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Internal wave breaking and the fate of planets around solar-type stars

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Abstract. Internal gravity waves are excited at the interface of convection and radiation zones of a solar-type star, by the tidal forcing of a short-period planet. The fate of these waves as they approach the centre of the star depends on their amplitude. We discuss the results of numerical simulations of these waves approaching the centre of a star, and the resulting evolution of the spin of the central regions of the star and the orbit of the planet. If the waves break, we find efficient tidal dissipation, which is not present if the waves perfectly reflect from the centre. This highlights an important amplitude dependence of the (stellar) tidal quality factor Q', which has implications for the survival of planets on short-period orbits around solar-type stars, with radiative cores.

Keywords. hydrodynamics, instabilities, waves, stars: planetary systems, stars: rotation, binaries: close.

1. Introduction

Tidal interactions are important in determining the fate of short-period extrasolar planets and the spins of their host stars. The extent of the spin-orbit evolution that results from tides depends on the dissipative properties of the body. These are usually parametrized by a dimensionless quality factor Q', which is an inverse measure of the dissipation, and which in principle depends on tidal frequency, the internal structure of the body, and the amplitude of the tidal forcing. The mechanisms of tidal dissipation that contribute to Q' in fluid bodies are not well understood. We can generally decompose the response to tidal forcing into an equilibrium tide, which is a quasi-hydrostatic bulge, and a dynamical tide, which is a residual wave-like response. Dynamical tides in radiation zones of solar-type stars take the form of internal (inertia-) gravity waves (IGWs), which have frequencies below the buoyancy frequency N. These have previously been proposed to contribute to Q' for early-type stars (e.g. Zahn, 1975). We consider a nonlinear mechanism of tidal dissipation in solar-type stars, extending an idea by Goodman & Dickson (1998). A short-period planet excites IGWs at the base of the convection zone, where $N \sim 1/P$, where P is its orbital period. These waves propagate downwards into the radiation zone, until they reach the centre of the star, where they are geometrically focused and can become nonlinear. If their amplitudes are sufficient, convective overturning occurs, and the wave breaks. This has consequences for the tidal torque, and the stellar Q'. We study this mechanism, primarily using numerical simulations.

2. Numerical results and their implications

We solve the Boussinesq-type system of equations derived in Barker & Ogilvie (2010), which are valid in the central few per cent of the radius of a solar-type star, where $g \propto r$ and $N = Cr$. The parameter C measures the strength of the stable stratification at the centre, and takes a value $C_\odot \approx 8.0 \times 10^{-11}\mathrm{m}^{-1}\mathrm{s}^{-1}$, for the current Sun. A Cartesian spectral code is used to solve these equations, with our model being an initially

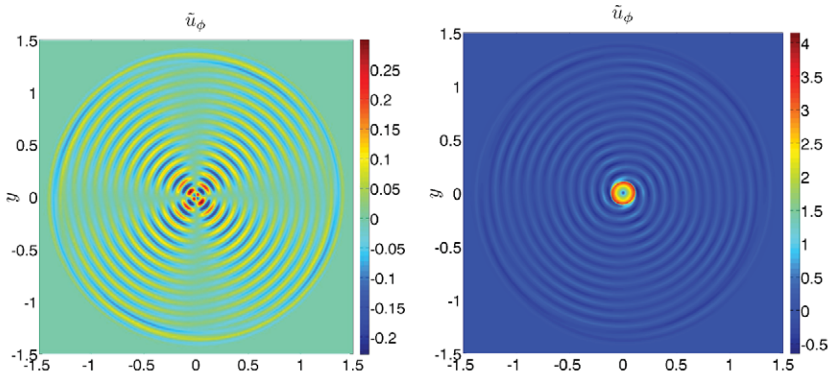

Figure 1. Plot of the normalised azimuthal velocity near the centre of a solar-type star in two simulations with small (left) and large (right) amplitude forcing.

non-rotating, 2D cylindrically symmetric star†. We artificially excite $m = 2$ waves in the outer parts of the computational domain, which are the dominant response for a planet on a circular, equatorial orbit. Fig. 1 shows the azimuthal velocity, normalised to the farfield radial phase speed of gravity waves in the simulation for a calculation with small-amplitude (left) and large-amplitude (right) forcing.

If waves are excited with small-amplitude forcing, such that they do not overturn the entropy stratification near the centre, then the waves reflect perfectly from the centre of the star, and global modes can form in the radiation zone. In this case efficient tidal dissipation only occurs at discrete resonances (Terquem *et al.*, 1998).

If the criterion

$$\left(\frac{C}{C_\odot}\right)^{\frac{5}{2}} \left(\frac{m_p}{M_J}\right) \left(\frac{M_\odot}{m_\star}\right) \left(\frac{P}{1\ \text{day}}\right)^{\frac{1}{6}} \gtrsim 3.3, \tag{2.1}$$

is satisfied, where $m_{\star,p}$ are the stellar and planetary masses, waves are excited with large enough amplitudes so that isentropes are overturned by fluid motions in the wave, within the innermost wavelength. This leads to wave breaking and the deposition of angular momentum, which spins up the mean flow to the orbital angular velocity. This results in the formation of a critical layer, at which ingoing wave angular momentum is efficiently absorbed, and the star is spun up from the inside out. This results in efficient dissipation, leading to (for waves launched where N^2 increases linearly from the interface),

$$Q'_\star \approx 1.5 \times 10^5 \left(\frac{P}{1\ \text{day}}\right)^{\frac{8}{3}}, \tag{2.2}$$

which results in a rapid and accelerating planetary inspiral, on a timescale on the order of Myr, for a one-day Jupiter-mass planet around the current Sun.

This is a potentially important nonlinear mechanism of tidal dissipation, which only operates in (solar-type) G or K stars, with radiative cores. This process requires massive planets or older/more centrally condensed stars. It is not in conflict with current observations of extrasolar planets, and may explain the absence of massive close-in planets around G-stars. This would not operate in F-type stars, with convective cores, and so its absence may partly explain the survival of massive close-in planets around F-stars, e.g. WASP-18.

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† 3D simulations with a spherically symmetric background have since been performed, which confirm these results.

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