Modelling the Climate and Phase Curve of 55 Cancri E

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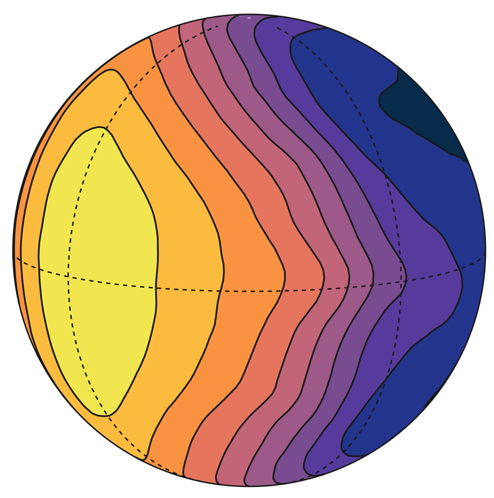
The thermal phase curve of 55 Cancri e suggests that it has a hot-spot 40 degrees east of the substellar point and a 1300K day-night temperature difference. We use a 3D GCM to model possible climates and simulate their phase curves, and discuss the relation between atmospheric parameters and the features of the measured thermal phase curve.

Introduction



55 Cancri e is a Super-Earth with mass 8.63 M_E and radius 2.00 R_E in a tidally locked orbit. The thermal phase curve measured by Demory (2016) [1] has a large amplitude and a 41 degree offset between its secondary eclipse and its phase maximum.

This implies a maximum brightness temperature of 2700K, a day-night contrast of 1300K, and a hot-spot shifted eastwards by 41°. This is surprising because the hot-spot shift needs a strong heat circulation, which should decrease the day-night contrast.

Our tests of several climates show that a simple atmosphere can partly explain the large hot-spot shift and day-night contrast observed on 55 Cancri e.

Model

We modelled the atmosphere of 55 Cancri e using Exo-FMS, an idealised general circulation model (GCM) based on a finite-volume dynamical core in the software framework FMS.

It uses the 3D fluid-dynamical core on a 144x96x40 grid, a 1D grey-gas radiative solver, and a 1D dry-convective adjustment routine.

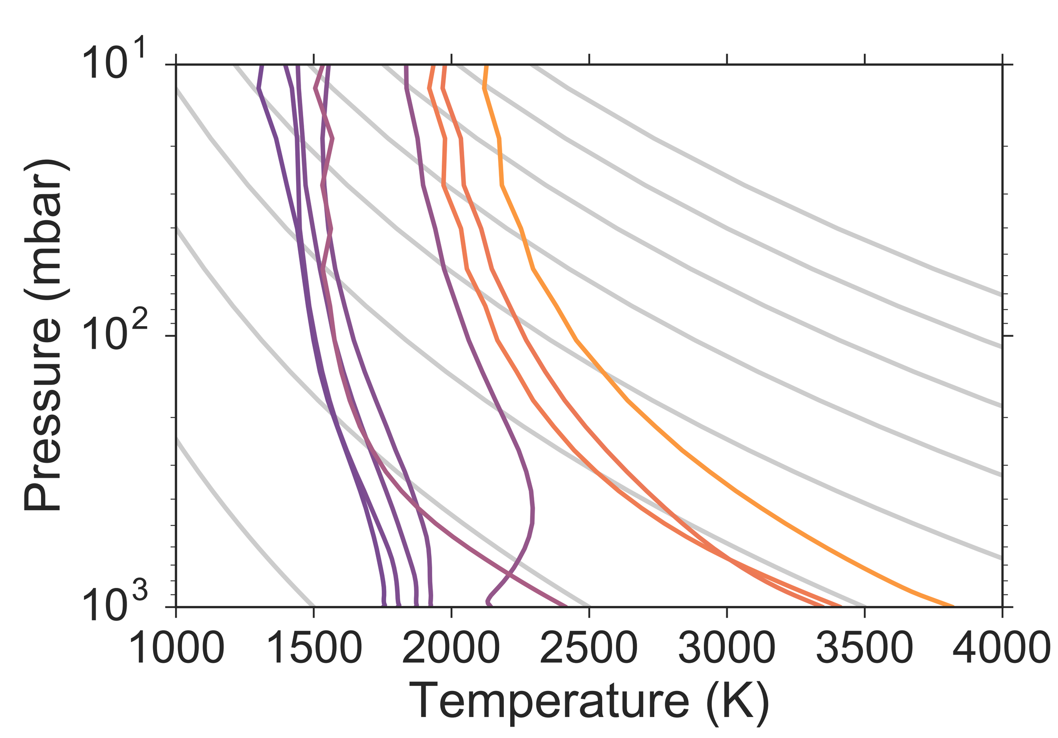


Figure 1: Temperature profiles for an N_2 atmosphere

Tidally Locked Circulation

The circulation of tidally locked planets is dominated by equatorial Rossby and Kelvin waves. These cause super-rotation, shift the planetary hot-spot to the east, and warm the night-side.

The temperature distribution depends mainly on the balance between the radiative and advective timescales of the atmosphere. Zhang (2017) [2] formulated a theory based on heat transport via advection:

$$\text{Hot-Spot Shift} \sim \xi = \frac{\tau_{rad}}{\tau_{adv}}$$

$$\text{Day-Night Contrast} \sim 1 - 1/(1 + \frac{\tau_{rad}\Delta \ln p}{\Omega \tau_{wave}^2})$$

This means that these features depend oppositely on ξ. It suggests that an atmosphere could support a significant offset and amplitude with a large ξ and a low pressure or a low heat capacity.

Exo-FMS Results

We ran two initial experiments, designed to vary the hot-spot shift and day-night contrast:

- H_2, ps = 10 bar, $\tau_{inf} = 8.0$
- N_2, ps = 10 bar, $\tau_{inf} = 8.0$

The 10 bar hydrogen atmosphere has a longer radiative timescale and large ξ, so has a large hot-spot offset. The 10 bar nitrogen atmosphere has a short radiative timescale and a long wave timescale so a large day-night contrast.

Figure 2: H_2 10 bar; temperature at half-pressure

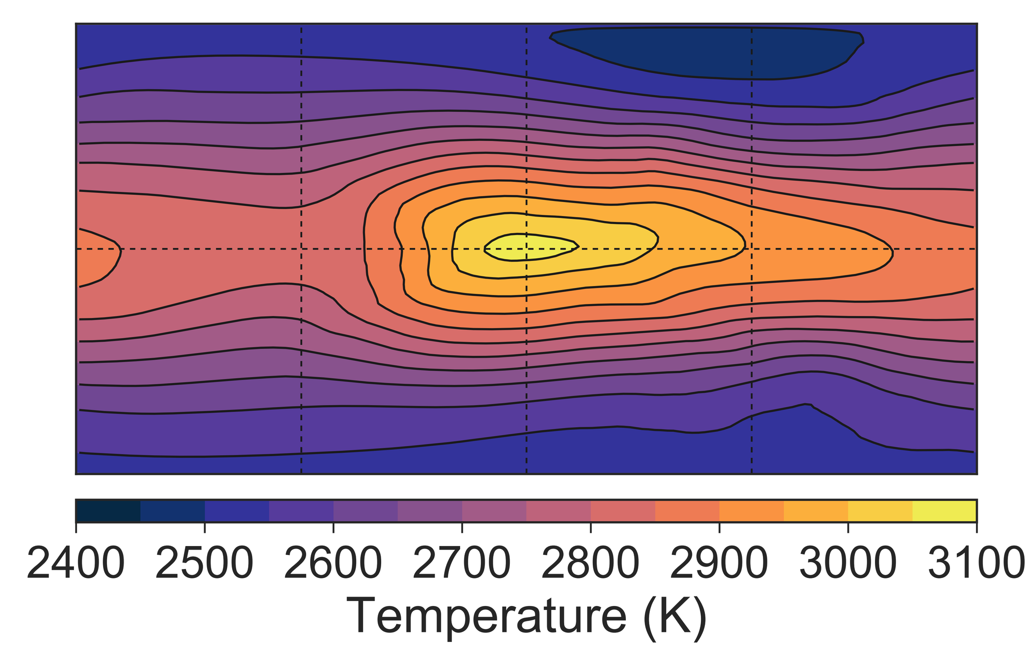
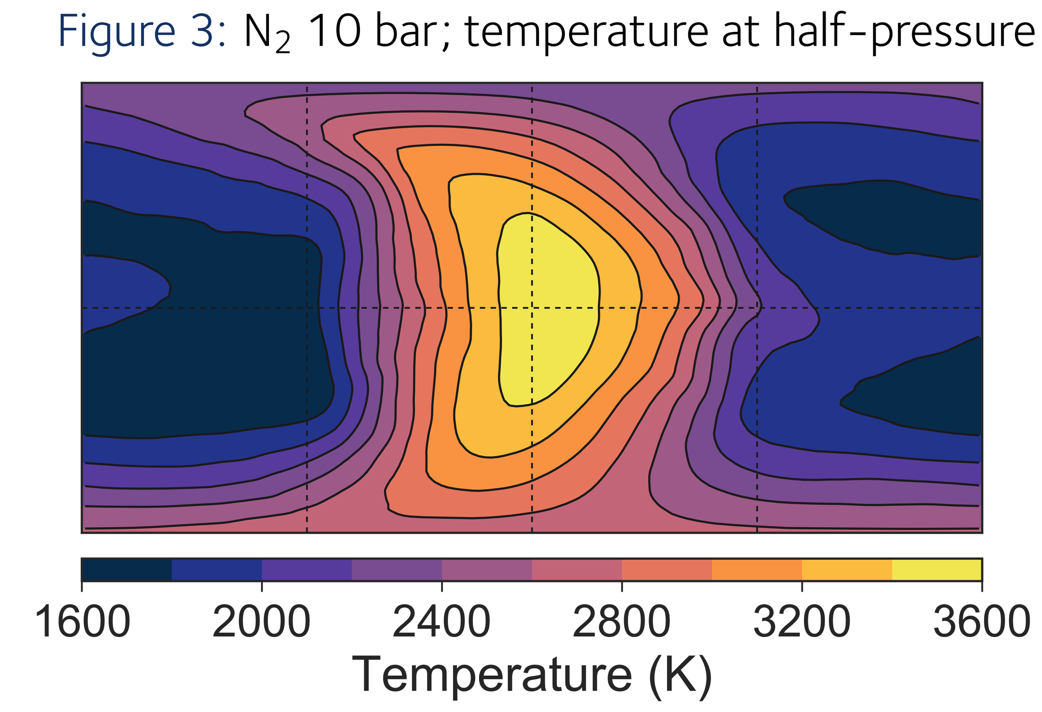


Figure 3: N_2 10 bar; temperature at half-pressure



Best-Fit Run

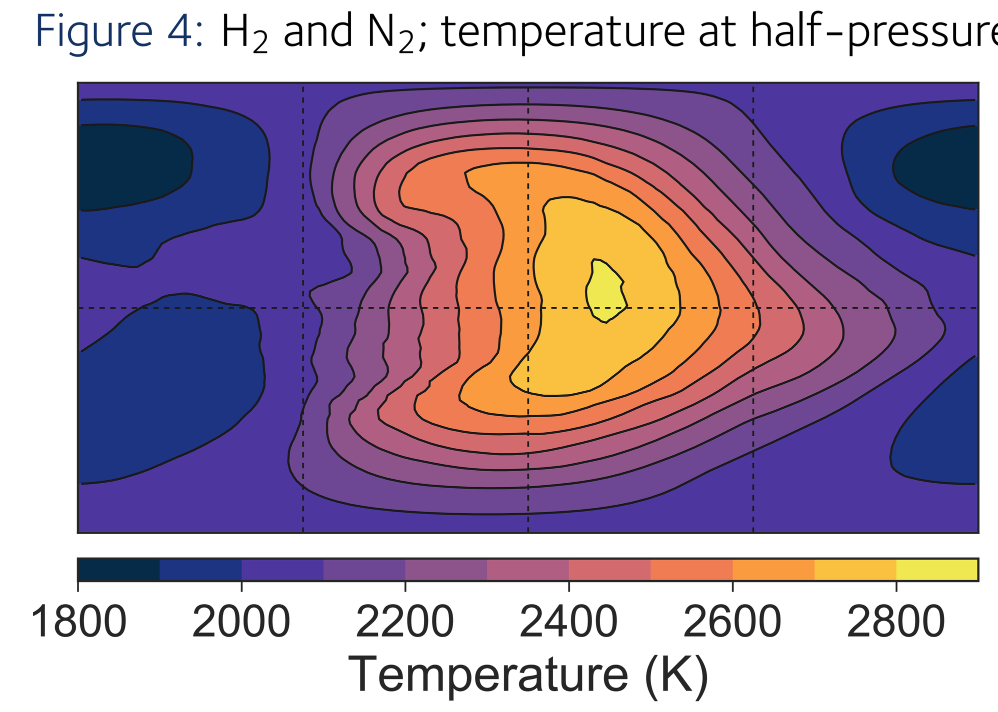
A large phase curve offset and amplitude are linked to high optical thickness τ_{inf}, low molecular weight, low heat capacity c_p, low surface pressure, and $t_{rad} > t_{adv}$.

We tried to recreate this with a mixture of 50% H_2 and 50% N_2 with p_s 4 bar.

We used an optical thickness of 8.0, which would require some strong trace greenhouse gas in reality. This gas might need a window at 4.5 microns as the real observations of high temperatures and day-night contrast should correspond to low in the atmosphere.

This experiment showed a large hot-spot shift and day-night contrast, although not as large as the measurements.

Figure 4: H_2 and N_2; temperature at half-pressure



Simulating Observations

We simulated the 4.5 micron phase curves of our tests to directly compare them to the observations of 55 Cancri e.

The flux is calculated at 4.5 microns from the brightness temperature of the outgoing radiation from each column, then the columns are weighted according to their angle to the observer and summed [3].

Figure 5: Phase curves of our three tests

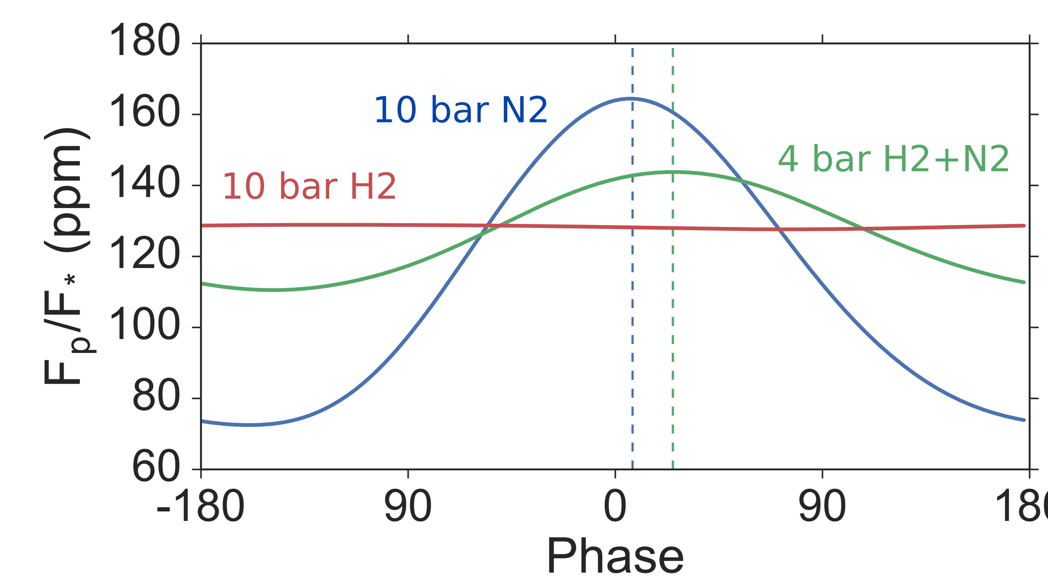
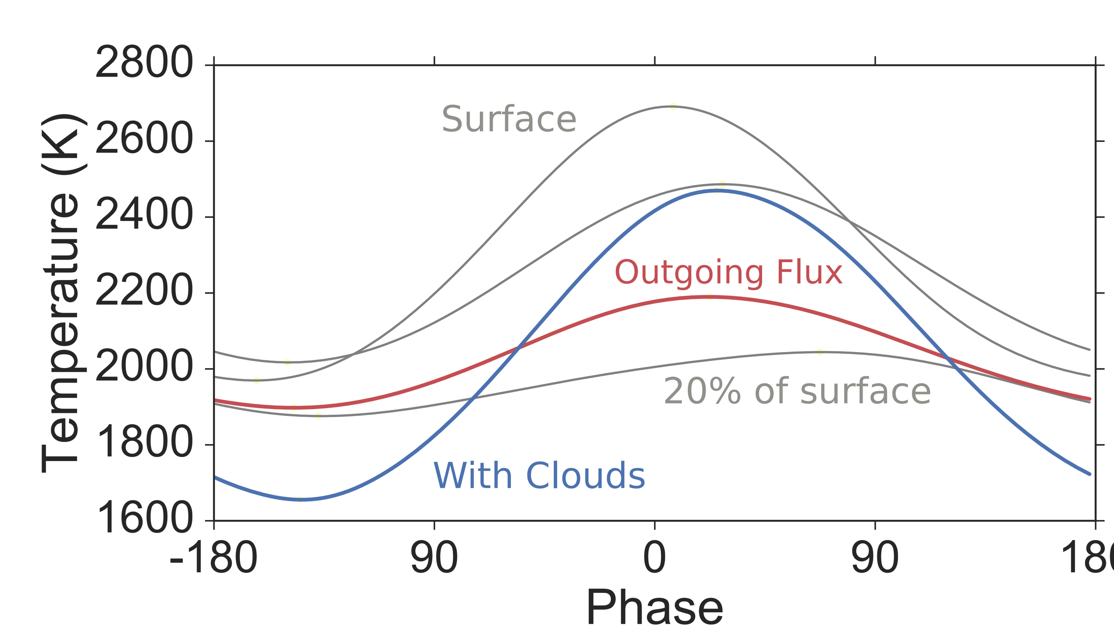


Figure 5 shows the 4.5 micron phase curves for each of the three tests. The N_2 atmosphere has the largest amplitude but almost no offset. The H_2 atmosphere has such a small amplitude that its offset is not apparent. The H_2+N_2 atmosphere has a notable offset and amplitude.

Figure 6 hows how the measured offset and amplitude depends strongly on the radiating level. The red curve is the brightness temperature of the outgoing flux, while the grey curves are the brightness temperatures from several different pressure levels.

Figure 6: Phase curves at different pressures in H_2+N_2



The blue curve shows the possible effect of silicate clouds - wherever the radiating temperature is less than 2100K, the radiating level is set to the top of atmosphere which makes the night-side appear colder and increases the phase curve amplitude.

Conclusion

We have shown that a significant hot-spot shift and day-night contrast can be supported by a simple atmosphere on 55 Cancri e. We can constrain its thermodynamic parameters, and suggest that it has a significant greenhouse gas with a window at 4.5 microns. Our next step will be investigating more of the parameter space, and considering the effect of spectral radiative transfer, condensables, and clouds on the phase curve features. Further observations at different wavelengths would be invaluable to future modelling work.

REFERENCES: 1) Demory et al. (2016). A Map of the Large Day–night Temperature Gradient of a Super-Earth Exoplanet.
2) Zhang & Showman (2017). Effects of Bulk Composition on the Atmospheric Dynamics on Close-in Exoplanets.
3) Koll & Abbot (2015). Deciphering Thermal Phase Curves of Dry, Tidally Locked Terrestrial Planets.

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