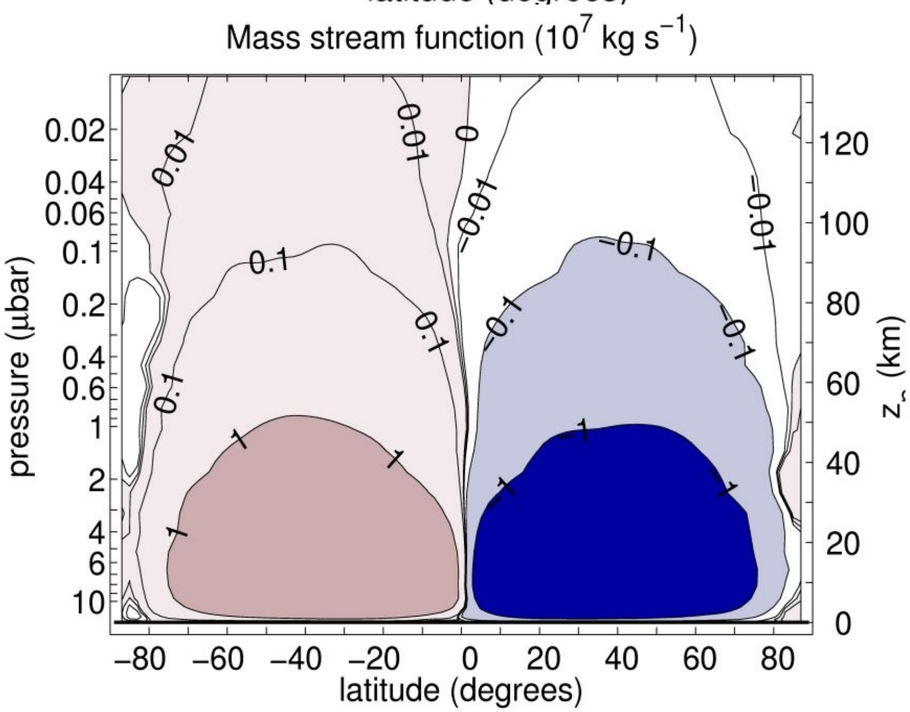
Zalucha et al. (2010) modified the terrestrial MIT GCM to Mars conditions. To test the importance of dynamics on the temperature structure, this GCM has yet again been modified for Pluto. The obvious choice for the radiation scheme is the Strobel et al. (1996) model, but at present it is not compatible with the MIT GCM. Therefore, I have adjusted the simple Mars radiation scheme to work as an approximation for Pluto conditions.

MIT GCM Held-Suarez configuration

*Newtonian relaxation to equilibrium temperature
*Simple drag-law friction scheme in boundary layer
*Rayleigh drag in top three model levels
*30 vertical levels
*32 x 32 x 6 cube-sphere configuration (about 2.8° x 2.8° horizontal resolution)
*Run at perpetual season
*No frost cycle, temperature is instantaneously reset to frost temperature with no change in mass







The equilibrium temperatures used to thermally force the simple Pluto GCM are shown on the upper left. The resulting zonally and temporally averaged temperatures are shown on the upper right. They differ due to the effects of dynamics. The mass stream function is shown on the lower left, indicating that the circulation is dominated by a Hadley circulation. In the next phase of this project, light curves will be calculated from GCM temperatures and compared with the occultation data.

Summary

Previous methods for determining atmospheric temperature from stellar occultation data required the assumption of a mathematically convenient expression for the dependence of temperature with radius.

The Strobel et al. (1996) radiative-conductive model, which predicts atmospheric temperature based on surface radius, temperature, and pressure, CH_4 mixing ratio and CO mixing ratio, was used to least-squares fit the 2006 Siding Spring light curve. The results from this fit were surface radius = 1180 ± 2 km, surface pressure = 13.2 μbar, and CH_4 mixing ratio = $(9.4 \pm 2.7) \times 10^{-3}$.

This model predicts radiative equilibrium temperatures; however, since Pluto's atmosphere is not likely to be in radiative equilibrium, future work with a Pluto GCM is planned to better model the Pluto occultation data.

Related topic:

Zalucha et al. (2007) analyzed Titan occultation data using mathematically convenient models for the temperature structure. A radiative model for Titan would be desirable to better analyze this data.

Acknowledgments

This work was supported in part by NASA grants NNX08AE92G, NNX07AK73G, and NNG05GO91G.

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