Climate variations on water-rich circumbinary planets and their impact on habitability

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Why study circumbinary planets?

• Binary and other multi-star systems are fairly common and are therefore potentially interesting targets to look for habitable planets.

• Several circumbinary planets have already been discovered: Kepler-16b, Kepler-34b, Kepler-35b, Kepler-413b, ...

• Compared to single-star circumbinary systems pose additional challenges to habitability.
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Challenges for habitability

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• Due to the changing distance between the three bodies, the relative distance between the planet and its host-stars is bound to change constantly.
Challenges for habitability

Periodic forcings:

TSI: Total Solar Irradiance (= Insolation)
Challenges for habitability

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• Due to the changing distance between the three bodies, the relative distance between the planet and its host-stars is bound to change constantly.
  The insolation of a planet in a circumbinary system changes continuously.
Previous studies

For high eccentricity planets:

- Williams and Pollard 2002: Habitability depends only on the temporal mean insolation (3D Climate Model).
- Bolmont et al. 2016: The mean-flux approximation does not always hold (synchronous orbits, 3D Climate Model).

Circumbinary planets:

- Forgan 2014, 2016: Suggest that several binary systems have large habitable zones, depending on the eccentricity and the strength of the Milankovitch cycles (latitudinal energy balance model).
- Eggl et al. 2014: The gravitational interactions in the three-body system may constrain the habitable zone of binary star systems (evaluated based on a 1D radiative convective equilibrium model).
Motivation

1. Circumbinary planets receive a strongly varying amount of sunlight, and
2. this might influence the habitability of binary star system, but
3. this has only been investigated with simplified climate models.

Therefore we performed the first simulations with a 3D climate model of a water-rich planet around a binary star.
Experimental setup

- We use a modified version of the atmospheric climate model ECHAM6 (Popp et al. 2016) coupled to a slab ocean.

- The GCM is coupled to an analytical orbit propagator for circumbinary planets (Georgakarakos & Eggl, 2015).

- We perform simulations of an aqua-planet setup (fully water covered planet) in a Kepler-35-like system with $0^\circ$ obliquity and Earth-like parameters (mass, radius, etc.).

- We explore different orbits.

<table>
<thead>
<tr>
<th>Fixed model parameters</th>
<th>Kepler-35A</th>
<th>Kepler-35B</th>
<th>aquaplanet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$0.8877 , M_{\text{Sun}}$</td>
<td>$0.8094 , M_{\text{Sun}}$</td>
<td>$1.000 , M_{\text{Sun}}$</td>
</tr>
<tr>
<td>Radius</td>
<td>$1.0284 , R_{\text{Sun}}$</td>
<td>$0.7861 , R_{\text{Sun}}$</td>
<td>$1.000 , R_{\text{Earth}}$</td>
</tr>
<tr>
<td>Effective temperature</td>
<td>$5606 , K$</td>
<td>$5202 , K$</td>
<td>-</td>
</tr>
<tr>
<td>Rotation period</td>
<td>-</td>
<td>-</td>
<td>$1.000 , P_{\text{Earth}}$</td>
</tr>
<tr>
<td>Obliquity</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
</tr>
</tbody>
</table>
### Experimental setup & Overview results

- For the same insolation the global-mean surface temperatures are very similar.

- The climate is somewhat colder in the Kepler-35 system in a priori cold climates.

- Therefore, the periodic variation do not substantially affect the habitability of the planet.

<table>
<thead>
<tr>
<th>Semimajor axis</th>
<th>Mean insolation</th>
<th>Final state</th>
<th>Mean temperature</th>
<th>Albedo</th>
<th>Absorbed insolation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kepler-35</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.140 au</td>
<td>1.050 $S_0$</td>
<td>Moist Greenhouse</td>
<td>337.9 K</td>
<td>0.291</td>
<td>0.744 $S_0$</td>
</tr>
<tr>
<td>1.165 au</td>
<td>1.004 $S_0$</td>
<td>Earth-like</td>
<td>291.0 K</td>
<td>0.280</td>
<td>0.723 $S_0$</td>
</tr>
<tr>
<td>1.195 au</td>
<td>0.954 $S_0$</td>
<td>Earth-like</td>
<td>271.5 K</td>
<td>0.332</td>
<td>0.636 $S_0$</td>
</tr>
<tr>
<td>1.225 au</td>
<td>0.907 $S_0$</td>
<td>Snowball</td>
<td>196.5 K</td>
<td>0.735</td>
<td>0.240 $S_0$</td>
</tr>
<tr>
<td><strong>Kepler-35, solar spectrum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.165 au</td>
<td>1.004 $S_0$</td>
<td>Earth-like</td>
<td>291.0 K</td>
<td>0.285</td>
<td>0.718 $S_0$</td>
</tr>
<tr>
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<td>0.954 $S_0$</td>
<td>Earth-like</td>
<td>271.9 K</td>
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<td>0.632 $S_0$</td>
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<tr>
<td><strong>Sun</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.975 au</td>
<td>1.052 $S_0$</td>
<td>Moist Greenhouse</td>
<td>337.8 K</td>
<td>0.304</td>
<td>0.732 $S_0$</td>
</tr>
<tr>
<td>1.000 au</td>
<td>1.000 $S_0$</td>
<td>Earth-like</td>
<td>291.0 K</td>
<td>0.286</td>
<td>0.714 $S_0$</td>
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<tr>
<td>1.025 au</td>
<td>0.952 $S_0$</td>
<td>Earth-like</td>
<td>272.8 K</td>
<td>0.337</td>
<td>0.631 $S_0$</td>
</tr>
<tr>
<td>1.050 au</td>
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<td>Snowball</td>
<td>197.4 K</td>
<td>0.774</td>
<td>0.233 $S_0$</td>
</tr>
</tbody>
</table>

$S_0$: Mean insolation on present-day Earth

Results published: Popp & Eggl (2017), Nat. Comm. 14957
Results

- The meridional structure of main climate indicators is similar in the Kepler-35 and our solar system in all states.

- The cloudiness and the albedo are somewhat lower in the Kepler-35 than in our solar system.

Results published: Popp & Eggl (2017), Nat. Comm. 14957
Results

• However, on short time-scales the variations in surface temperature are clearly visible.

• The variations in surface temperature decrease with increasing mean surface temperature.

• The higher heat capacity of open water compared to sea ice, the ability to store more latent heat in warmer climates and the stronger feedbacks at higher temperatures all contribute to this effect.

Results published: Popp & Eggl (2017), Nat. Comm. 14957
The variations in surface temperature from the orbital periods of the binary and planetary orbits show clearly in the spectra.

For the surface temperature, the longer period with smaller period from the planetary orbit dominates the spectrum, whereas for the outgoing longwave radiation and the precipitation the shorter period with larger amplitude from the binary orbit dominates.

Results published: Popp & Eggl (2017), Nat. Comm. 14957
Results

- The amplitude of the response of a quantity increases with the period and the amplitude of the forcing.

- Which of the periods dominates the response depends on the quantity and on the climate state.

- In general the amplitudes of global-mean quantities are smaller than the global-mean of zonal-mean amplitudes.

Implications for observations: Without knowledge of the climate-state the amplitudes of observables will be underestimated.

Results published: Popp & Eggl (2017), Nat. Comm. 14957
### Outlook

It appears that the periodic forcing experienced by circumbinary planets does not affect the mean climate much, because:

1. If the planet is close to the host stars the periods are too short to alter the climate.
2. If the planet is far from the host stars the amplitudes are too small.

Other parameters, such as the solar spectra have a larger influence on the climate.

<table>
<thead>
<tr>
<th>Semimajor axis</th>
<th>Stellar spectrum</th>
<th>Slab ocean depth</th>
<th>Insolation</th>
<th>Surface temperature</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Sun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.000 au</td>
<td>solar</td>
<td>50 m</td>
<td>1.000</td>
<td>291.0 K</td>
<td>0.286</td>
</tr>
<tr>
<td>Kepler-35</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>solar</td>
<td>50 m</td>
<td>1.004</td>
<td>291.0 K</td>
<td>0.285</td>
</tr>
<tr>
<td></td>
<td>solar</td>
<td>2 m</td>
<td>1.004</td>
<td>288.6 K</td>
<td>0.294</td>
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<tr>
<td>Kepler-34</td>
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<tr>
<td>1.670 au</td>
<td>Kepler-34</td>
<td>50 m</td>
<td>1.001</td>
<td>283.0 K</td>
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<tr>
<td></td>
<td>solar</td>
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<td>1.001</td>
<td>290.9 K</td>
<td>0.286</td>
</tr>
<tr>
<td></td>
<td>solar</td>
<td>2 m</td>
<td>1.001</td>
<td>287.6 K</td>
<td>0.299</td>
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<td>Kepler-413</td>
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<tr>
<td>0.552 au</td>
<td>Kepler-413</td>
<td>50 m</td>
<td>1.001</td>
<td>337.6 K</td>
<td>0.250</td>
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<td>solar</td>
<td>50 m</td>
<td>1.001</td>
<td>290.9 K</td>
<td>0.286</td>
</tr>
<tr>
<td></td>
<td>solar</td>
<td>2 m</td>
<td>1.001</td>
<td>287.7 K</td>
<td>0.298</td>
</tr>
</tbody>
</table>
Take home message

- The periodic variations in insolation on circumbinary planets clearly show on short time scales, but do not substantially alter the mean climate.

  Binary star systems similar to those studied here are excellent candidates to look for habitable planets.

- Without knowledge of the planets climate, the amplitude of climate variations cannot be correctly inferred from distant observations (unless high resolution mapping would be possible).

  3D climate simulations of potentially habitable planets in circumbinary planets are crucial to estimate the planets’ climate variations.

- There are different time-scales and amplitudes involved in the climate response to periodic forcing experienced by circumbinary planets that lead to interesting short-term climate effects that are not yet understood.

  Studying these effects is not only important for a better understanding of climates on potential circumbinary planets, but also for the understanding of the response time-scales of the climate system in general.
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