Imagining Exoplanets

Visualizing Faraway Worlds Using Global Climate Models

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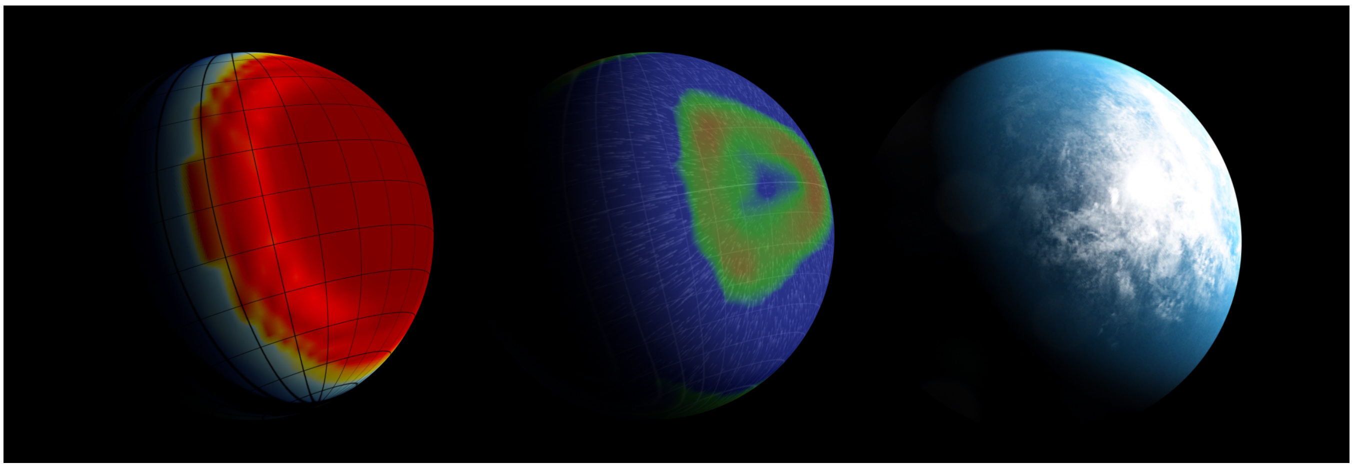

Figure 1: Composite image depicting the exoplanet TOI-700 d using three different methods (left to right): Climate model using the three-dimensional general circulation model ExoCAM, visualization using the GlobES module of the Planetary Spectrum Generator, and conceptual art generated using Adobe After Effects.

ABSTRACT

In the past decade, we've discovered over 4,000 exoplanets[1], or faraway worlds orbiting other stars. However, we can't yet take a clear picture of any of them, so how can we begin to imagine what they look like?

Three teams at NASA's Goddard Space Flight Center developed a unique approach to tackling this problem for an exoplanet called TOI-700 d. By combining 3D climate models, a newly-developed module for an exoplanet visualization tool, and Adobe After Effects, they successfully visualized possible scenarios for the planet (Figure 1) and offer an effective model for approaching future discoveries.

ACM Reference Format:
Christopher J. Smith, Geronimo L. Villanueva, and Gabrielle Suissa. 2020. Imagining Exoplanets: Visualizing Faraway Worlds Using Global Climate Models. In *Special Interest Group on Computer Graphics and Interactive Techniques Conference Talks (SIGGRAPH '20 Talks), August 17, 2020.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3388767.3407354

[1]https://exoplanetarchive.ipac.caltech.edu/

SIGGRAPH '20 Talks, August 17, 2020, Virtual Event, USA

ACM ISBN 978-1-4503-7971-7/20/08.
https://doi.org/10.1145/3388767.3407354

1 INTRODUCTION

TOI-700 d is an exoplanet approximately 100 light-years away discovered by the Transiting Exoplanet Survey Satellite [*TESS,* Ricker et al. 2015] in 2019. *TESS* detects exoplanets by keeping track of when a faraway star dims due to an orbiting planet passing in front of it and blocking its light.

TOI-700 d was discovered by astronomer Emily Gilbert and her team using *TESS* observations *TESS* observations [Gilbert et al. 2020]. Astronomer Joey Rodriguez and his team then used the *Spitzer Space Telescope* to confirm that TOI-700 d is a real planet [Rodriguez et al. 2020]. Both sets of *TESS* and *Spitzer* observations revealed a few basic pieces of information about the planet. It is Earth-size, which leads us to believe that it is most likely rocky. It orbits an M dwarf, a type of star that is much smaller, cooler, and redder than our own Sun. Finally, TOI-700 d lies within its star's habitable zone, meaning that it could potentially support liquid water on its surface. We currently have detected only a handful of Earth-size planets in habitable zones, making TOI-700 d an exciting discovery.

However, while TOI-700 d lies in the habitable zone, this does not necessarily mean that the planet has the required conditions to support life. Understanding its atmosphere is the next step in visualizing the world and determining how good a candidate it is to support life. We do not yet have a space observatory that can characterize the atmospheres of these small exoplanets, so it is necessary to use models to simulate atmospheres to prepare for visualizations, conceptual renderings, and future observations.

2 SIMULATING POTENTIAL CLIMATE STATES

To further our understanding of what the atmosphere of the planet may be like, researcher Gabrielle Suissa and her team at NASA's Goddard Space Flight Center were asked to model potential climate states for the planet [Suissa et al. 2020]. TOI-700 d is close enough to its host star that it has become "tidally locked" – meaning only one side of the planet faces the star at all times, much like how the moon is tidally locked to the Earth. This unique tidal locking leads to intrinsically three-dimensional atmospheric effects which can only be properly captured through 3D climate models.

As a result, Gabrielle's team used a three-dimension general circulation model (GCM) called the Exoplanet Community Atmosphere Model[2] (ExoCAM) to simulate potential climates for TOI-700 d. These scenarios included completely ocean- and land-covered worlds, as well as atmospheric conditions like modern Earth, Early Mars, and Archean Earth (our planet 2.7 billion years ago). However, to get a better understanding of these climate states, Gabrielle reached out to a team with unique climate visualization experience.

3 VISUALIZING CLIMATE DATA

Geronimo Villanueva had developed the Planetary Spectrum Generator [PSG, https://psg.gsfc.nasa.gov/, Villanueva et al. 2018], a tool used to imagine the potential spectra — or unique radiation signatures — of newly discovered exoplanets, particularly in the search for key molecular and habitability characteristics. In the case of TOI-700 d, a newly developed module of PSG was used called Global Exoplanet Spectra, or GlobES. This module allows users to import 3D climatological data to compute potential realistic spectra for a known planet. Geronimo used Gabrielle's data with this module to generate potential spectra for TOI-700 d, which enabled him to create weather animations and global visualizations of potential different climate states for the planet (Figure 2).

4 CONCEPTUALIZING TOI-700 d

At this point, Chris Smith, an artist in NASA Goddard's Astrophysics communications team, was asked to develop conceptual renderings (not produced directly from data) of TOI-700 d. Initially, he produced a rendering in Adobe After Effects based on general information about potential cloud cover and wind patterns (Figure 3, left). However, after seeing models and visualizations from Gabrielle and Geronimo, he updated the rendering to more closely match them (Figure 3, middle and right). Cloud cover provided an interesting challenge. For example, one model showed a large potential hole in the center (Figure 3, middle), but it was later understood that the model represented surface cloud cover, meaning no hole would be visible from space (Figure 3, right).

[2]https://github.com/storyofthewolf/ExoCAM

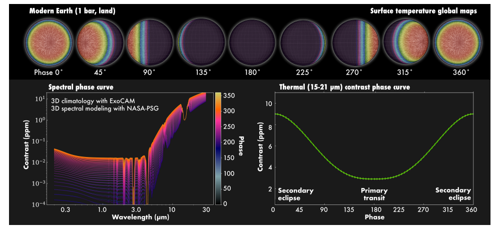

Figure 2: As the planet TOI-700 d moves along its orbit, it shows a different phase or hemisphere to Earth. Gabrielle Suissa and her team employed a realistic exoplanet weather forecasting model to simulate the climate of the planet and to estimate the intensity of the planetary signatures. The upper panel shows the 3D rendering of the different planetary phases, while the lower panels show the spectra of the planet as seen at different instances across the planet's orbit.

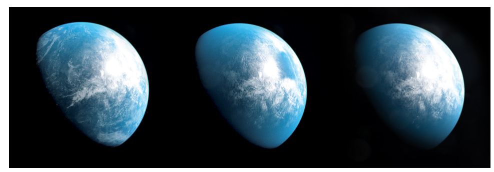

Figure 3: Progression of conceptual art development for TOI-700 d (from left to right): Initial rendering, intermediate rendering using visualization references, and final rendering based on additional model references.

5 CONCLUSIONS AND FUTURE WORK

While we continue to discover many new exoplanets, visualizing them remains a difficult challenge. Until new tools enable us to obtain a fuller understanding of these worlds, combining efforts across teams with a wide range of modeling and visualization capabilities presents a powerful approach to imagining the possibilities.

ACKNOWLEDGMENTS

Gilbert et al. 2020, Rodriguez et al. 2020 and Suissa et al. 2020 were presented during the 235th American Astronomical Society meeting in Honolulu in January 2020.

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