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Elliptical instability in hot Jupiter systems

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ABSTRACT

Several studies have already considered the influence of tides on the evolution of systems composed of a star and a close-in companion to tentatively explain different observations such as the spin-up of some stars with hot Jupiters, the radius anomaly of short orbital period planets and the synchronization or quasi-synchronization of the stellar spin in some extreme cases. However, the nature of the mechanism responsible for the tidal dissipation in such systems remains uncertain. In this paper, we claim that the so-called elliptical instability may play a major role in these systems, explaining some systematic features present in the observations. This hydrodynamic instability, arising in rotating flows with elliptical streamlines, is suspected to be present in both planet and star of such systems, which are elliptically deformed by tides. The presence and the influence of the elliptical instability in gaseous bodies, such as stars or hot Jupiters, are most of the time neglected. In this paper, using numerical simulations and theoretical arguments, we consider several features associated to the elliptical instability in hot-Jupiter systems. In particular, the use of *ad hoc* boundary conditions makes it possible to estimate the amplitude of the elliptical instability in gaseous bodies. We also consider the influence of compressibility on the elliptical instability, and compare the results to the incompressible case. We demonstrate the ability for the elliptical instability to grow in the presence of differential rotation, with a possible synchronized latitude, provided that the tidal deformation and/or the rotation rate of the fluid are large enough. Moreover, the amplitude of the instability for a centrally-condensed mass of fluid is of the same order of magnitude as for an incompressible fluid for a given distance to the threshold of the instability. Finally, we show that the assumption of the elliptical instability being the main tidal dissipation process in eccentric inflated hot Jupiters and misaligned stars is consistent with current data.

1. Introduction

1.1. Tides in extrasolar planetary systems

The search for planetary systems shows that a substantial fraction of the observed stars hosts extrasolar planets. Methods of detection, such as the radial-velocity method or the transit method, are most sensitive to large planets on close orbits. Consequently, many known extrasolar planets have a mass comparable to that of Jupiter and orbit very close to their host stars (Howard, 2010; Mayor et al., 2011). This population of planets, the so-called hot Jupiters, currently includes about 25% of all known planets (see exoplanets.org, exoplanets.eu). The increasing amount of data on these systems leads to the possibility to test more precisely the theoretical models of interaction between celestial bodies, such as tidal or magnetic mutual influences (e.g. Cuntz et al., 2000; Gu and Suzuki, 2009). Indeed, the permanent and systematic presence of tides in binary systems leads to clear observational evidence of their crucial roles (see the recent review of Mazeh (2007)). For instance, the ellipsoidal effect or the apsidal motion (precession of the line of apsides of a non-circular orbit, due to the mutual tidal distortion in a binary system) are clear signatures of the tidal deformations, whereas the tidally induced dissipation and angular momentum exchanges control the orbital evolution of the system, driving it toward a synchronized state on a circular orbit (excluding possible thermal tides, which can drive a planet away from synchronism: e.g. Gold and Soter, 1969).

The role of tides has been recently investigated for systems composed of a star and a close-in companion to tentatively explain, for instance, the spin-up of stars with hot Jupiters (Pont, 2009; Damiani and Lanza, 2010), the radius anomaly of short orbital period planets (Leconte et al., 2010a,b), and the synchronization or quasi-synchronization of the stellar spin (Aigrain, 2008). Recent observations have attracted our interest to reconsider the possible consequences of an often neglected phenomenon: the so-called elliptical instability.

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For instance, the star τ Boo has a massive planet in close orbit (4.5 M_{Jup} minimum mass and 3.31-day period), and a stellar surface rotating synchronously with the planetary orbit (Butler et al., 1997; Walker, 2008). It is possible that tides from the planet onto the star have synchronized the thin convective zone of this F7 star, since the mass ratio between the planet and the convective zone is larger than 10 and the stellar angular momentum represents typically 60–70% of the total angular momentum. It has been possible to reconstruct the global magnetic topology of the star since 2006 and its evolution using recurrent spectropolarimetric observations. Two polarity reversals have been observed in 2 yr (Donati, 2008; Fares, 2009), which represent an evidence for a magnetic cycle of 800 days, much shorter than the cycle of the Sun (22 yr). The role of the planetary tides on the star in this short activity cycle was questioned; a strong shear may take place at the bottom of the convective zone, triggering a more active and rapidly evolving dynamo (Donati, 2008; Fares, 2009).

The spin–orbit misalignment (i.e. the angle between the stellar spin axis and planetary orbit normal) of one third of transiting hot Jupiters (Winn et al., 2010) also questions the role of tides in such systems, since tides are responsible for alignment, circularization of the orbit and synchronization of periods (or orbital migration, if the stellar moment of inertia of the star is too large compared to that of the planetary orbit). The usual idea of planet formation and migration within a disk was also challenged by such observations. Elliptical instabilities may cause the rotational axis of both bodies in the system to change orientation with time, with a relatively short timescale. Misaligned systems could thus show unstable rotation axes of stars, rather than tilted orbital planes of the planet. Tidal implications on the internal structure of planets were already reported (Leconte et al., 2010a,b). However, the actual mechanisms responsible for this dissipation are still a matter of debate, especially considering the fact that most mechanisms predict dissipation rates that are too weak compared to the one observed in gaseous bodies. Quantifying the power generated by elliptical instabilities (e.g. Le Bars et al., 2010, for a fluid layer of a terrestrial body) is thus crucial to enhance the predictive ability of coupled orbital/planet interiors models.

1.2. The elliptical instability

The elliptical instability is a generic instability that can affect rotating fluids whose streamlines are elliptically deformed (see the review by Kerswell (2002)). A three-dimensional flow may be excited in the bulk of rotating fluid bodies when (i) the amplitude of the elliptical forcing characterized by the ellipticity of the streamlines β is sufficiently large compared to viscous dissipation effects characterized by the Ekman number E and (ii) when a difference in angular velocity exists between the mean rotation rate of the fluid and the elliptical distortion. In an astrophysical context, the elliptical deformation has often been related to the gravitational deformation of the fluid domain, coming from the static and periodic terms of the tidal potential. The elliptical instability has thus been suggested in tidally deformed accretion disks (Goodman, 1993; Lubow et al., 1993; Ryu and Goodman, 1994; Balbus and Hawley, 1998; Lebovitz and Zweibel, 2004) and tidally deformed stars (Rieutord, 2003). But note that such an elliptical distortion can also come from a rigid boundary which has been deformed in the past and remains frozen in this deformed state, as for instance the Moon mantle (Le Bars et al., 2011). Second, this distortion can also come from a local vortex interaction in the fluid: elliptical vortices present in accretion disks could then be destabilized by the elliptical instability (e.g. Lesur and Papaloizou, 2009a,b; Lyra and Klahr, 2010). Third, the ellipticity of streamlines may also appear spontaneously in rapidly rotating isolated fluid bodies. To understand this less intuitive configuration, let us consider a simple rotating homogeneous isolated fluid body. The problem of the equilibrium figure of such a body has been first solved by Newton (1687) in the case of small rotation rates, and extended by Maclaurin (1742) to arbitrary rotation rates for spheroidal figures of equilibrium. Jacobi (1834) showed that a class of triaxial ellipsoids are also solutions of the problem (in this case, the fluid rotates as a rigid body, which makes possible to omit viscosity). It was shown later (Meyer, 1842; Liouville, 1846, 1855) that the Maclaurin spheroids become unstable above a certain deformation (Fig. 1), bifurcating into triaxial ellipsoids (see Lyttleton (1953) for historical details). More specifically, denoting by a and c the equatorial and polar radii, a dynamic instability appears at $c/a \approx 0.30$, whereas the secular instability appears at $c/a \approx 0.58$, where the triaxial Jacobi ellipsoid solutions branch on (in the limit of circular equator). Adding an internal uniform vorticity leads to consider two parts in the fluid velocity: an angular velocity of rigid-body rotation, and a motion of uniform vorticity superimposed on the latter. Each of these motions can be characterized by a three-component vector (time-dependent, in the general case). Riemann (1860) solved the general problem of the figures of equilibrium in this case (ellipsoids in the zone between the uppermost and the lowest solid black lines in Fig. 1), and discussed the stability of the steady state solutions, which are now usually referred to as the Riemann ellipsoids (see also Chandrasekhar (1969) for details).

Naturally, the stability of triaxial ellipsoids with internal uniform vorticity is directly related with the elliptical instability. However, the stability analysis of Riemann considers only perturbations that are linear polynomials of space coordinates and the energy criterion used by Riemann has been shown to be erroneous by Lebovitz (1966): Riemann (1860) found that the unstable ellipsoids for this perturbation are located between the solid blue line and the black solid upper line in Fig. 1, whereas the correct unstable zone is actually smaller, given by the dark gray (blue) area in Fig. 1, as shown by Chandrasekhar (1965, 1966) who considered also other kinds of perturbations (e.g. quadratic perturbations, which lead to unstable ellipsoids in the light gray (green) zone of Fig. 1). The link with the elliptical instability has been made by Lebovitz and Lifschitz (1996a,b), using a local analysis. These

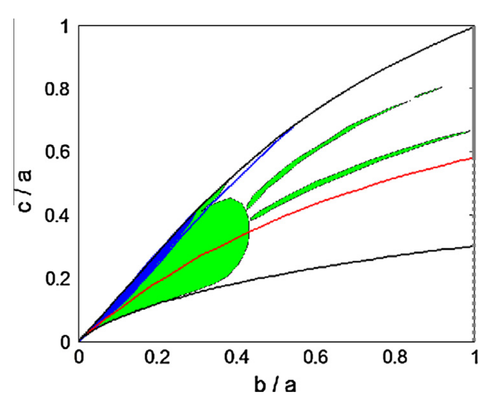

Fig. 1. Riemann ellipsoids (for direct configurations, see Lebovitz and Lifschitz, 1996a), with a (resp. b) the longest (resp. shortest) equatorial axis and c the polar axis. The Jacobi ellipsoids (red solid line) branch off the Maclaurin spheroids (gray line, solid and dashed for stable and unstable spheroids respectively) at $c/a \approx 0.58$, and the addition of an internal uniform vorticity extends the solutions domain to the zone between the uppermost and the lowest solid black lines. For perturbations that are linear in the spatial coordinates, Riemann obtained unstable ellipsoids between the solid blue line and the black solid uppermost line, but Chandrasekhar (1965) and Chandrasekhar (1966) showed that the correct unstable zone is the dark gray (blue) one. The light gray (green) zone corresponds to unstable ellipsoids for quadratic perturbations (e.g. Lebovitz and Lifschitz, 1996a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)