The First Habitable Zone Earth-sized Planet from TESS: Climate States and Characterization Prospects for TOI-700 d

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TOI-700 d

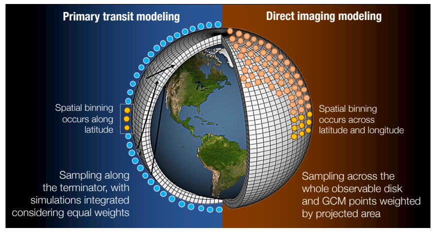
The TOI-700 system is a newly discovered TESS system of three planets around an M star with an effective temperature of 3480 K. TOI-700 d, the third planet from the star, has an orbital period of 37 days and is in the Habitable Zone (Gilbert et al. submitted, Rodriguez et al. submitted). In this work, we take a first cut at 3-D modeling potential climates of TOI-700 d, evaluating its potential for habitability, and assessing the requirements for future observation and characterization.

Method

As TOI-700 d is in the Habitable Zone of an M star, we expect the planet to be tidally locked, which leads to complicated atmospheric circulation patterns that only 3-D General Circulation Models (GCMs) can properly capture. We use ExoCAM to consider a variety of atmospheric compositions and planet archetypes that are typically associated with habitable worlds.

	Aqua			Land		
	Atmospheric Specifications	*Atm. Pressure*		*Atmospheric Specifications*	*Atm. Pressure*	
"Modern Earth"	400 ppm CO_2, 1.7 ppm CH_4	1 bar		400 ppm CO_2, 1.7 ppm CH_4	1 bar	
"Archean Earth"	0.01 bar CO_2, 0.0001 bar CH_4	1 bar		0.1 bar CO_2, 0.001 bar CH_4	1 bar	Synch
	0.1 bar CO_2, 0.001 bar CH_4	0.5 bar				
		1 bar	Synch			
			2:1			2:1
		4 bar				
		10 bar				
	0.1 bar CO_2, 0.002 bar CH_4	1 bar				
"Early Mars"	CO_2 dominated	0.5 bar		CO_2 dominated	1 bar	
		1 bar				
		2 bar			4 bar	
		4 bar			10 bar	
"H_2-supporting"	0.1 bar CO_2, 0.001 bar CH_4, 0.1 bar H_2	1 bar				
"Plain"	N_2 dominated	1 bar				

Table 1. Grid of simulations. We explore different compositions, surface types (aquaplanet vs desiccated), atmospheric pressures, and orbital phenomenon (synchronously rotating or in a 2:1 spin:orbit resonance).



We synthesize transmission and emission spectra with the Planetary Spectrum Generator's GlobES module, a radiative transfer tool.

Results: Climate States

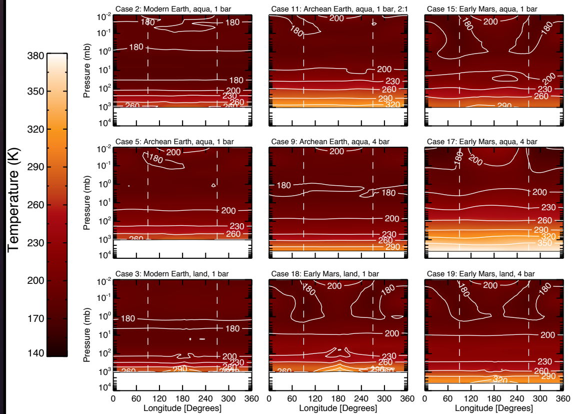


Fig 3. Vertical temperature profiles taken along the equator from 9 characteristic cases. The substellar point is located at 180 degrees. Our aquaplanet cases have global mean surface temperatures that range from 236.7 K to 364.2 K.

TOI-700 d is a robust candidate for a habitable world, and can potentially maintain temperate surface conditions and significant fractions of surface liquid water under a wide variety of atmospheric compositions.

Results: Transmission Spectra

Some prominent features visible in our spectra are the 2.7 µm, 4.3 µm and 15 µm CO_2 features, the 3.4 µm and 7.6 µm CH_4 features, the 1.1 µm, 2.4 µm and 6 µm water bands and the 4.3 µm N_2-N_2 collision-induced absorption.

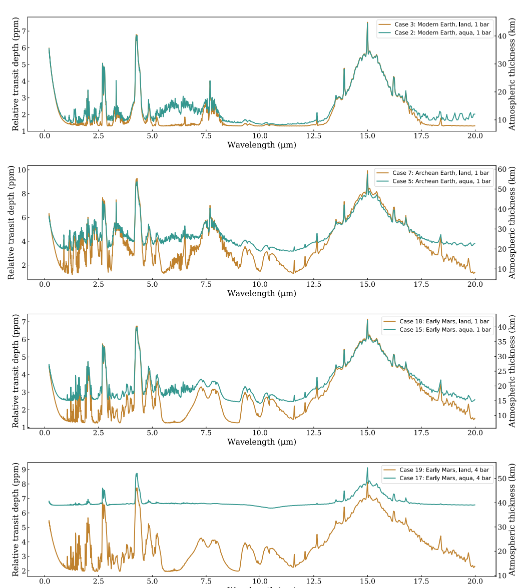


Fig 5. Comparison of synthesized transmission spectra of aquaplanets to their desiccated counterparts. The ocean-covered planets have higher continuum levels due to the presence of clouds. While the 15 µm CO_2 feature, irrespective of its abundance, may betray the presence of an atmosphere, its detection alone cannot specify an atmospheric archetype or surface condition.

Results: Phase Curves

We use GlobES to synthesize combined-light (thermal emission and reflected light) spectra and integrated phase curves. The morphology of a broadband phase curve is driven by atmospheric composition and dynamics. This aspect highlights the advantage of using a 3-D climate model, where the global cloud distribution can be self-consistently simulated to assess its effect on observables.

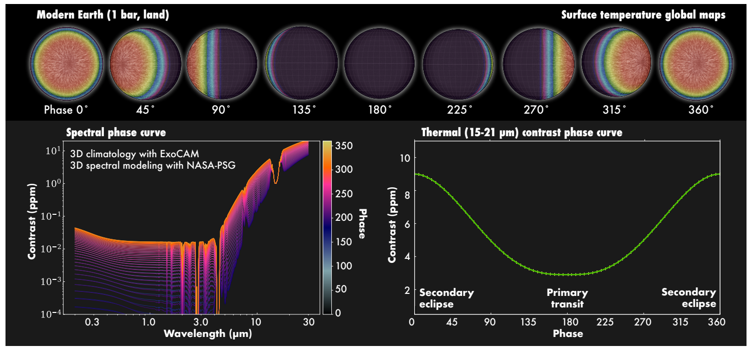


Fig 6. Combined-light phase-dependent spectra (left panel) and integrated broadband phase curves (right panel) for the Modern Earth desiccated planet. Surface temperature maps from GlobES (top panel) show drastic day-to-night temperature contrast.

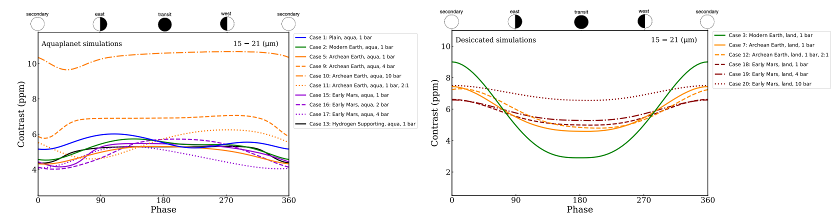


Fig 7. Synthesized phase curves for the majority of our simulations, divided into aquaplanets (left panel) and desiccated planets (right panel). All of our simulations yield maximum variation below 10 ppm, with the average maximum contrast being ~6 ppm.

While the detection of the spectral signals for this particular planet are unfeasible for near-term observing opportunities, the end-to-end atmospheric modeling and spectral simulation study that we have performed in this work is an example of how global climate models can be coupled with a spectral generation model to assess the potential habitability of any terrestrial planets discovered in the future, as we have done here with TOI-700 d.

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