An Energy-balance model for tidally-heated ocean planets

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Abstract:

GJ1214b represents a new class of planet: close-in ocean planet or mini-Neptune. Close-in to an M-class star, it has very large tidal forcings as well as significant stellar heating. Such planets can be expected to be tidally locked, with the existence of an ocean dependent on albedo and zonal heat transfer. A new Energy-balance model is presented, to describe the 2D heat transfer and dissipation of tidally generated energy within a hypothesised ocean. On such planets, the climate will be dominated by the nature of the ocean, which is currently poorly understood.
The exact heat distribution depends critically on the nature of the ocean mixing and dissipative mechanisms. For an air-liquid phase transition to exist, a high albedo and hence cloud cover is required. The cloud cover and albedo are hence modelled for two cases: that of a Neptune-like H_2 / CH_4 / H_2O atmosphere, and that of a CO_2-dominated super-Earth. We show that it may be possible to infer ocean state such as composition, etc. from heat transport and cloud cover.

Ocean Planets

Ocean planets are earth-like planets with high water content (eg 50 %) such that no continents are present. The oceans may be 100 km deep, terminating in a high-pressure ice mantle. Their geophysical cycles are as yet unknown: With no land present there will be no weathering, no carbonate-silicate cycle to control atmospheric CO_2 levels. So what would the atmosphere look like ?
For life to be present, minerals would be required near the surface in the photic zone. So,is there is a deep circulation to bring minerals up from the deep, or will they precipitate out to leave a sterile surface ?
Oceans dominate the climate. Here we start modelling exoplanet oceans, concentrating on their observable effects on the atmosphere: heat distribution and clouds.

Tidally-driven Circulation

Unlike the atmosphere, Earths ocean circulation is not a heat engine. It is driven instead by:

- Wind stresses
- Inertial (Coriolis) forces
- Buoyancy differences due to heat and salinity differentials; at the poles, cool, salty water masses sink.

Tidal forces drive the circulation by mixing water masses: without mixing the water becomes stratified and sinking stops when it meets an intermediate layer of the same density. This happens in the North Pacific, for example, while well-mixed layers in the Atlantic allow water to sink to the bottom. But is this tidal mixing sufficient on ocean planets to create a deep circulation ?
Secondly, the direction of circulation on Earth is driven by topography as westerly-driven currents hit continents to form boundary currents; mixing is dominated by internal waves generated on bottom topography. Since ocean planets lack these features, tidally-driven mixing and buoyancy will drive the circulation pattern and hence heat transport. So determining the mixing features is crucial.
Rossby-waves are planetary-scale inertial waves. Tyler (2008) showed that these can be driven by obliquity tidal interactions: while ocean tides on Earth were believed to be damped by interaction with faster gravity-waves, Tyler showed that Rossby-Haurwitz waves, with no vertical extent (and hence no gravitational interaction) would not be damped but could be forced by obliquity tides.
To date, nobody has yet modelled the actual circulation expected. Such modelling is the main goal of the PhD work pursued.

Maximum Entropy Production Principle

In 1975, Partridge hypothesized that climates are in a state of Maximum Entropy production. This has since been shown to be true of many climate system (See Ozawa (2003) for a review). By requiring MEP to hold we can test if a heat distribution is physical.

Cloud cover

The presence of cloud cover is critical to the existence of an ocean. Bond Albedo can vary from 0.05 to 0.75: a high albedo can reduce stellar heating to the point where an ocean can condense. Alternatively the lack of clouds on the dark-side of the planet can help cooling. However the presence and location of cloudsa will depend sensitively on convection and upwelling of water vapour from the ocean, which can depend on the location of ocean heating by tidal mixing.

Ocean composition and mixing

We do not know the composition of exoplanetary seawater, which will depend on circulation and life if present. We can make a first estimate of the composition by referring to different sea waters in soda brines (eg Kempe et al, 2010), paleo-Earth, paleo-Mars (eg Fairen et al, 2008) and Enceladus' plumes (Porco et al.) For our purposes, the water can be treated as Earth-like with different 'salinities'. This will have effects on the circulation: the mixing of water bodies of different 'salinity' leads to thermobaric effects, cabelling, double diffusion, etc. which can have detectable effects on the changes in bouyancy and dissipation of tidal energy. Hence it may be possible to infer the water composition from observable climate consequences.

The Model

CEO is model is 2-D energy balance model for tidally-locked planets. It's main components are:

- Atmospheric / ocean thermodynamics are based on Wiktorowicz (2007). This follows the moist adiabat down from a known (or guessed) photospheric (p,T) until the mixing ratio intersects the ocean floor, if present. This is re-formulated based on enthalpy to avoid singularities in heat flow at critical points.
- Energy input is both from stellar radiation and tidal heating
- Heat flow (zonal and radiative-correction) assumes Maximal Entropy Production, following Lorenz (1998).
- Clouds are parameterized as per Kitzmann et al (2010), and albedo calculated.
- Dissipation of tidal energy is then calculated for different ocean mixing parameterisations, resulting in a planetary heat and cloud cover map.

GJ 1214b

GJ 1214b was detected by transit (MEarth project) in 2009, and confirmed by radial velocity (HARPS). This gave simultaneous mass and radius measurements for the planet, giving an average density of 1.9 gcm^{-3} , much lower than Earths 5.5 gcm^{-3}.

This favours an ocean planet, or a planet with a small dense core and large hydrogen atmosphere.
The two most likely atmospheres being a H_2 dominated or steam, possibly CH_4, CO_2 or N_2.
While some work has been done on possible hydrogen-based atmospheres (Miller-Ricci, 2009) this is the first work to investigate clouds and their effect on heat distribution.
The effective temperatures above give standard effective temperatures, averaged over the whole planet. However Cowen (2009) has shown that a wide range of albedos and heat circulation efficiencies can be found in exoplanets. Below are plotted the effective temperatures assuming different heat circulation efficiencies:

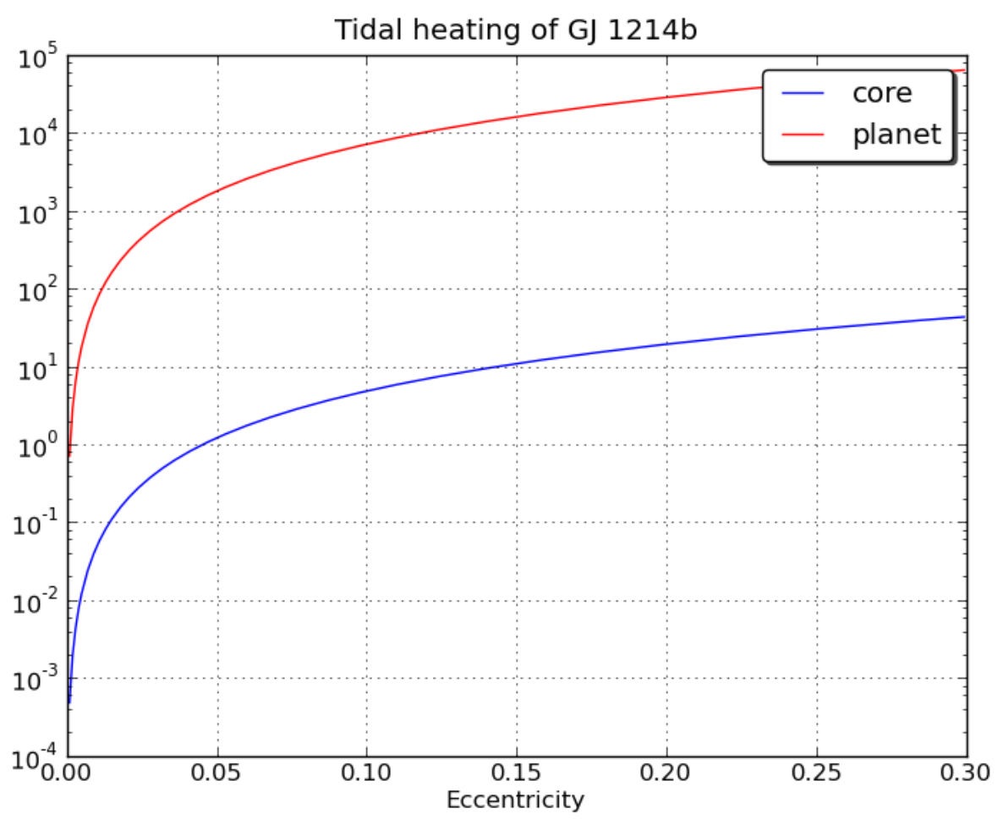
Results

GJ 1214b was modelled for scenarios with a H_2 dominated atmosphere (Neptunian mixing ratios) and a H_2O steam atmosphere, as per Miller-Ricci (2009).
The CHEMCLIM 1-D coupled climate chemistry model (Segura 2005) modified to estimate possible stratospheric conditions and estimate an initial (p,T). As no FUV spectra are available for GJ 1214b, the ROSAT-derived spectra for AD Leo, a similar M4.5 active star was used. The model was used with fixed mixing ratios for gases at a lower boundary of 100 kPa; this was used to find the top of tropopause and start of cloud deck. In this model the albedo was inserted as a parameter rather than derived ab initio.

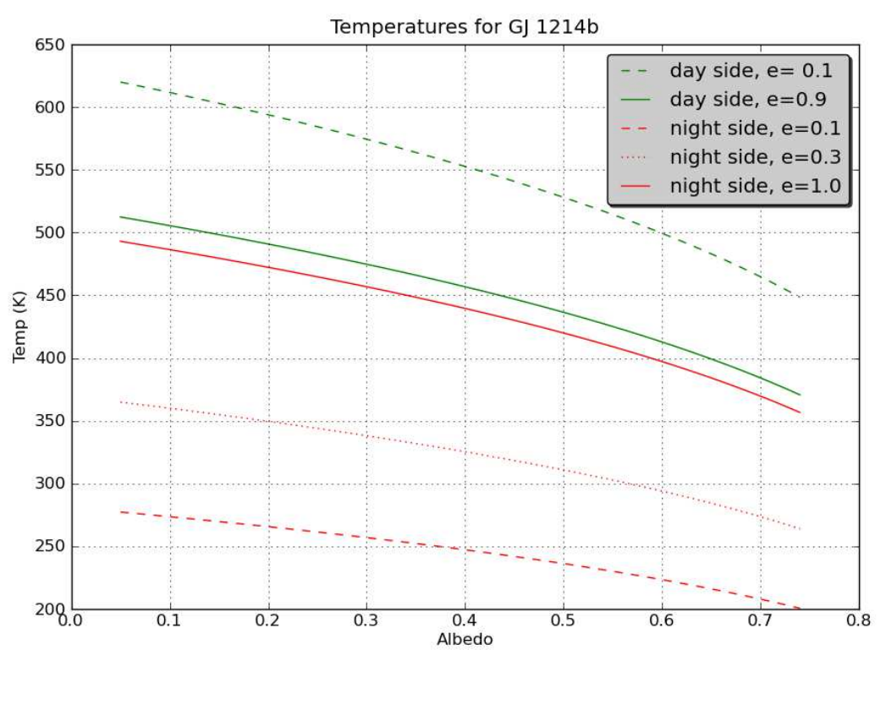
The calculated T-P profiles show a nearly isothermal stratosphere: unlike Earth, where temperatures rise. Similar isothermal stratospheres have been seen in exoplanet models around M dwarfs before; (e.g Segura 2005). The stratospheric H_2O profiles then allow for the injection of considerable water high into the stratosphere.

Tidal Heating

Tidal heating was calculated according for eccentricities < 0.27 as per Barnes. In practice tidal drag is assumed to circularise the orbit to $e < 0.01$ in a few kyr.



Tidal heating, for different assumed eccentricities
At e 0.01 we see tidal heating from a possible ocean of $\sim$ 70–100 Wm^{-2}. This can be expected to be localised around the longitude of the tidal bulges near the terminator, possibly leading to large-scale evaporation and convection, with deep cumulus clouds (with high albedo). A fully coupled Global Circulation Model is required to see if this leads to net cooling (light reflected on the planets dayside) or warming (by trapping of radiation on the night side).



For a heat recirculation efficiency $\varepsilon < 0.5$ and high albedo , the dark side could be cool enough to sustain an ocean.

Conclusions and Observables

Observations should be possible either today (with Hubble) or soon (JWST) to constrain Hydrogen fraction, temperature map and cloud cover. See Miller-Ricci (2009) for the detection of hydrogen in the atmosphere; Determining whether or not the atmosphere is hydrogen-dominated is crucial for interpreting other results. Further work needs to be done to understand the nature of the stellar wind in the vicinity of GJ 1214b to interpret hydrogen measurements, however.

Ocean presence

Ocean comoposition may be inferred by the distribution of surface temperatures of the ocean, due to the location and magnitude of tidal dissipation. While the sea surface temperatures are not expected to be remotely measurable, their effect on cloud patterns (eg creation of cyclones, etc. with large cloud masses) may be.

Clouds:

- Clouds can be determined by (a) Albedo. Bond albedo can vary from 0.05 (cloud free) to 0.75 (Venus-like), This is potentially detectable, depending on instrument. Additionally clouds will present a flat, featureless emission spectrum.
- Two types of cloud may be expected: water clouds and methane-based stratospheric hazes. The latter may be seen in transit spectra (as per Titan). To distinguish between water clouds and methane or other clouds, detection of water features in 1-3 μm. may be possible. Further distinction of H_2O and CO_2 atmosphere components would require spectral resolution of 10^5, though. (Miller-Ricci, 2009)
- Given that water is heavier than H_2, a H_2O-dominated cloud deck in a H_2 atmosphere requires significant convective energy, and hence heating from below.

Detection of a cloud base in itself does not require a liquid-water ocean (See Wiktorowicz, 2007) but with albedo constraints and water vs. stratospheric methane determination it should be possible to infer the presence / lack of ocean.

Future Work

The model is being tested to find the likelihood of an ocean from the observed or hypothesized heat distribution of a planet for different ocean mixing parameterisations.
A fully tidally-driven ocean general circulation model, based on the MITgcm is being developed to determine the circulation on ocean planets, using GPGPU acceleration for tidal calculations. It is hoped that this, coupled to existing atmospheric models, will enable the characterisation of ocean planets for comparison with observations.

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