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Effects of tides on the infrared light curve of rocky exoplanets

A.-S. Maurin (1,2), F. Selsis (1,2), F. Hersant (1,2), S. N. Raymond (1,2), J. Leconte (3, 4, 5), M. Delbo (6)
(1) Université de Bordeaux, OASU, BP 89, F-33271 Floirac Cedex, France (maurin@obs.u-bordeaux1.fr)
(2) CNRS, UMR 5804, Laboratoire d'Astrophysique de Bordeaux, BP 89, F-33271 Floirac Cedex, France
(3) Ecole Normale Superieure de Lyon, 46 allee d?Italie, 69364 Lyon Cedex 07, France
(4) Universite Lyon 1, 69622, Villeurbanne, France
(5) CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon, France
(6) UNS-CNRS-Observatoire de la Cote d'Azur, Laboratoire Cassiopee, BP 4229, 06304 Nice cedex 04, France

Abstract

Short-period exoplanets undergo strong tidal interactions that affect their orbital and spin evolution and their internal structure via tidal heating. Tidal models are, however, limited by uncertainties on key processes such as the dissipation rate. We show here that infrared photometric monitoring of eccentric rocky exoplanets can be used to determine the rotation period and constrain the tidal dissipation within the planet. The comparison of tidal models with measured rotation and dissipation rates of exoplanets would allow us to constrain unknown parameters and discriminate between models.

1. Introduction

Tidally-evolved exoplanets on eccentric orbits should rotate in either a pseudo-synchronous equilibrium state or a spin-orbit resonance that is crossed at some point in the evolution. Timescales to reach the final rotation period and a 0° obliquity are much shorter than timescales to circularize the orbit, which can be longer than the age of the system. We show here that the rotation period can be measured by the modulation it produces in the apparent thermal emission of the planet. We also show that some exoplanets can experience such strong tidal dissipation that the resulting surface heat flux alters the variations of the thermal emission in an observable way.

2. The model

We model the surface temperature of rocky planets with no atmosphere including vertical diffusion of heat in the subsurface. The upper boundary condition is given by the stellar insolation (that varies with the planet rotation and orbital motion) and the lower boundary condition is imposed by the internal heat flux. In the absence of thermal inertia and for a negligible internal flux, the surface temperature is simply given by the local radiative equilibrium. From the temperature map, we can compute the disk-integrated emission seen by a remote observer and its variations with the orbital phase.

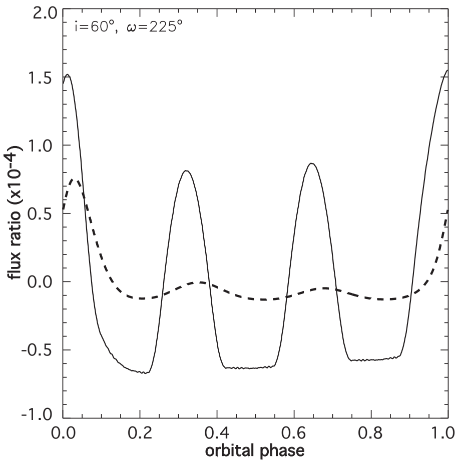

Figure 1: Variation of the thermal emission (8 μm) of a rocky exoplanet with the orbital phase. The planet has no atmosphere and a surface thermal inertia of 3000 SI. Its orbit around a 0.1 $M_\odot$ has an eccentricity of 0.6 and a semi-major axis of 0.05 AU. The orbit is seen with an inclination of 60°. The dashed line is obtained in the absence of internal heat flux, while the model that produces the solid line assumes that a equatorial hot spot covering 3% of the planet releases a heat flux 10 times larger than on the rest of the surface.

3. Results

If the planet is synchronized and on a circular orbit, then the surface insolation and the temperature map do not vary. For an unsynchronized planet on a circular orbit, the observer would see no modulation by the rotation unless large spots with different albedos exist on the surface. This is because the apparent temperature map "seen" by a remote observer is only determined by the phase of the planet, although the temperature at a given location does vary with the rotation. In the case of an eccentric orbit, however, the substellar insolation varies with the planet-star distance. As a consequence, the periastron passage produces a hot spot on the surface that cools on a timescale determined by the thermal inertia. This timescale can be a fraction of a rotation period to several rotation periods depending on the surface thermal inertia. In the latter case the hot spot produces a clear modulation in the infrared light curve. To be observable, the relative photometric variations must be larger than 10^{-5} (a precision achieved by Kepler in the visible and aimed by EChO in the infrared). An example of the signal to be observed is shown in Fig. 1. The fact that only certain rotation rates should exist (resonances and pseudo-synchronization) makes it possible to constrain both the thermal inertia and the rotation rate. A measurement of the rotation rate therefore allows us to determine whether an exoplanet is trapped into spin-orbit resonances or has reached pseudo-synchronization. In the latter case, the observation could discriminate between tidal models, for instance time-lag vs phase-lag [1]. For a given rotation rate (for instance pseudo-synchronization) and a given mass-radius relationship (for instance that of silicate-rich planets) we can estimate the rate of tidal dissipation with a tidal model [2]. Figure 2 shows, for a 10 $M_\oplus$ planet, the region of the a-e-M_* parameter space within which (1) the surface heat flux generated by tidal dissipation exceeds the mean radiative flux received from the star, (2) the circularization timescale $(e/\dot{e})$ is longer than 1 Gyr, and (3) the planet-to-star contrast ratio is larger than 10^{-5} in the mid-IR. The thermal emission of planets fulfilling these conditions will be modified in an observable way by tidal dissipation. If the tidal heat flux is uniformly distributed over the planetary surface, it can damp out the phase and rotation modulation and make them less detectable. However, if the dissipated heat is predominantly released in a few large hot spots (as occurs on Io), then the planet will behave as an infrared lighthouse and modulate the light curve at the rotation period. This effect illustrated by the solid line in Fig. 1.

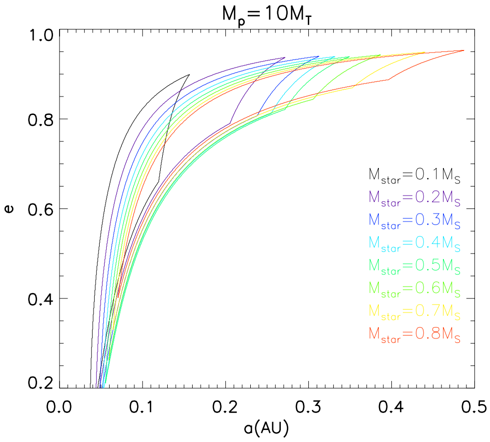

Figure 2: Observability of tidal dissipation. These contours represent the regions in the parameter space where tidal heating affects the thermal emission of the planet in an observable way (see text).

4. Summary and Conclusions

We use a thermophysical model to compute the surface temperature of a rocky exoplanet with no atmosphere and with an internal heat flux produced by tidal dissipation. From the time-dependent temperature map we compute the variability of the thermal emission measured by a distant observer. We show that for some combinations of orbital and stellar parameters and surface thermal inertia the rotation period of the planet can be determined from photometric IR observations done with EChO or JWST. We also show that the direct contribution of the tidal dissipation to the thermal emission can affect the infrared light curve of the planet in an observable way. Depending on how uniformly distributed the heat flux is over the planetary surface it can result either in a strong rotational modulation or in the total disappearance of both the phase and rotational modulations.

Acknowledgements

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