Stable climates for temperate rocky circumbinary planets

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Key Points:

- Planets with Earth-like surfaces and atmospheres that orbit both stars of a binary system do not undergo extreme climate perturbations.
- Local maximum temperatures of circumbinary planets that receive an average instellation equal to that of Earth are conducive for life.
- Rocky circumbinary planets are promising targets to search for biosignatures and key habitability indicators with future observatories.

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Abstract

Circumbinary planets may comprise a significant fraction of the temperate rocky planets in our galaxy. A wide range of previous work has explored the climate of circumbinary planets with one-dimensional energy balance models, but studies utilizing three-dimensional general circulation models (GCMs) have only explored gaseous or ocean-covered planets. Recent GCM results from Wolf et al. (2020) determine the impact of the time-varying stellar forcing on the climate of Earth-like circumbinary planets in a broad range of twelve modeled systems with stellar spectral types from G2 to M0. The planets modeled are assumed to have the same continental and oceanic configuration as Earth and receive the same time-averaged stellar instellation as Earth. In all cases the climate variability has a low amplitude, with local maximum temperatures never exceeding the wet bulb threshold for human life. As a result, Earth-like life could persist on circumbinary planets that undergo large-amplitude orbital variations in instellation, and such planets remain viable targets to search for biosignatures and other key habitability indicators.

Plain Language Summary

Recent discoveries of "circumbinary" planets that orbit multiple stars have spurred advances in understanding their climate. Notably, such planets have strong seasonal-like variations in received starlight due to the motion of the planet relative to that of their host stars. Wolf et al. (2020) uses numerical modeling techniques similar to those used to study climate change on Earth to determine if these variations in starlight cause significant variations in the planetary surface temperature. They find that the variations are small for planets with similar properties to Earth, and as a result temperatures never get too hot or cold for Earth-like life to exist. This indicates that circumbinary planets that have a similar size as and receive a similar amount of incident starlight to Earth are promising targets to search for signs of life.

1 Introduction

Stories of life on planets with multiple host stars have made for compelling science fiction, from Tatooine to Trisolaris. However, searching for Earth-sized planets orbiting multiple host stars is also compelling from a practical perspective, as about half of stars surveyed are part of multiple star systems (Raghavan et al., 2010). In recent years, the *Kepler* and *TESS* missions have found a range of circumbinary planets that orbit exterior to binary star systems (e.g., Doyle et al., 2011, Orosz et al., 2012, Welsh et al., 2012, Kostov et al., 2013, Schwamb et al., 2013, Kostov et al., 2014, Welsh et al., 2015, Orosz et al., 2019, Kostov et al., 2020). All of the observed circumbinary planets to date are likely gaseous in nature (Martin, 2018, Welsh & Orosz, 2018), with radii above the $\sim$ 1.6 Earth radius threshold above which planets are likely not rocky (Rogers, 2015).

Orbits of many detected circumbinary planets lie near their inner stability threshold, beyond which the circumbinary orbit would be unstable (Dvorak & Froeschle, 1989, Holman & Wiegert, 1999). For many systems, this inner stability threshold lies near the region where the instellation that the planet receives (i.e., the flux of incident radiation from the host stars) is such that liquid water would be stable at its surface assuming that the planet has an Earth-like atmospheric composition and long-term tectonic feedbacks. This region in which surface liquid water would be stable is known as the "habitable zone" (Kasting et al., 1993). Figure 1 shows an example orbital diagram for the circumbinary system Kepler-16, where the planet lies within the optimistic habitable zone throughout its orbit. The possibility that rocky circumbinary planets can also lie within the habitable zone has inspired modeling of the possible climates of circumbinary planets.

A hierarchy of models have been applied to study the climates of both rocky and gaseous circumbinary planets. These include analytic calculations of habitable zone lo-

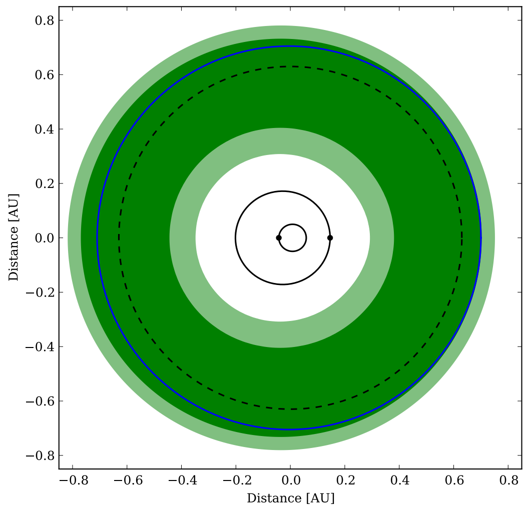

Figure 1. Orbital diagram of the Kepler-16 system. The orbit of Kepler-16b is shown in blue, while the orbits of each star are shown in black. The dashed black line represents the orbital stability threshold, while the green color denotes the habitable zone (with the light green representing the optimistic thresholds for the habbitable zone). Figure courtesy of Tobias Müller (Institute for Astronomy & Astrophysics, University of Tübingen) obtained from the P-type HZ calculator (`http://astro.twam.info/hz-ptype`) of Kaltenegger & Haghighipour (2013) and Haghighipour & Kaltenegger (2013). See Welsh & Orosz (2018) for further discussion.

cations for circumbinary systems (e.g., Haghighipour & Kaltenegger, 2013, Kaltenegger & Haghighipour, 2013, Kane & Hinkel, 2013, Wang & Cuntz, 2019), which have shown that a significant fraction of the observed circumbinary planets lie within the habitable zone. Recently, Cukier et al. (2019) studied the circumbinary habitable zone using the radiative-convective model of Kopparapu et al. (2013) and Kopparapu et al. (2014) that was originally applied to study the habitable zone for single stars, and found that the edges of the habitable zone are broadly consistent between the single and double star cases. Additionally, Forgan (2014), May & Rauscher (2016), and Haqq-Misra et al. (2019) have applied one-dimensional energy balance models to study how time-varying instellation affects the climate of circumbinary planets. These one-dimensional models all showed that if the surface of the planet has a sufficient heat capacity, it will effectively buffer the climate against the strong instellation variations from the host star. As a result, in a planet-averaged sense the surface temperature of circumbinary planets is not expected to undergo extreme variations that might preclude the stability of surface liquid water.

Three-dimensional models that solve for the dependence of the atmospheric circulation, climate, and radiation together are required to study the local climate variability of planets in detail. Such GCMs have been applied previously to study a wide range of exoplanets, from hot gaseous planets (see the reviews of Heng & Showman, 2015, Showman et al., 2020, and Zhang, 2020) to Earth-sized planets in the habitable zones of a wide range of single star systems (see Shields, 2019 for a recent review). Previously, May & Rauscher (2016) studied the climate of the Neptune-sized planet Kepler-47b with a GCM, finding temperature differences less than 1 K relative to the single-star case. Additionally, Popp & Eggl (2017) performed GCM studies of the climate of theoretical ocean-covered aquaplanets orbiting the binary system Kepler-35, similarly finding small-amplitude temperature variations on the order of a few K. As a result, previous work with both GCMs and one-dimensional models has found that if the surface or atmospheric heat capacity is large, the climates of circumbinary planets will not be greatly impacted by the time-varying instellation that they receive.

2 Earth as a circumbinary planet

Previous simulations of circumbinary planets focused on objects with a uniformly high heat capacity, either oceans or thick atmospheres, that precluded strong temporal variations in temperature. Additionally, the planets considered were not Earth-like in their atmospheric composition or surface properties. Wolf et al. (2020) instead considers Earth-like circumbinary planets in the sense that they have the same continent distribution and atmospheric composition as modern Earth and receive the same time-averaged instellation as Earth does. Additionally, Wolf et al. (2020) study a broad range of possible circumbinary systems by applying the dynamical model of Georgakarakos & Eggl (2015) to determine circumbinary orbital properties for a range of binary system separations and mass ratios.

To simulate the impact of circumbinary instellation variations on planetary climate, Wolf et al. (2020) perform twelve separate GCM simulations for Earth-like planets orbiting binary pairs ranging from two stellar twins to a G2V (Sun-like) star and a M0V (red dwarf) star. This range of systems encompasses a broader range of instellation amplitudes than considered in previous work, ranging from 0.89% in the case of two G2V stars to as large as 51.29% in the case of a G2V-M0V pair. They utilize the ExoCAM GCM, which has previously been applied to study a broad range of exoplanets (e.g., Wolf & Toon, 2015, Kopparapu et al., 2016, 2017, Wolf et al., 2017, Wolf, 2017, Haqq-Misra et al., 2018, H. Yang et al., 2019, Suissa et al., 2020, Wei et al., 2020) and, like many exoplanet GCMs, has heritage in studies of Earth's climate. Notably, for this work the authors updated the radiation scheme of the model to resolve the spectrum and zenith angle of both host stars, rather than only considering the combined light of the binary system.

Interestingly, Wolf et al. (2020) find that even in the most extreme cases they considered, the variability in surface temperature was small, with excursions in the surface temperature of tropical land only ≈ 15 K above a single-star control case. In the majority of simulations, the change in temperature was only a few degrees K due to the high thermal inertia of the oceans. In the case with the largest instellation variations, the maximum temperature of the planetary surface was 345 K, which is significantly warmer than the maximum temperature of Earth's present-day surface. However, this maximum local temperature reached in their case with the largest variability in instellation is still below the maximum wet bulb temperature at which humans can lose heat through perspiration, as the maximum temperature in their simulations generally occurs in sub-tropical deserts.

The amplitude of surface temperature variability in the simulations of Wolf et al. (2020) depends strongly on the surface type, as surfaces with higher thermal inertia (e.g., oceans) show reduced variability. Figure 2 shows how the maximum temperature over the course of a day varies with latitude and time for four different longitudes in the case with maximum variability in instellation. As expected, temperature variations are muted over oceans, with a minimum in temperature variability occurring over the Pacific ocean. This finding is in line with the GCM simulations of Popp & Eggl (2017), who found small temperature changes in ocean-covered simulations of otherwise Earth-like circumbinary planets. However, temperature variations can be significant over land in the tropics and sub-tropics, for example over Africa and South America. These would act as extreme seasons, with month-to-month temperature changes of dozens of degrees. Though these strong tropical temperature variations over land may be challenging for the evolution of life, mid-latitude regions experience significantly reduced local temperature variability and may be more clement.

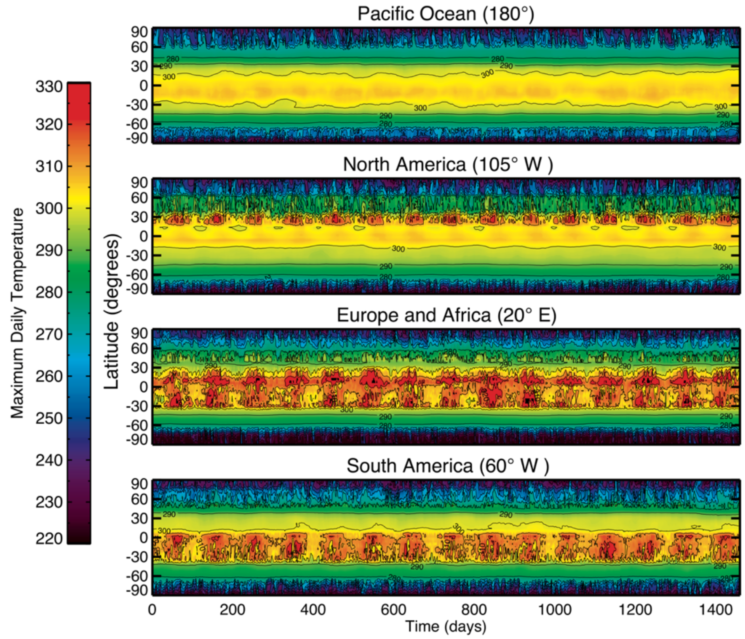

Figure 2. Figure 6 of Wolf et al. (2020), which shows the time-evolution of the maximum daily temperature at each latitude for four specific longitudes in their case with a maximal stellar flux amplitude due to variations in the binary instellation. The excursions in daily temperature are smallest over the ocean, and largest over tropical and sub-tropical land. Reproduced from Wolf et al. (2020).

3 Implications for exoplanet habitability

Wolf et al. (2020) demonstrate that if Earth-twins can form as circumbinary planets, their surfaces will remain habitable in spite of large-amplitude instellation variations. Due to the prevalence of binary systems, this result may have strong implications for the number of habitable exoplanets in our galaxy. If rocky circumbinary planets that orbit within the habitable zones of their systems are common and have an Earth-like distribution of continent and ocean, their surfaces are likely resilient to strong instellation perturbations. This result confirms the expectations of a wide range of previous 1D and 3D modeling work (e.g., Popp & Eggl, 2017, Cukier et al., 2019, Haqq-Misra et al., 2019), and extends it to the regime of a circumbinary Earth-twin.

Though Wolf et al. (2020) demonstrate that Earth would remain habitable if it were a circumbinary planet, the broad range of possible circumbinary planets has only begun to be explored. Future work studying the three-dimensional climate dynamics of rocky circumbinary planets can extend beyond the previously used assumptions of an Earth-like planet or aquaplanet and explore the full diversity of possible continent configuration, atmospheric composition, rotation rate, time-averaged instellation, and host star type. Each of these has been shown to greatly affect the climate of planets orbiting single stars – for example, the continent configuration can greatly impact the climate and ocean circulation of rocky planets orbiting M dwarf stars (Lewis et al., 2018, Salazar et al., 2020), and more slowly rotating planets have stronger dayside cloud cover which cools their surfaces (e.g., J. Yang et al., 2013, 2014, Kopparapu et al., 2017, Haqq-Misra et al., 2018, Way et al., 2018). Notably, all-land (or "dune") circumbinary planets could have considerably larger temperature variations (Haqq-Misra et al., 2019), and require further exploration with three-dimensional climate models. Additionally, more complicated climate variability could occur due to either external dynamical perturbations leading to cycles in planetary eccentricity or internal resonances with climate modes similar to the Madden-Julian Oscillation that occurs on Earth.

The resilience of rocky circumbinary planets to climate perturbations driven by varying binary star instellation motivates the detection and characterization of such planets. To date, no rocky planet orbiting a binary system has been detected, but current and upcoming surveys have the capability to detect these objects. Notably, *TESS* has already detected a ≈ 6.9 Earth radius circumbinary planet in the TOI-1338 system (Kostov et al., 2020), and *TESS* will survey a total of $\approx 500,000$ eclipsing binary systems within its nominal mission. If *TESS* or other observatories discover a rocky circumbinary planet transiting a small, cool M-dwarf star, then observations with the *James Webb Space Telescope* may be able to determine if the planet retained a significant atmosphere over its evolution (Kreidberg et al., 2019, Koll et al., 2019), and if so search the atmosphere for detectable signatures of life (Morley et al., 2017, Krissansen-Totton et al., 2018, Lustig-Yaeger et al., 2019).

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