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Tidal interactions of close-in extrasolar planets: The OGLE cases

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Abstract. Close-in extrasolar planets experience extreme tidal interactions with their host stars. This may lead to a reduction of the planetary radius and a spin-up of stellar rotation. Tidal interactions have been computed for a number of extrasolar planets in circular orbits within 0.06 AU, namely for OGLE-TR-56 b. We compare our range of the tidal dissipation value with two dissipation models from Sasselov (2003) and conclude that our choices are equivalent to these models. However, applied to the planet OGLE-TR-56 b, we find in contrast to Sasselov (2003) that this planet will spiral-in toward the host star in a few billion years. We show that the average and maximum value of our range of dissipation are equivalent to the linear and quadratic dissipation models of Sasselov (2003). Due to limitations in the observational techniques, we do not see a possibility to distinguish between the two dissipation models as outlined by Sasselov (2003). OGLE-TR-56 b may therefore not be well suited to serve as a test case for dissipation models. The probable existence of OGLE-TR-3 b at 0.02 AU and the discovery of OGLE-TR-113 b at 0.023 AU and OGLE-TR-132 b at 0.03 AU may also counter Sasselovs (2003) assumption of a pile-up stopping boundary at 0.04 AU.

Key words. planetary systems – stars: rotation – planets and satellites: general

1. Introduction

Since the discovery of the companion of 51 Pegasi (Mayor & Queloz 1995), many more extrasolar planets orbiting sun-like stars of spectral types F, G and K have been discovered in the mass range from 0.16 Jupiter masses (M_{J}) to 15 M_{J}. The total number of known extrasolar planets is now 122 (June 2004), including thirteen planetary systems with two or more planets. Only the minimum planetary mass $\tilde{M}_{\mathrm{P}} = M_{\mathrm{P}} \sin i$ can be derived with the radial velocity method since the inclination angle i of the planetary orbital plane cannot be determined unambiguously. The elements of these planetary orbits are determined from the analysis of the variation of radial velocities of the central star. From the precise determination of the radial velocity variation period, interpreted as the extrasolar planet's orbital period, and an estimate of the stellar mass, the semi major axis can be derived with the aid of Kepler's third law. Surprisingly, planets were found from very close distances to their host stars to distances as far as 4 AU (the outer known planet of 55 Cnc). So far, only one planet has allowed us to derive its true mass M_{P} (and size and therefore density) from its transit across the stellar disk of HD 209458 in combination with radial velocity measurements (Charbonneau et al. 2000; Jha et al. 2000; Henry et al. 2000). In addition, upper limits of true masses exist for few other planets, but are not verified.

OGLE-TR-56 b is the closest extrasolar planet discovered which is also a transiting planet, was reported by Konacki et al. (2003a) from the OGLE survey (Udalski et al. 2002). Improved orbit and planetary parameters have been determined by Torres et al. (2004). Sasselov (2003) speculates on the stability of the orbit and atmosphere. There are further possible transit candidates from the OGLE survey: OGLE-TR-113 b (Konacki et al. 2004; Bouchy et al. 2004) and OGLE-TR-3 b (Dreizler et al. 2003) which (if the existence of the latter is verified) are both as close as OGLE-TR-56 b, OGLE-TR-10 b, OGLE-TR-58 b (Konacki et al. 2003b) and OGLE-TR-132 b (Bouchy et al. 2004). The close vicinity of OGLE-TR-56 b and OGLE-TR-3 b to their respective host star results in orbit perturbation by tidal forces exchanged between the star and the planet. We shall apply the equations described by Pätzold & Rauer (2002) to these OGLE cases which are exact because of the circular nature of their orbits ($e = 0$). Other planets with circular orbits but which are farther away will be included in this work for comparison. We discuss the coupled effects of orbital decay and spin-up of the stellar rotation as a function of time in the context of the speculations given in Sasselov (2003).

2. Tidal interaction

Close-in extrasolar planets experience strong tidal interactions with their central star. If the planet's orbital period P is smaller

Table 1. Parameters of close-in extrasolar giant planets and their host stars with circular orbits with semi major axis <0.06 AU (as of June 2004).

Parameter			OGLE-TR 56	OGLE-TR 3	OGLE-TR-113	OGLE-TR 10	OGLE-TR 132
Spectral type			G0	G0	K	G0	F
Planetary mass	[M_J]		1.450	0.500	1.35	0.700	1.010
Semi major axis	[AU]		0.023	0.023	0.023	0.042	0.0306
revolution period	[days]		1.212	1.190	1.43	3.101	1.690
Orbit excentricity			0.000	0.000	0.000	0.000	0.000
Stellar rotation	[days]		18.399	27.757[a]	27.757[a]	27.757[a]	27.757[a]
Stellar mass	[$M_\odot$]		1.040[b]	1.000[b]	0.770[b]	1.000[b]	1.340[b]
Stellar radius	[$R_\odot$]		1.100[b]	1.106[b]	0.822[b]	1.106[b]	1.489b
Planetary radius[c]	[R_J]	average	1.230	0.870	1.080[d]	1.300[d]	1.150[d]
		maximum	1.972	1.383			
		minimum	0.861	0.604			
Roche zone	[$R_\odot$]		2.706	2.721	2.022	2.721	3.663
Stellar J_2	[10^{-6}]		−2.749	−1.277	−0.681	−1.277	−2.325
I_*			0.07	0.07	0.07	0.07	0.07
k_{2*}			0.168	0.168	0.168	0.168	0.168
System property factor	[$10^{-3}\ M_\odot^{\frac{1}{2}}\ R_\odot^5$]		2.290	0.827	0.577	1.158	6.386

Parameter			OGLE-TR 58	BD-10 3166	HD 209458	HD 76700	HD 49674
Spectral type			G0	G4	G0	G6	G5
Planetary mass	[M_J]		1.600	0.480	0.690	0.197	0.120
Semi major axis	[AU]		0.052	0.046	0.045	0.049	0.057
revolution period	[days]		4.345	3.487	3.525	3.971	4.948
Orbit excentricity			0.000	0.000	0.000	0.000	0.000
Stellar rotation	[days]		27.757[a]	27.757[a]	15.700	27.757[a]	27.757[a]
Stellar mass	[$M_{*\odot}$]		0.990[b]	1.100[b]	1.050[b]	1.000[b]	1.000[b]
Stellar radius	[$R_\odot$]		1.106[b]	1.006[b]	1.200[b]	0.956[b]	0.981[b]
Planetary radius[c]	[R_J]	average	1.600[d]	0.850	0.970	0.632	0.535
		maximum		1.349	1.540	1.003	0.850
		minimum		0.589	0.673	0.438	0.371
Roche zone	[$R_\odot$]		2.721	2.475	2.952	2.352	2.414
Stellar J_2	[10^{-6}]		−1.290	−0.874	−4.855	−0.825	−0.892
I_*			0.07	0.07	0.07	0.07	0.07
k_{2*}			0.168	0.168	0.168	0.168	0.168
System property factor	[$10^{-3}\ M_\odot^{\frac{1}{2}}\ R_\odot^5$]		2.661	0.472	1.676	0.157	0.109

[a] If the true stellar rotation period is not known, the value was set, without loss of generality, to the sun's rotation period.
[b] Derived from Aller et al. (1982).
[c] If the planetary radius is not known, then upper and lower limits can be derived by setting the planetary bulk density to 250 kg/m^3 (Henry et al. 2000; Jha et al. 2000) and 3000 kg/m^3 (Cameron et al. 1999), respectively. As an average, the density of 1000 kg/m^3 was assumed.
[d] This is the true radius as derived from transit observations (Charbonneau et al. 2000; Konacki et al. 2003b).

than the star's rotation period P_*, tidal friction will lead to a spin-up of the star and, due to the conservation of momentum, will also lead to a decrease of the semi major axis of the planet's orbit.The parameters of the planets and the stars considered in this work are listed in Table 1. Only planets with circular orbits within 0.06 AU are used in this study. A more detailed study for elliptical orbits in general is in preparation.

The rotation periods of only two stars (OGLE-TR-56 via $v \sin i$ and HD 209458) in Table 1 are known. Due to the small revolution periods of the planets, all other stars must be fast rotators ($P_* < 3$ days) and the condition $P_* > P$ for the decrease of the orbit does not hold and is considered as not very probable. The stellar rotation periods are set to the solar rotation period of 27 days if these parameters are not explicitly known

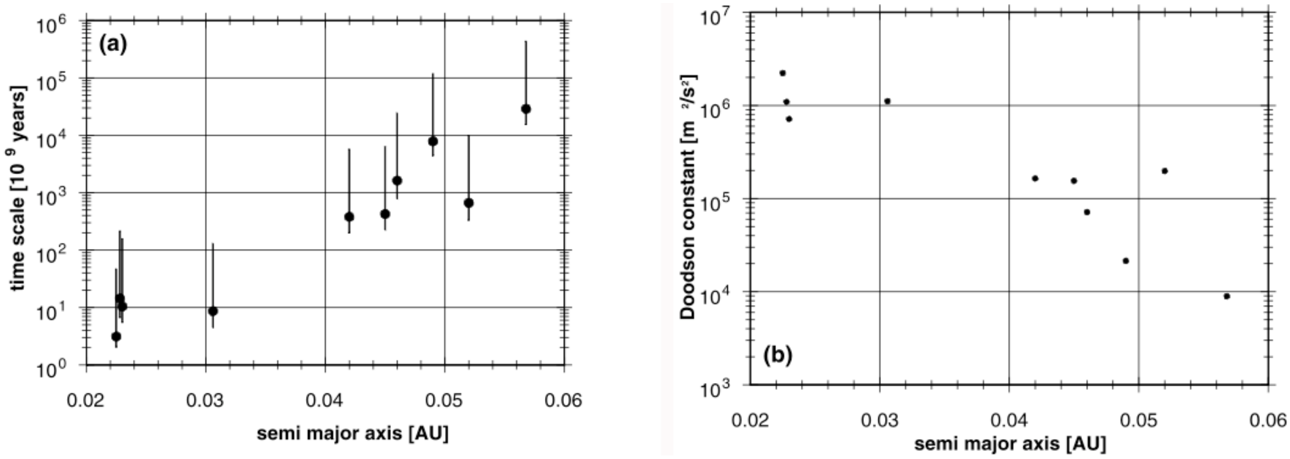

Fig. 1. a) The time scales for spiralling into the host stars (according to Eq. (5)) of the extrasolar planets located at semi major axis of today. The symbols mark the average value of $\frac{Q_*}{k_{2*}}$, the error bar the selected range of $\frac{Q_*}{k_{2*}}$ (see Sect. 2). **b)** The Doodson constant of extrasolar planets with $e = 0$ for a semi major axis less than 0.06 AU.

or estimated otherwise. Following Murray & Dermott (1999), Goldreich & Soter (1966), Goldreich & Nicholson (1977) and Zahn (1977), we derive for the change in stellar rotation and the change in orbit radius

$$\frac{\mathrm{d}\Omega_*}{\mathrm{d}t} = -\mathrm{sign}\,(\Omega_* - n)\frac{3k_{2*}}{2C_*Q_*}\left(\frac{\tilde{M}_\mathrm{P}^2}{M_*}\right)\left(\frac{R_*^5}{a^3}\right)\frac{GM_*}{a^3} \quad (1)$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \mathrm{sign}\,(\Omega_* - n)\frac{3k_{2*}}{Q_*}\left(\frac{\tilde{M}_\mathrm{P}}{M_*}\right)\left(\frac{R_*}{a}\right)^5 a\sqrt{\frac{GM_*}{a^3}} \quad (2)$$

where Ω_* and n are the stellar rotation and planetary revolution, respectively, k_{2*} is the stellar Love number, C_* is the stellar moment of inertia, Q_* is the stellar dissipation factor which includes tidal friction, M_* and R_* are the stellar mass and radius, respectively, a is the semi major axis of the planetary orbit and G is the gravitational constant. The relations (1) and (2) are valid for a circular orbit ($e = 0$) which is assumed from the observations for the OGLE candidates. We used the stellar moment of inertia C_* which is usually expressed in (1) as $C_* = I_*M_*R_*^2$ where I_* is the normalized stellar moment of inertia. The mass distribution of the standard solar model, as well as the GONG model, yield an $I_* = 0.07$ (Bahcall et al. 2001; Christensen-Dalsgaard et al. 1996). Both the stellar Love number k_{2*} and the tidal energy dissipation factor Q_* are only poorly known. We use $10^6 < Q_* < 3\times10^7$, and $0.02 \le k_{2*} \le 0.17$ which results in $5\times10^6 \le \frac{Q_*}{k_{2*}} \le 1.5\times10^9$ (Pätzold & Rauer 2002) for these two combined parameters, with $\frac{Q_*}{k_{2*}} = 1.2\times10^8$ as an average. This is in agreement with the range of energy dissipation for main sequence stars used in the literature (Lin et al. 1996; Trilling et al. 1998; Bodenheimer et al. 2001). Fixing the Love number at $k_{2*} = 0.17$ (Pätzold & Rauer 2002), the average dissipation factor is in agreement with the value found by Pätzold & Rauer (2002) for the F-stars; a Love number of $k_{2*} = 0.02$ yields $Q_* = 2.4\times10^6$.

The stellar radius is another important input parameter for the relations (1) and (2). We derive these values from calibration curves based on stellar evolution models (Aller et al. 1982). Integration of (1) yields for the stellar rotation

$$\Omega_*(t) = -\frac{\tilde{M}_\mathrm{P}\sqrt{GM_*}}{C_*}\left\{\left[a_0^{\frac{13}{2}} + \mathrm{sign}\,(\Omega_* - n) \times\frac{13}{2}\frac{3k_{2*}}{Q_*}\frac{\tilde{M}_\mathrm{P}}{M_*}R_*^5\sqrt{GM_*}t\right]^{1/13} - \sqrt{a_0}\right\} + \Omega_{*0} \quad (3)$$

and for the semi major axis

$$a(t) = \left[a_0^{\frac{13}{2}} + \mathrm{sign}\,(\Omega - n)\frac{13}{2}\frac{3k_{2*}}{Q_*}\frac{\tilde{M}_\mathrm{P}}{M_*}R_*^5\sqrt{GM_*}t\right]^{\frac{2}{13}}. \quad (4)$$

The time scale for spiralling inward to the stellar Roche limit $a_\mathrm{roche} = 2.46\,R_*$ (Chandrasekhar 1987) from the present semi major axis a_0 is (as derived from Eq. (4))

$$\tau_{a*} = \frac{\frac{2}{13}\left[a_0^{\frac{13}{2}} - a_\mathrm{roche}^{\frac{13}{2}}\right]}{3\frac{k_{2*}}{Q_*}\frac{\tilde{M}_\mathrm{P}}{M_*}R_*^5\sqrt{GM_*}}. \quad (5)$$

Here and in all following equations we have replaced the true planetary mass M_P with the minimum mass $\tilde{M}_\mathrm{P} = M_\mathrm{P}\sin i$. Aside from the larger uncertainties of Q_*, the time scale τ_{a*} in Eq. (5) has to be considered as an upper limit because the true planetary mass ($M_\mathrm{P} \ge \tilde{M}_\mathrm{P}$) will further decrease this value. The time scale τ_{a*} represents the remaining time for the tidal process and not the time since formation of the stellar system.

3. Discussion

Figure 1a shows the time needed to let the planets spiral into the central star starting from their orbital position of today. The error bars reflect the variation of the parameter $\frac{k_{2*}}{Q_*}$. The closest planets, OGLE-TR-56 b and OGLE-TR-3 b, will spiral in within a few billion years on average, even much faster considering the lowest boundary of $\frac{k_{2*}}{Q_*}$. The upper boundary of $\frac{k_{2*}}{Q_*}$ is obviously generously chosen so that no influence on the orbit can be seen. This orbit may be considered as stable. Possible candidates for strong orbital decay can be found by

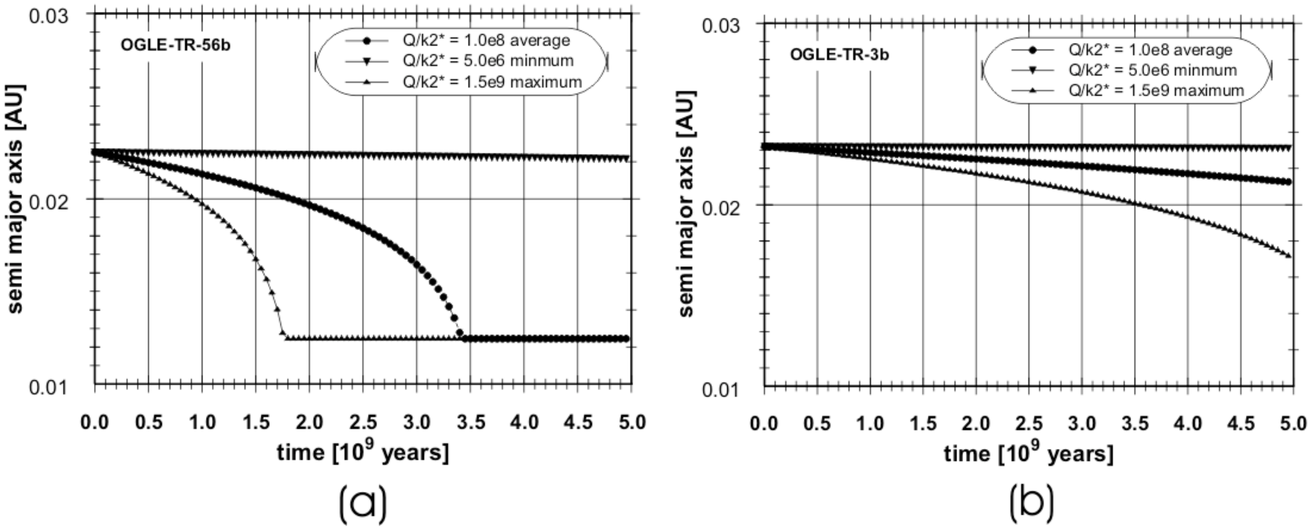

Fig. 2. The change in semi major axis of OGLE-TR-56 b **a)** and OGLE-TR-3 b **b)** within 5 billion years for different values $\frac{Q_*}{k_{2*}}$. For values of $\frac{Q_*}{k_{2*}}$ smaller than the average, the planet needs less than a few billion years to spiral into the star.

examining the system property factor $\frac{M_P}{\sqrt{M_*}}R_*^5$ (Pätzold & Rauer 2002). Another possibility is the well known Doodson constant (Fig. 1b) which describes the amplitude of tidal forces exchanged between the two partners:

$$D_P = \frac{3}{4}\frac{GM_P}{a^3}R_*^2. \quad (6)$$

Although our model does include viscosity and friction inside the star expressed by the dissipation factor Q_*, we do not agree with Sasselov (2003) who considers the existence of OGLE-TR-56 b as counterproof of the orbit decay description in Pätzold & Rauer (2002). The computed time scale (5) is counted from today to the time of planetary disruption and not from the time of creation of the planetary system. Having in mind the many theories of planet formation, migration and tidal movement, it is very difficult to assess how the close-in planets finally achieved the current observed positions. Let us compare the Eq. (2) used by Pätzold & Rauer (2002) and the relation used by Sasselov (2003), which was given by Rasio et al. (1996):

$$\frac{\dot{a}}{a} = \frac{1}{\tau_{a*}} = \frac{f}{\tau_C}\frac{M_{CZ}}{M_*}\frac{M_P}{M_*}\left\{1+\frac{M_P}{M_*}\right\}\frac{R_*}{a}^8 \quad (7)$$

where $f = \min\left[1, \left(\frac{1}{n\tau_C}\right)\right]$ or $f = \min\left[1, \left(\frac{P}{2\tau_C}\right)\right]$ is the total integrated turbulent viscosity in the quadratic viscosity suppression case and the linear suppression case, respectively. $\tau_C = 18$ days is the turbulent time scale (Sasselov 2003) and $M_{CZ} = 0.1M_*$ is the mass of the convection zone for a sun-like star as derived from the standard solar model. Comparing directly Eqs. (2) with (7), we have:

$$\frac{k_{2*}}{Q_*} = \frac{1}{3}\frac{0.01}{n\tau_C^3}\frac{R_*^3}{GM_*} \quad \text{for the quadratic suppression case and}$$

$$\frac{k_{2*}}{Q_*} = \frac{1}{3}\pi\frac{0.01}{\tau_C^2}\frac{R_*^3}{GM_*} \quad \text{for the linear suppression case.}$$

The former one yields $\left.\frac{Q_*}{k_{2*}}\right|_{\text{quadratic}} \approx 2.7\times10^{10}$ which is comparable to the upper boundary of our chosen range of Q_* while the latter one yields $\left.\frac{Q_*}{k_{2*}}\right|_{\text{linear}} \approx 9\times10^7$ which is slightly smaller than our chosen average value of Q_*. Figure 2 shows the time dependence of the orbital decay of OGLE-TR-56 b and OGLE-TR-3 b. The three curves describe the minimal, average and maximal value of $\frac{Q_*}{k_{2*}}$ as discussed above in Eq. (2). For OGLE-TR-56 b, the average value of $\frac{Q_*}{k_{2*}} = 10^8$ lets the planet spiral into the star (Roche limit of $2.46R_*$) within a few billion years, the lower value of $\frac{Q_*}{k_{2*}}$ achieves the same result in about 1.5 billion years. If the linear suppression case which considers dissipation is true, the planet is doomed, since in that case $\frac{Q_*}{k_{2*}}$ is even smaller than our chosen average value. No effect within the life time of the star is observed for the upper boundary value of $\frac{Q_*}{k_{2*}}$ which is more or less identical with the quadratic suppression case. Figure 2b shows the temporal dependence of OGLE-TR-3 b. Although this planet is slightly further away from its central star than OGLE-TR-56 b, its mass is lower ($0.5M_J$ (Dreizler, priv. comm.)) and its Doodson constant is smaller. The result is that the tidal effects are weaker than for OGLE-TR-56 b (Figs. 1b and 2b).

Due to the conservation of angular momentum, the star is spun up as the orbit decays. Equation (1) describes the stellar spin-up by assuming the star being a solid body, represented by the introduction of the total moment of inertia relative to the rotation axis C_*. We neglected friction within the star. Figure 3 shows that the spin-up of the entire solid body according to Eq. (1) leads to a rapid decrease of the rotation period from 18 days to less than 15 days within the time of 800 million years needed for the planet to spiral-in towards the stellar Roche zone. For the upper boundary of $\frac{Q_*}{k_{2*}}$ no significant effect can be seen. It may be argued that mass loss of the star due to stellar wind decreases the angular momentum with increasing stellar age and thus leads to a decrease in stellar rotation, counteracting the tidal spin-up. But we assume that this effect can safely be neglected since our dataset contains only sun-like stars which will not lose a considerable amount of mass during the next four to five billion years. However,

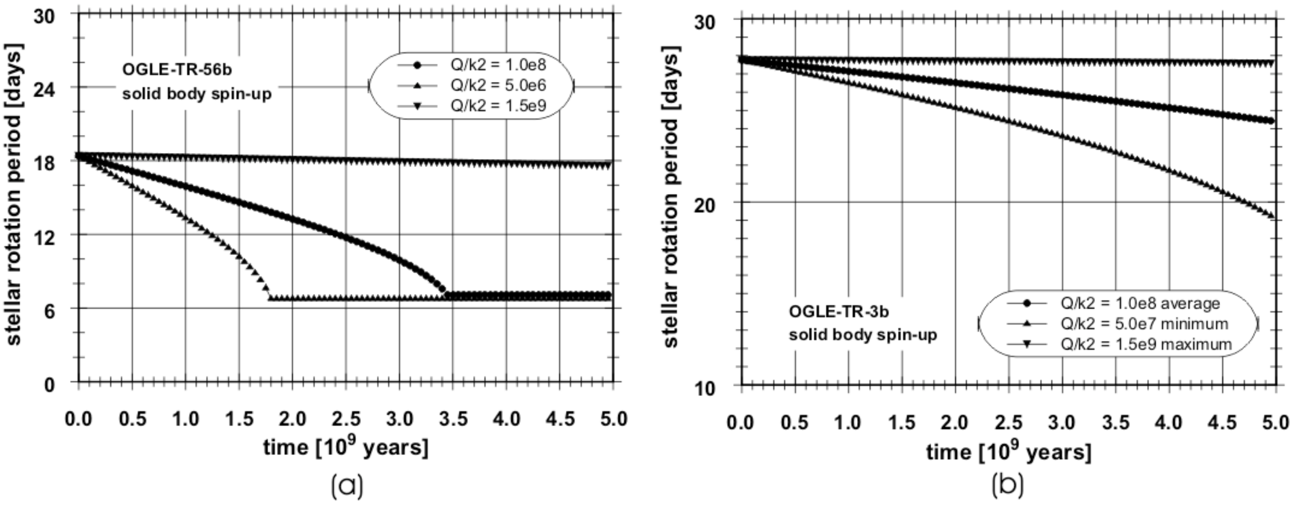

Fig. 3. The change in stellar rotation period of the host stars of OGLE-TR-56 b **a)** and OGLE-TR-3 b **b)** due to tidal friction.In this case, it was assumed that the stellar body is rigid. For values of $\frac{Q_*}{k_{2*}}$ smaller than the average, the star is significantly spun up.

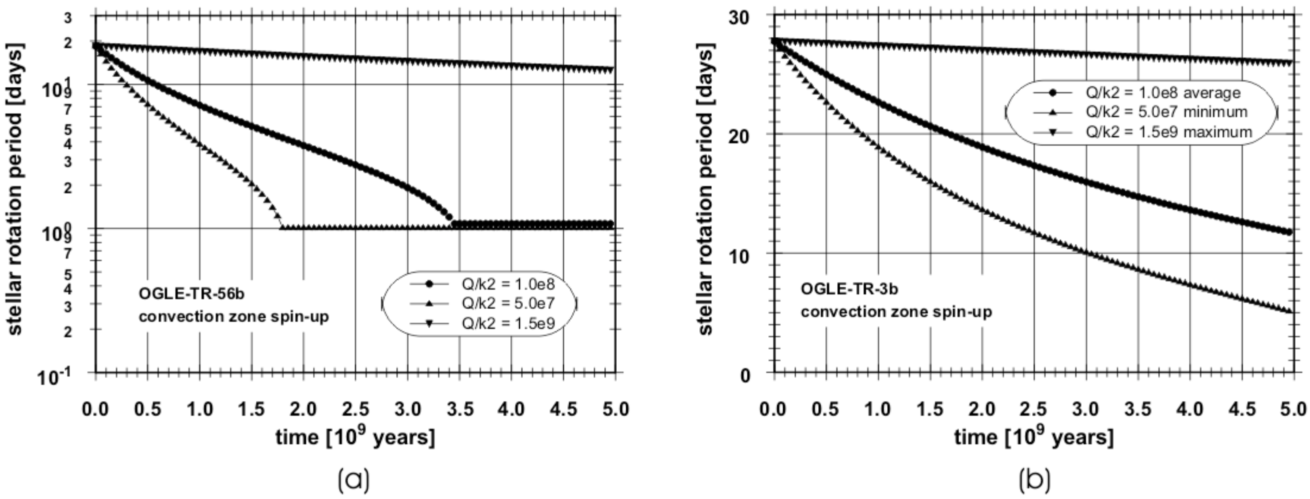

Fig. 4. The change in stellar rotation period of the host stars of OGLE-TR-56 b **a)** and OGLE-TR-3 b **b)** due to tidal friction. In this case, it was assumed that the tidal enery is dissipated in the outer stellar layers. Neglecting friction between the outer layers and the core, the spin-up of the outer stellar layer is significant even for the maximum value of $\frac{Q_*}{k_{2*}}$.

we did not consider friction within the stellar body and effects of the stellar magnetic field which might counteract the tidal spin-up of the stellar body.

There is discussion that not the entire stellar body is spun up, but only the convection zone (Rasio et al. 1996; Sasselov 2003). That would mean that in Eq. (1) the moment of inertia of the entire body needs to be replaced by the moment of inertia of the convection cell.

$$\frac{\mathrm{d}\Omega_*}{\mathrm{d}t} = -\mathrm{sign}\,(\Omega_* - n)\frac{3k_{2*}}{2C_{\mathrm{CZ}}Q_*}\left(\frac{M_{\mathrm{P}}^2}{M_*}\right)\left(\frac{R_*^5}{a^3}\right)\frac{GM_*}{a^3} \tag{8}$$

where $C_{\mathrm{CZ}} = \frac{2}{5}\sum_{i=r_{\mathrm{C}}}^{R_*} m_i \frac{r_{i+1}^5 - r_i^5}{r_{i+1}^3 - r_i^3} M_* R_*^2 = I_{\mathrm{CZ}} M_* R_*^2$ and I_{CZ} is the normalized moment of inertia of the convection zone, r_{c} is the radius of the inner boundary of the convection zone in stellar radii, and m_i is the mass of the layer between r_{i+1} and r_i in stellar masses. Using again the standard solar model, the normalized moment of inertia of the convection zone is $I_{\mathrm{CZ}} = 0.01$, $m_{CZ} = 0.01$ and $r_{\mathrm{c}} = 0.75$. Figure 4 shows the change of the rotation of the stellar convection zone.

4. Conclusion

We do not agree with Sasselov (2003) that his derived long orbit decay time of about 14.3 billion years for the quadratic suppression case is a proof of his description of turbulent viscosity dissipation, simply justified by the fact that the planet still exists. The derived time scales in Eq. (5) describe the remaining time for orbit decay and not the time since the formation of the system. On average, OGLE-TR-56 b will spiral into the Roche zone of its respective host star within 3.5 billion years. Because of its lower mass, OGLE-TR-3 b may be safe, if this planet exists at all. Correcting Sasselov (2003), we have shown that the suppression case for dissipation in the stellar convective layers is considered by our choice of $\frac{Q_*}{k_{2*}}$. Assuming the linear suppression case, the dissipation in the convection zone is considered as our average value of $\frac{Q_*}{k_{2*}}$. The quadratic suppression case is covered by our upper boundary value for $\frac{Q_*}{k_{2*}}$. Applying this model would yield absolutely no tidal effect for any planet at any distance.

Would it be possible to distinguish between these two dissipation models? This would mean to measure the orbital decay rate of the planet via the transit time across the stellar disk. The velocity in a circular orbit is $v^2 = \frac{GM_*}{a} = \frac{R_*^2}{\Delta t^2}$. Assuming that the orbital radius a is decaying with the rate at first order (2) $a(t_2) = a(t_1) - \frac{da}{dt}(t_2 - t_1)$ it is clear that

$$\Delta t^2(t_2) - \Delta t^2(t_1) = \frac{R_*^2}{GM_*}\frac{\mathrm{d}a}{\mathrm{d}t}(t_2 - t_1) = \frac{3k_{2*}}{Q_*}\frac{M_\mathrm{P}}{M_*}\left(\frac{R_*}{a}\right)^7\sqrt{\frac{a^3}{GM_*}}(t_2 - t_1). \quad (9)$$

Thus, the transit times would change by 0.1 s in one hundred years or by 1 ms per year for the average value of $\frac{Q_*}{k_{2*}}$, and would require a timing accuracy of the transit times better than 0.1 ms. With the current observation methods and integration times this accuracy is simply not achievable. Therefore, one would not be able to judge which of these models describes the convective dissipation and the proposal of Sasselov (2003) to use OGLE-TR-56 b as a test case for convection dissipation models cannot hold.

We have also shown that the consequence of orbital decay results in the spin-up of the stellar rotation. For all selected values of $\frac{Q_*}{k_{2*}}$, the convection zone is spun-up significantly. If this is true, one should find all stars with close-in extrasolar planets to be fast rotators. However, this is not observed. Friction between the convection zone and the remaining inner radiation zone and core avoids a fast acceleration of the convection zone, in particular of the observable outer layers.

We also do not agree with the conception of a "pile-up" of close-in planets at about 0.04 AU due to an unknown stopping mechanism for the inward migration (Sasselov 2003). First, this concept is based on an extremely limited observation base which does not allow any conclusions. Second, we have shown here that the orbital decay of planets closer than 0.04 AU is fast if the planetary mass is sufficiently large and only in rare cases allows the observation of planets within 0.04 AU which are in the process of spiraling toward the host star. Third, OGLE-TR-3 b, if it exists at all, and OGLE-TR-10 b are the counterproofs: due to their low masses the tidal interaction is negligible.

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References

Aller, L. H., Appenzeller, I., Baschek, B., et al. 1982 in Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology, Group VI, volume 2b, ed. K. Schaifers, & H. H. Voigt (Springer)
Bahcall, J., Pinsonneault, M. H., & Basu, S. 2001, ApJ, 555, 990
Bodenheimer, P., Lin, D. N. C., & Mardling, R. A. 2001, ApJ, 548, 466
Bouchy, F., Pont, F., Santos, N. C., et al. 2004, A&A, 421, L13
Cameron, A. C., Horne, K., Penny, A., & James, D. 1999, Nature, 402, 751
Chandrasekhar, S. 1987, in Ellipsoidal figures of equilibrium (New York: Dover)
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Christensen-Dalsgaard, J., Dappen, W., Ajukov, S. V., et al. 1996, Science, 272, 1286
Dreizler, S., Hausschildt, P. H., Kley, W., et al. 2003, A&A, 402, 791
Goldreich, P., & Nicholson, P. D. 1977, Icarus, 30, 301
Goldreich, P., & Soter, S. 1966, Icarus, 5, 375
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Jha, S., Charbonneau, D., Garnavich, P. M., et al. 2000, ApJ, 540, L45
Konacki, M., Torres, G., Jha, S., & Sasselov, D. D. 2003a, Nature, 421, 507
Konacki, M., Torres, G., Sasselov, D. D., & Jha, S. 2003b, ApJ, 597, 1076
Konacki, M., Torres, G., Sasselov, D. D., et al. 2004, ApJ, 609, L37
Lin, D. N. C., Bodenheimer, P., Richardson, D. C. 1996, Nature, 380, 606
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Murray, C. D., & Dermott, S. F. 1999 in Solar System Dynamics (Cambridge University Press)
Pätzold, M., & Rauer, H. 2002, ApJ, 568, L117
Rasio, F. A., Tout, C. A., Lubow, S. H. & Livio, M. 1996, ApJ, 470, 1187
Sasselov, D. D. 2003, ApJ, 596, 1327
Trilling, D. E., Benz, W., Guillot, T., et al. 1998, ApJ, 500, 428
Torres, G., Konacki, M., Sasselov, D. D., & Jha, D. 2004, ApJ, 609, 1071
Udalski, A., Zebrun, K., Szymanski, M., et al. 2002, Acta Astron., 52, 115
Zahn, J.-P. 1977, A&A, 57, 383