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TIDAL HEATING OF EXTRASOLAR PLANETS

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ABSTRACT

Extrasolar planets close to their host stars have likely undergone significant tidal evolution since the time of their formation. Tides probably dominated their orbital evolution once the dust and gas cleared away, and as the orbits evolved there was substantial tidal heating within the planets. The tidal heating history of each planet may have contributed significantly to the thermal budget governing the planet's physical properties, including its radius, which in many cases may be measured by observing transit events. Typically, tidal heating increases as a planet moves inward toward its star and then decreases as its orbit circularizes. Here we compute the plausible heating histories for several planets with measured radii, using the same tidal parameters for the star and planet that have been shown to reconcile the eccentricity distribution of close-in planets with other extrasolar planets. Several planets are discussed, including, for example, HD 209458b, which may have undergone substantial tidal heating during the past billion years, perhaps enough to explain its large measured radius. Our models also show that GJ 876d may have experienced tremendous heating and is probably not a solid, rocky planet. Theoretical models should include the role of tidal heating, which is large but time-varying.

Subject heading: celestial mechanics

1. INTRODUCTION

A substantial fraction of known extrasolar planets are so close to their host stars that they must have undergone significant amounts of tidally driven evolution. Changes in their orbits include the linked evolution of their eccentricities e and semimajor axes a. It has generally been assumed that the eccentricities of the close-in planets (those with $a < 0.2$ AU) began larger and were reduced by tidal damping (e.g., Rasio et al. 1996; Marcy et al. 2005; Jackson et al. 2008). Recently we confirmed that the current distribution of eccentricities could have evolved from a distribution identical to that of the farther-out planets, and that this result can be achieved using a reasonable and consistent set of tidal parameter values (Jackson et al. 2008).

Significant contributions to a planet's orbital evolution can come from tides raised on a star by a planet and from tides raised on the planet by the star (Jackson et al. 2008). During the course of the tidal evolution, tidal distortion of the figure of the planet can result in substantial amounts of internal heating at the expense of orbital energy. The heating rate as a function of time is coupled to the evolution of the orbit. Compared with their current orbits, many close-in planets probably were farther from their host star (larger semimajor axis) at the time that the planetary system's formation had ceased and the gaseous nebula dissipated. In a typical case, tidal heating might have begun modestly but then increased as tides reduced the semimajor axis a. As the tides became stronger, they would have circularized the orbit, which in turn would shut down the tidal heating mechanism.

Thus, two competing effects are in play: the reduction of a, which increases tidal heating, and the damping of e, which decreases the heating. The relative strength and timing of these two effects would determine a planet's history, typically with a gradual increase in the heating rate followed by a decrease.

The thermal history of a planet is critical to determining its physical properties. For example, models of extrasolar planets have considered the effects of heating on their radii, which can be measured directly by transit observations. Heat sources that have been considered in these models include the energy of planetary accretion and radiation from the star, as well as tidal heating (Bodenheimer et al. 2003; Winn & Holman 2005; Mardling 2007). In many cases the theoretical predictions match the observations reasonably well. However, there are notable exceptions. HD 209458b has been observed by Knutson et al. (2007) to have a radius of 1.32 Jupiter radii ($R_{\rm Jup}$), which is about 10%–20% larger than predicted by theoretical modeling (Guillot 2005; see also Burrows et al. 2007). HAT-P-1b is also larger than predicted by theory (Bakos et al. 2007a). On the other hand, HAT-P-2b is observed (Bakos et al. 2007c) to have a radius about 12% *smaller* than that predicted by theory (Fortney et al. 2007).

Theoretical models must make multiple assumptions about the behavior of gases at high pressures, atmospheric heat flow, and radiative cooling, among others. Moreover, theoretical models to date have not taken into account the history of tidal heating for close-in planets. Of course, those are the planets most likely to have radii measurable by transits. As a first cut at addressing this issue, we here present the tidal heating histories that would accompany the orbital evolution as computed in Jackson et al. (2008).

2. METHOD

The computation of the tidal evolution was described in Jackson et al. (2008). The method is based on the tidal evolution equations for da/dt and de/dt assembled by Kaula (1968) and Goldreich & Soter (1966). These equations had been applied to extrasolar planets previously, although certain terms were often neglected. For example, consideration of the changes in orbital eccentricity often disregarded the term due to tides on the star, while changes in semimajor axes were estimated ignoring tides raised on the planet. Moreover, changes in e were often represented by a damping timescale, which implicitly neglects the coupling of the evolution of e and a. Jackson et al. (2008) considered tides raised on both the planet and the star, as well as the strong coupling between evolution of the orbital elements. By integrating the orbits of close-in planets (i.e., the so-called hot Jupiters) back in time to the end of their formative period, the distribution of their e-values was found to match that of the planets with larger a-values. The best fit was obtained with values of Q'_p of $10^{6.5}$ for all the planets and $10^{5.5}$ for all the stars, although the value of Q'_* was relatively unconstrained. Here the tidal dissipation parameter Q'_p includes a factor that accounts for the deviation of the tidal Love number k from a nominal value of 3/2. It is likely that individual planets and stars have different dissipation parameters, but the values found in Jackson et al. (2008) are consistent with previous estimates (Yoder & Peale 1981; Lin et al. 1996) and provide a basis for estimating the potential significance of tidal heating in governing the physical properties of the planets.

The theory applied in Jackson et al. (2008) will certainly need to be updated as understanding of the response of stars and planets to a time-varying tidal potential improves. For example, that paper showed that past eccentricities may have been quite large, but there is considerable uncertainty regarding rates of tidal evolution under such conditions. Understanding of the frequency dependence of Q'_p will allow the formulation of governing equations that have more credibility for large values of e (e.g., Mardling & Lin 2002) or for cases with a comparable rotation period of the star and orbital period of the planet (Dobbs-Dixon et al. 2004). Considerable progress is being made in this area (Ogilvie & Lin 2004, 2007). However, given our current understanding, the formulation used in Jackson et al. (2008) is reasonable and can be readily updated, pending improved tidal models.

The dissipation of energy within a planet due to tides comes directly from the planet's orbit (except very early on while the planetary spin is quickly reduced). The orbital energy depends on only one orbital element, the semimajor axis. Thus the term in the equation for da/dt that corresponds to tides raised on the planet by the star also gives the heating rate. In this way, the heating rates can be extracted from the same numerical integrations that were done for the tidal evolution of orbits in Jackson et al. (2008). In addition, we have considered for various planets of interest the range of heating histories, given the range of uncertainties in their current orbital elements. For example, planets with nominal reported eccentricities of zero were not considered in Jackson et al. (2008). If e were really zero, there would be no tidal heating, either now or in the past. Here we consider the possible heating, even for those planets, using the full range of e- and a-values consistent with observational uncertainty. The planets that we discuss here are of particular interest because in each case there is some basis for comparison of thermal models with an observationally measured radius.

3. TIDAL HEATING HISTORIES

The tidal heating rate H can be expressed as

$$H = \frac{63}{4}\frac{(GM_*)^{3/2}M_*R_p^5}{Q'_p}a^{-15/2}e^2, \qquad (1)$$

where G is the gravitational constant, M_* is the stellar mass, R_p is the planetary radius, and $Q'_p = 3Q_p/2k$. Q_p and k are the tidal dissipation parameter and Love number, respectively. Tidal evolution of the orbital elements reduces both a and e, with competing effects on the heating rate: Reducing a increases the heating, but reducing e decreases it. The evolutionary histories computed in Jackson et al. (2008) are such that the change in a usually dominates earlier on, while the damping of e dominates later. Thus, a typical heating history involves an increase to a maximum rate, followed by a decrease to the current rate. In what follows, we consider the variation in heating rate for several planets of interest. The orbital and physical parameters we adopted for our modeling are listed in Table 1, in which M_p is a planet's mass and R_* is the stellar radius. The minimum ("Min."), nominal ("Nom."), and maximum ("Max.") values of orbital parameters that are allowed by observation are listed there as well.

3.1. *Planets with Published Orbital Eccentricities*

3.1.1. *HD 209458b*

Figure 1 shows the time history of the tidal heating rate for HD 209458b. The solid curve is based on the nominal current $e = 0.014$ and $a = 0.0473$ AU (Laughlin et al. 2005). The dashed curve is based on the maximum current heating rate consistent with the observational constraints on the orbital elements, that is, with the maximum plausible current value of e (0.042) and the minimum plausible value of a (0.0459 AU). The integrations go back 15 Gyr, although the nominal age of the system (*vertical line*) is 2.5 Gyr (Takeda et al. 2007). Burrows et al. (2007) suggest that a heating rate of about 4×10^{19} W would be required to maintain the observed planetary radius. Therefore, even with the largest possible current e-value, the current tidal heating rate is too small to resolve the discrepancy between the large observed planetary radius and theoretical models. However, the history plotted in Figure 1 shows that the required heating rate was maintained for about a billion years after the system formed, and dropped off only about a billion years ago. If the lag in the response of the planet to the heating rate were on the order of a billion years, it might explain the observed large radius. Such a lag seems reasonable based on the long duration of the influence of heat of formation on the planet's radius in the modeling by Burrows et al. (2007).

The evolution shown in Figure 1 is an example of the most general case of a rising heating rate followed by a decrease. In this case, it is likely that the system was near or at the peak at the end of its formative period. If the current e-value is less than the nominal value, then the heating rate has probably been decreasing throughout the lifetime of the planet. Note too that for this planet, observations do not rule out a circular orbit. If that is the case, tidal dissipation could have been negligible. Nevertheless, the best-fit case, with a current e of 0.014 or larger, corresponds to a heating history that may help to explain the large observed radius of this planet.

We note that some authors have estimated that the tidal circularization timescale for HD 209458b was so short that a mechanism is needed to explain the planet's substantial current eccentricity. For example, Mardling (2007) proposed that an additional planet is needed to maintain the eccentricity. However, transit timing observations rule out the existence of another planet with a period less than 15 days (Miller-Ricci et al. 2008). In fact, the issue may be moot, because our calculations show that tides have taken billions of years to circularize HD 209458b's orbit. As discussed in Jackson et al. (2008), the short circularization timescales estimated by previous workers were based on the exponential solution of the equation for tidal damping (de/dt), which ignores concurrent and codependent changes in semimajor axis. Because tides reduce both a and e together, ignoring changes in a significantly underestimates the time required to circularize orbits. Using the coupled equations for tidal evolution, we find that it is perfectly reasonable for the eccentricity to remain fairly large. Thus, tidal heating has likely been large during the past billion years, perhaps explaining the planet's surprisingly large radius.

3.1.2. *HAT-P-1b*

Like HD 209458b, the observed radius of 1.36 $R_{\rm Jup}$ for HAT-P-1b (Bakos et al. 2007a) is larger than expected from theoretical

TABLE 1

Physical and Orbital Parameters

Planet	M_* ($M_\odot$)	R_* ($R_\odot$)	M_p (M_{Jup})	R_p (R_{Jup})	a (AU) Min.	a (AU) Nom.	a (AU) Max.	e Min.	e Nom.	e Max.	Age (Gyr)	References[a]
HD 209458b	1.14	1.13	0.64	1.32	0.0459	0.0473	0.0487	0	0.014	0.042	2.44	1, 1, 2, 2, 3, 3, 4
HAT-P-1b	1.12	1.15	0.53	1.36	0.0536	0.0551	0.0566	0	0.09	0.11	3.6	5 (all)
GJ 436b	0.44	0.44	0.0706	0.3525	0.0276	0.0255	0.0293	0.14	0.16	0.18	9.23[b]	6 (all)
TrES-1	0.88	0.81	0.75	1.08	0.0386	0.0393	0.04	0.039	0.135	0.231	2.5	7, 7, 7, 7, 7, 8, 9
HAT-P-2b	1.35	1.80	9.05	0.982	0.0673	0.0685	0.0697	0.495	0.507	0.519	2.7	10, 10, 11, 11, 11, 11, 11
HD 149026b	1.3	1.45	0.36	0.73	0.042	0.043	0.044	0	0	0.02	2.0	12 (all)
TrES-2	1.08	1.00	1.25	1.24	0.0362	0.0367	0.0379	0.001	0.01	0.03	...	13, 13, 13, 13, 13, ..., ...
WASP-2b	0.79	0.81	0.88	1.04	0.0296	0.0307	0.0318	0.001	0.01	0.03	...	14, 14, 14, 14, 15, ..., ...
OGLE-TR-56b	1.17	1.32	1.29	1.3	0.0221	0.0225	0.0229	0.001	0.01	0.03	2.5	16, 16, 16, 16, 16, ..., 9
XO-1b	1.00	0.93	0.9	1.18	0.0483	0.0488	0.0493	0.001	0.01	0.03	4.6	17, 17, 17, 17, 18, ..., 18
OGLE-TR-10b	1.02	1.16	0.63	1.27	0.0423	0.043	0.0436	0.001	0.01	0.03	2.0	16, 16, 16, 16, 16, ..., 9
OGLE-TR-111b	0.81	0.83	0.52	1.07	0.046	0.047	0.048	0.001	0.01	0.03	5.55	19, 19, 19, 19, 19, ..., 20
OGLE-TR-113b	0.78	0.77	1.32	1.09	0.0227	0.0229	0.0231	0.001	0.01	0.03	5.35	21, 21, 21, 21, 21, ..., 20
OGLE-TR-132b	1.35	1.43	1.19	1.13	0.0298	0.0306	0.0314	0.001	0.01	0.03	1.25[b]	22, 22, 22, 22, 22, ..., 6
HD 189733b	0.82	0.76	1.15	1.15	0.0309	0.0313	0.0317	0.001	0.01	0.03	5.26	23, 23, 23, 23, 24, ..., 20
GJ 876d	0.32	0.36	0.018	0.143	0.0208	0.0208	0.0208	0.001	0.01	0.03	9.9	25, 25, 25, 26, 25, ..., 27
Gl 581c	0.31	0.38	0.016	0.138	0.0714	0.073	0.0746	0.09	0.16	0.23	2.0[c]	28, 28, 29, 26, 29, 29, 29
HD 69830b	0.86	0.895	0.032	0.167	0.0785	0.0785	0.0786	0.06	0.1	0.14	7.0[b]	30, 30, 30, 26, 30, 30, 30

References.—(1) Butler et al. 2006; (2) Knutson et al. 2007; (3) Laughlin et al. 2005; (4) Takeda et al. 2007; (5) Bakos et al. 2007a; (6) Gillon et al. 2007; (7) Winn et al. 2007a; (8) Cochran et al. (2005); (9) Melo et al. 2006; (10) Bakos et al. 2007b; (11) Bakos et al. 2007c; (12) Sato et al. 2005; (13) O'Donovan et al. 2006; (14) Charbonneau et al. 2007; (15) Collier Cameron et al. 2007; (16) Pont et al. 2007; (17) Holman et al 2006; (18) McCullough et al. 2006; (19) Winn et al. 2007b; (20) Burrows et al. 2007; (21) Gillon et al. 2006; (22) Moutou et al. 2004; (23) Bakos et al. 2006; (24) Bouchy et al. 2005; (25) Rivera et al. 2005; (26) Sotin et al. 2007; (27) Saffe et al. 2005; (28) Bonfils et al. 2005; (29) Udry et al. 2007; (30) Lovis et al. 2006.

[a] For M_*, R_*, M_p, R_p, a, e, and age, respectively.

[b] Average of the minimum and maximum ages reported.

[c] Minimum age reported.

modeling that did not include tidal heating (Fortney et al. 2007). Figure 1 shows the tidal heating history for this planet. Similar to HD 209458b, the heating rate ~1 Gyr ago was substantially higher than the present tidal heating, based on either the nominal best-fit e-value (*solid curve*) or the maximum current e-value (*dashed curve*). In this case the planetary system is probably much older, so the history extends further back in time and thus includes a 7 Gyr period of increasing tidal heating (due to the decrease in semimajor axis), followed by a decrease in heating (as the orbit circularizes). For both HD 209458b and HAT-P-1b, the substantial heating rate of $\sim(3-4) \times 10^{19}$ W about 1 Gyr ago may help to account for the discrepancy between the

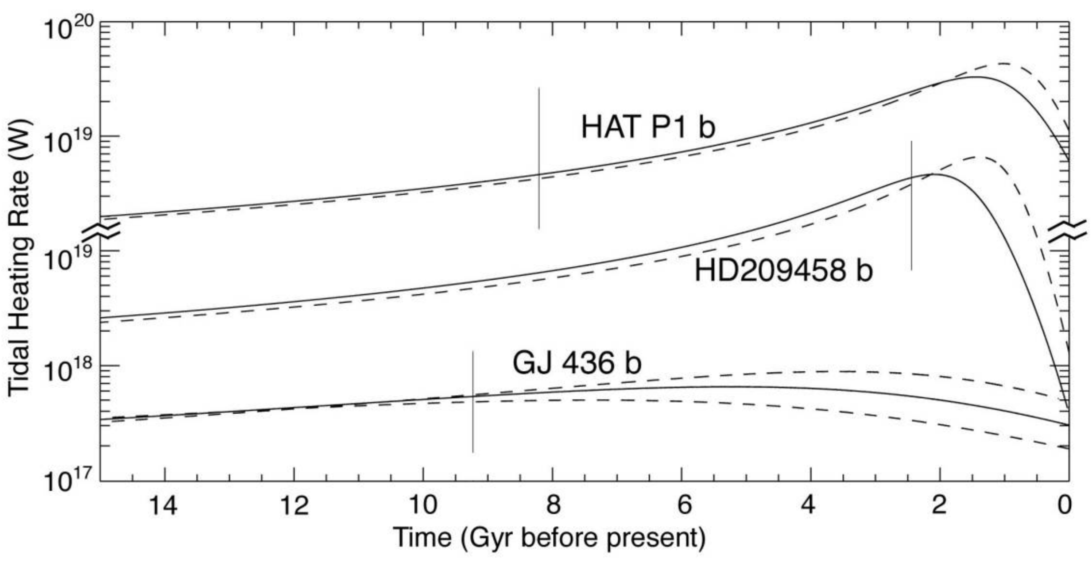

Fig. 1.—Tidal heating rates for the planets HAT-P-1b, HD 209458b, and GJ 436b as a function of time. The present time ($t = 0$) is at the right, and the scale indicates time before the present. Vertical lines indicate the best estimate of the formation time for the planet. Note that the vertical scale has been shifted (by a factor of 10) for HAT-P-1b to make its curves more visible. For each planet, here and in the subsequent figures, the vertical scale that corresponds to each curve is the scale intersected by that curve. The solid curve for each planet is based on the current nominal eccentricity value, while the dashed curves assume the maximum and minimum heating consistent with the observational uncertainty in the orbital elements. For HAT-P-1b and HD 209458b, the observations could not exclude a current eccentricity of zero, so the lower bound on heating rates is formally zero. Hence, in these cases only one dashed line is shown, representing the upper limit. The following figures use the same conventions.

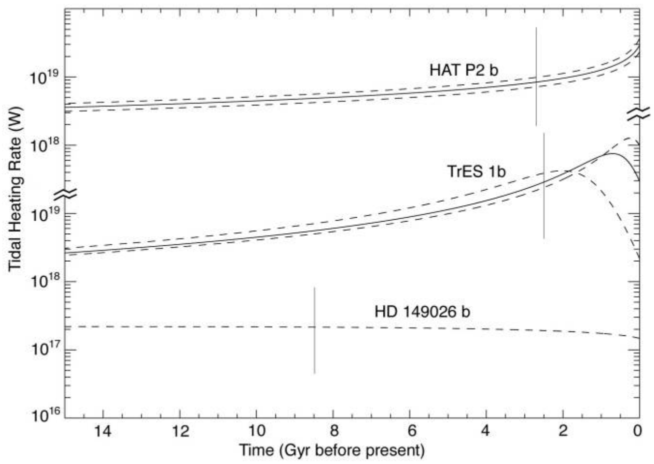

FIG. 2.— Same as Fig. 1, but for HAT-P-2b, TrES-1b, and HD 149026b. The vertical scale has been shifted (by a factor of 100) for HAT-P-2b to make its curves more visible. For HD 149026b, the dashed line represents the maximum heating consistent with the observational limits, while the nominal eccentricity is zero, corresponding to zero heat (off-scale) throughout the history.

large observed planetary radii and the predictions of physical modeling.

3.1.3. *GJ 436b*

The planet GJ 436b has a measured radius consistent with theoretical models, independent of tidal heating (Gillon et al. 2007). The tidal heating history shown in Figure 1 is consistent with that result. Compared with the previous two cases, the maximum heating rate was less by 2 orders of magnitude. This lower rate of dissipation may be partially offset by the fact that the duration of the maximum heating was several billion years; that is, the peak in seen in the figure is much broader than those for HD 209458b and HAT-P-1b. However, the total tidal heating is still much smaller than those cases, and most of it occurred so long ago that its residual effects are probably negligible, which may explain why the measured radius fits the tide-free physical model.

3.1.4. *TrES-1*

TrES-1 may have experienced more tidal heating than any of the previous cases, as shown in Figure 2. Based on this result, and by analogy with HD 209458b and HAT-P-1b, one might expect the measured radius to be larger than predicted by previous physical modeling. However, Winn et al. (2007a) report that the measured radius does fit theory. It seems that the expected large amount of tidal dissipation did not affect the radius in this case, a surprising result that calls for an explanation. One possibility is that we have overestimated the tidal heating. In fact, a slightly more recent transit-based determination of the eccentricity (Charbonneau et al. 2005) put the value at the lower end of the range from Cochran et al. (2005) that is shown in Figure 2. This change is too little to reduce the heating very much. Another way to explain the observed radius is that the theoretical modeling may need adjustment so as to accommodate more heat without increasing the inferred radius.

3.1.5. *HAT-P-2b*

In the case of HAT-P-2b also, there has been a substantial amount of tidal heating (Fig. 2). The current heating rate is similar to the maximum rate attained by HD 209458b and HAT-P-1b, so again one might expect a larger radius than predicted by theory that ignores tidal heating. In this case, however, the measured radius is actually smaller than predicted (Bakos et al. 2007c). Thus, there is a discrepancy between theory and observation even if tidal heating is neglected. Correction to the theoretical modeling seems to be necessary, and the correction would need to be in the same sense as that for TrES-1 (i.e., a smaller radius for a given amount of heating). The fact that there is likely a high rate of tidal dissipation makes the problem even worse.

On the other hand, a key factor in the reconciliation may be that while the current tidal heating rate is high and increasing, in the recent past the heating rate was much lower. HAT-P-2b is still on the increasing part of the heating curve, which is unusual among the planets considered here, most of which have passed their peak. The fact that the heating rate was several times smaller a billion years ago than it is now may help to explain the small radius.

Compare that result with what we found above for the planets in which the observed radii are larger than expected (HD 209458b and HAT-P-1b). In those cases, the fact that the heating rate was several times *larger* a billion years ago may help to explain the *large* radius. In all these cases it seems that the heating rate in the past ($\sim$1 Gyr ago) may been the crucial factor in determining the current radius.

3.1.6. *HD 149026b*

For HD 149026b, the maximum e allowed by observations is 0.02, although the nominal adopted e-value is zero. Even assuming a current orbit that would allow maximum heating (Fig. 2, *dashed curve*), given the observational constraints on the current orbit, tidal heating has been only about 2×10^{17} W for most of the 8 Gyr age of the system and has dropped by about 30% during the past 1 Gyr as the eccentricity has damped down. Similarly to GJ 436b, tidal heating is probably not a factor in determining its radius. In fact, transit observations show that HD 149026b has the smallest radius measured for any extrasolar planet, 0.726 $R_{\rm Jup}$ (Charbonneau et al 2006). Interior models require a large core, with a mass of $\sim$80 Earth masses, to be consistent with this small observed radius (Sato et al. 2005). Conceivably, such a core would have a lower Q'_p than we have assumed as the bulk value for this planet, because rocky bodies generally have $Q'_p \sim 100$. In that case, the tidal heating may have been great enough to have been a factor in the planet's geophysical history. However, if additional heat were incorporated into the theoretical modeling, it might tend to increase the model radius, perhaps requiring an even larger core to match the observed radius. In any case, the theoretical models need to take into account the possible addition of considerable tidal heating.

3.2. *Planets with Undetermined Eccentricities*

For most extrasolar planets whose eccentricities have not yet been measurable, the value is customarily tabulated as zero (Butler et al. 2006). For at least nine such planets, radii have been measured and can be compared with theoretical predictions. In most cases the models fit the observations, but in four of the nine cases, the theory predicts radii smaller than observed. Next we consider for each of these planets whether tidal heating, which has not yet been incorporated into the modeling, might potentially play a role. Even for the planets with tabulated e-values of zero, the true values may be as large as 0.03 (Butler et al. 2006). Thus, for each of the nine planets we consider the implications that would follow if the current e actually has a value of 0.001, 0.01, and 0.03, in order to sample the range of possible values. The results are shown in Figures 3 and 4. For each planet, the results for a current eccentricity of 0.01 are shown with a solid curve and the results

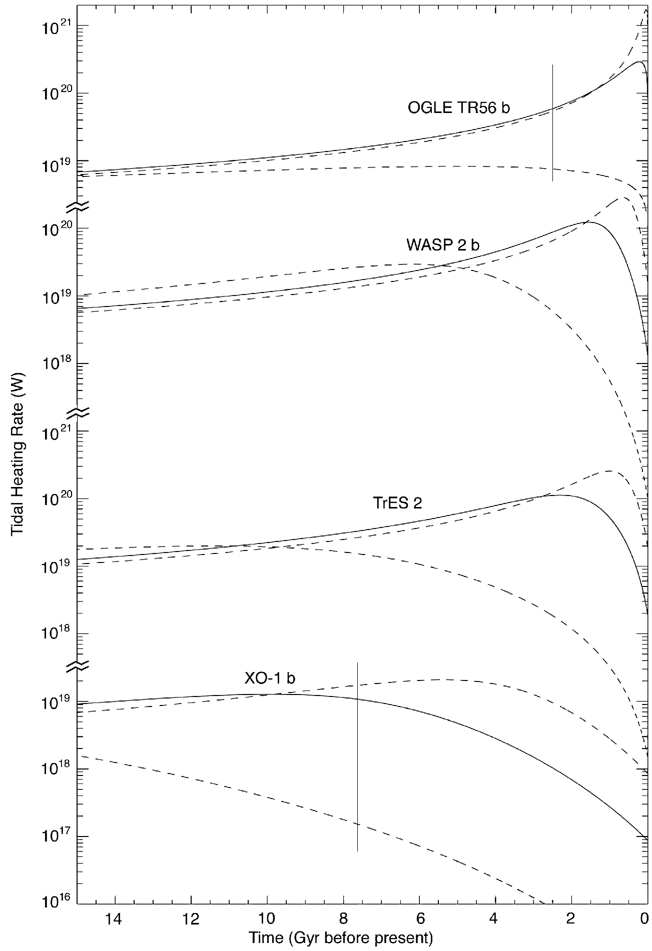

FIG. 3.— Tidal heating rates for four planets for which the nominal (tabulated) current e-value is zero but noncircular motion is likely. For each planet, a heating curve is computed for assumed current values of e of 0.001, 0.01, and 0.03. The solid lines are for 0.01, and greater current e corresponds to greater current heating. The scale on the ordinate is shifted by factors of 10 to allow the separate results to be displayed clearly. For planets where the vertical age bar is missing, no age estimate is available.

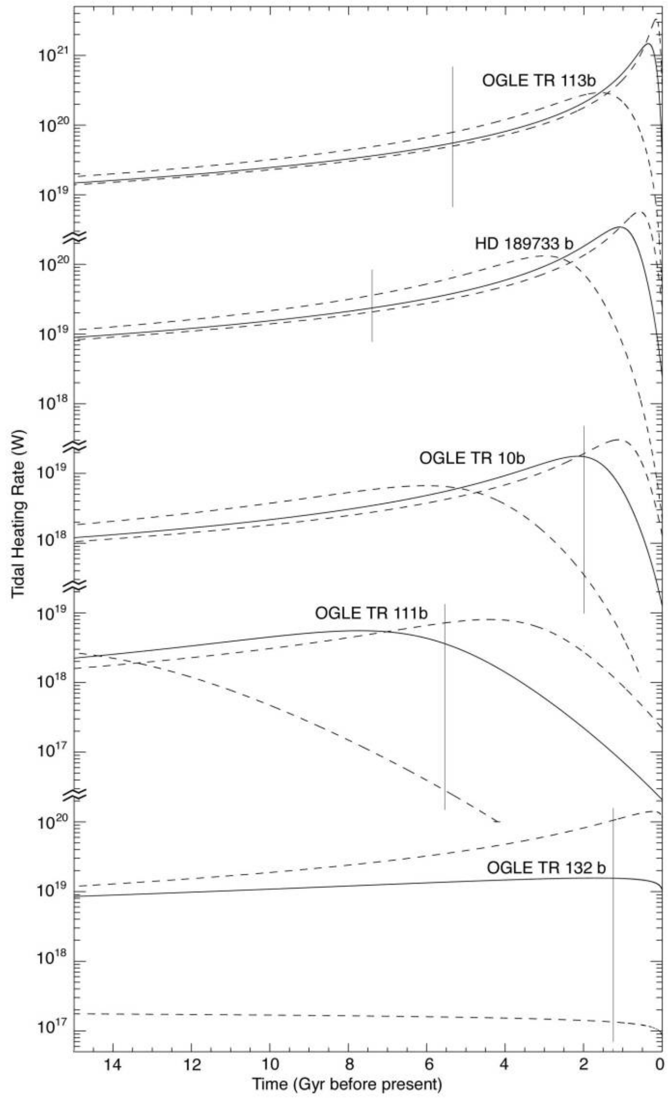

FIG. 4.— Same as Fig. 3, but for five more planets for which the nominal (tabulated) current e-value is zero but noncircular motion is likely.

for the smaller and larger values (and thus smaller and larger current heating rates, respectively) are shown with dashed curves.

The following planets have larger radii than predicted by models: TrES-2 (Sozzetti et al. 2007), WASP-2b (Sozzetti et al. 2007), OGLE-TR-56b (Pont et al. 2007), and XO-1b (Holman et al. 2006). As shown in Figure 3, the first three may have had tidal heating well in excess of 10^{19} W within the past 1 Gyr and probably lasting for at least $\sim$1 Gyr, assuming their current e is actually $\geq$0.01 (and probably even if their current e is as small as a few times 10^{-3}). Thus, tidal heating needs to be included in the physical modeling and may help to reconcile the differences between theory and observation. For XO-1b, tides are unlikely to have played a significant role unless the current e is larger than 0.03. Thus, for this case, reconciliation will probably require some other correction to the theoretical models, so as to give a smaller radius, which is the same trend suggested for the several other cases discussed above.

The five cases that have radii consistent with theoretical models (Burrows et al. 2007; Winn et al. 2007b) are OGLE-TR-10b, -111b, -113b, and -132b and HD 189733b. As shown in Figure 4, in all cases except OGLE-TR-111b, heating rates may have been greater than 10^{19} W during the past billion years even if the current e-values are only 0.01. What is more, Figure 4 shows that two planets (OGLE-TR-113b and HD 189733b) would have reached 10^{20} W even if their current e were only 0.001. (OGLE-TR-111b would require the current e to be greater than 0.03 to have peaked at 10^{19} W, but even in that case the burst of heat was several billion years ago.) For several of these planets, there has likely been enough heating to be a factor in controlling the physical properties. Thus, the fact that the measured radii fit the models suggests that either the current e-values are smaller than the values considered here or, once again, that the theoretical models need to be revisited so as to keep the same radii while accommodating the additional heating due to tides.

3.3. *Terrestrial-Scale Planets*

Among known planets with masses less than about 10 times that of Earth, tidal heating could have played some role in the geophysical evolution. Here we assume that the planetary Q_p' is 100 and the Love number k is 0.3, reasonable choices for a rocky planet (Lambeck 1977; Dickey et al. 1994; Mardling & Lin 2002; Barnes et al. 2008).

For GJ 876d, the nominal e is zero, so following the same procedure as in the previous section for such cases, we consider the heating history under the assumption that the current e-value

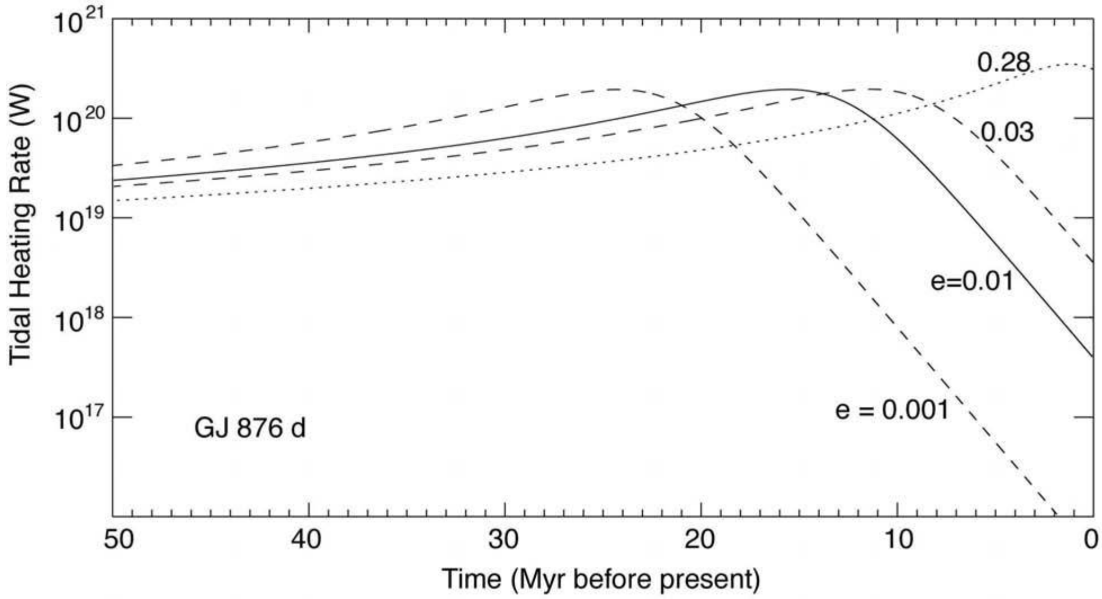

FIG. 5.—Tidal heating rates for GJ 876d, a possibly terrestrial-scale planet for which the nominal (tabulated) current *e*-value is zero but noncircular motion is likely. Heating curves were computed for an assumed current *e* of 0.001, 0.01, and 0.03, as well as for a possible maximum value of 0.28. Extensive internal melting might be expected if the heating rate is greater than $\sim 10^{18}$ W. Tidal heating may have been a significant factor in the geophysical history of this planet.

is actually 0.001, 0.01, or 0.03, as shown by the curves so labeled in Figure 5. We assume $R_p \sim 10{,}200$ km, based on the mass-radius relationship for terrestrial planets given by Sotin et al. (2007). In addition, we consider the implications of the upper limit on *e* of 0.28 reported by Rivera et al. (2005). The implied heating history in that case (as modeled by eq. [1]) is given by the dotted curve in Figure 5. In each of these four cases, as shown in Figure 5, the heating rate is well over 10^{19} W for tens of millions of years and peaks at $\sim 10^{20}$ W. The main difference among the four cases, depending on the assumed current *e*-value, is the timing of the peak, although it is within the past ~30 Myr in all four cases.

To put these numbers in context, consider the geophysical modeling of this planet by Valencia et al. (2007b), who report that 7×10^{17} W would be adequate to induce substantial internal melting of the mantle. According to that result, for GJ 876d the tidal heating (Fig. 5) has likely been 2 orders of magnitude greater than needed for melting. At the surface, in a steady state the tidal heating would correspond to a heat flux of $\sim 10^4$–10^5 W m^{-2}. For comparison, the surface heat flux for spectacularly active Io is ~3 W m^{-2} (McEwen et al. 1992) and is largely due to tides. For Earth the flux is ~0.08 W m^{-2} (Davies 1999), which is largely due to radiogenic heat. Valencia et al. (2007a) suggest that radiogenic heating of GJ 876d might have been adequate to initiate plate tectonics, but our results indicate that tidal heating may have been a major contributor to the geological and geophysical character of the planet. Tidal heating has provided an important component of the heat budget for this planet, perhaps the dominant component during at least the past $\sim 10^8$ yr. The tidal heating rate would be so large, in fact, that GJ 876d is unlikely to be a solid, rocky body.

For the nominal current orbit of Gl 581c (Butler et al. 2006) the tidal heating is about 10^{16} W, assuming the best-fit current *e* and *a*. It has been nearly constant over the past billion years and was only slightly larger early in its history 9 Gyr ago. Considering the range of uncertainty for the current orbit, the values could have been a few times higher or lower, but still $\sim 10^{16}$ W, far less than GJ 876d. Nevertheless, this rate could be geophysically important. Assuming $R_p \sim 10{,}000$ km (again scaling from the mass), the tidal contribution to the geophysical heat flux would be ~10 W m^{-2} at the surface, more than twice that of Io and 100 times the heat flux at the surface of Earth.

The mass of HD 69830b is greater than 10 $M_\oplus$, so it is more likely a Uranus-/Neptune-class planet than a terrestrial one. Nevertheless, Valencia et al. (2007b) considered the possibility that it is terrestrial in character, so we consider the implications for tidal heating if its Q_p' has the value expected for a rocky planet. For the best-fit current *e*-value, we find that tidal dissipation may generate $\sim 10^{17}$ W or up to a few times more given the most optimistic current orbital parameters. The heating rate has been fairly constant over the past billion years, but it decreased by a factor of a few since the planet's formation ~10 Gyr earlier (Lovis et al. 2006). Assuming a radius of ~12,000 km (based on its mass), the surface heat flux over the past 1 Gyr would be 55 W m^{-2} (20 times Io's). If HD 69830b is a terrestrial planet, tidal heat must have been a major factor in its geophysics throughout its history.

Note that in these calculations we have ignored the effect of interactions between the planets and other known (and some probably still unknown) planets in their systems. Secular interactions and orbital resonances may well have affected their orbital evolution in ways that modified the tidal heating histories. These effects would be in addition to the other uncertainties and assumptions intrinsic to the results presented here. Nevertheless, the point of our results is that tidal dissipation is likely to have been a significant factor in the geophysical evolution of extrasolar terrestrial-type planets.

4. DISCUSSION

The calculations here suggest that tidal heating may well have played an important role in the evolution of the physical properties of many extrasolar planets, the radius being the physical property for which we have the best constraints at present. We caution that the specific calculations displayed here depend on numerous assumptions and several uncertain parameters. The heating rates correspond to the orbital evolution trajectories that we computed in Jackson et al. (2008), and the caveats are discussed in detail there. In particular, the exact tidal histories presented here depend on the choice of Q'_*. However, most of the tidal histories presented here are not very sensitive to the choice of Q'_*, since tides raised on the planet usually dominate the evolution. HAT-P-2b is an important exception. Owing to the planet's unusually large mass ($\sim$9 $M_{\rm Jup}$), tides raised on the star may dominate the tidal evolution. As a result, the rate of tidal evolution depends sensitively on Q'_*; for example, a larger Q'_* results in slower tidal evolution. If tidal evolution were slower for this planet, it would mean that the past heating rate was closer to the current, large heating rate since the orbital parameters would not have changed much.

In any case, it is quite likely that the actual thermal history of any particular planet was different to some degree from what we have shown here. However, the unavoidable point is that tidal heating may be significant and should be considered as a factor in theoretical modeling of physical properties.

As shown in § 3, in most cases where the measured radius is greater than the theoretically predicted value (HD 209458b, HAT-P-1b, TrES-2, WASP-2b, and OGLE-TR-56b), the tidal heating has been significant and may thus resolve (or at least contribute to resolving) the discrepancy, once it is incorporated into the physical models. The greatest heating was typically $\sim$1 Gyr ago, so it may be that current planetary radii reflect the heating rate at that time in the past.

In only one case for which the measured radius is greater than that theoretically predicted (XO-1b) is the tidal heating too small to be a significant factor. Some other correction is probably needed to bring the model into agreement with the observation.

Among cases in which the theoretical models have seemed to be in good agreement with measured radii, two have experienced negligible tidal heating (GJ 436b and OGLE-TR-111b), so the agreement is preserved even when tides are taken into account. However, five cases may have undergone considerable tidal heating (TrES-1, HD 189733b, and OGLE-TR-10b, -113b, and -132b). Physical models will need to incorporate this heat source, which is likely to increase the radius predicted by the models. If the change is significant, other modifications will be required before the theory can be considered to be in agreement with observations.

In two of the cases considered here, the theoretical models have predicted radii larger than actually measured. For HD 149026b, tidal heating is probably not a factor. For HAT-P-2b, the tidal heating exacerbates the discrepancy between theory and observation. However, the problem is less severe if (as suggested by the other cases above) the current radius reflects the heating rate $\sim$1 Gyr ago, when the heating rate (in this case) was a few times less than at present.

Our study also suggests that the current state of physical modeling often gives radii that are too large for a given assumed amount of heating (or, equivalently, underestimates the amount of heat needed to yield a given radius). Tidal heat may resolve the discrepancy between theory and observations for most of the cases where measured radii were larger than expected, but it may make things worse in most of the cases in which measured radii seemed to fit the current models. In two cases, whether tidal heating is significant or not, the observed radii are smaller than predicted by the models. In summary, some discrepancies may be resolved by taking into account tidal heating, some remain even when tidal heating is taken into account, and some are exacerbated by tidal heating. Even when tidal heating is included, theoretical models will generally need to be adjusted and improved so as to yield smaller radii for a given amount of internal heat if they are to agree with measured values. Certainly, theoretical studies of the evolution of the physical properties of planets need to account for tides as a significant source of heat, and one that varies over time. Unlike heat of accretion, tidal heating varies over time, often reaching its maximum considerably later in the life of the planet.

Among terrestrial-scale planets, we find that tidal heating may have dominated the geological and geophysical evolution of the planets and may control their current character. The tidal heating rate for GJ 876d may be orders of magnitude greater than the magnitude considered by Valencia et al. (2007b) to be geophysically significant. For Gl 581c, tidal heating may yield a surface flux about 3 times greater than Io's, suggesting the possibility of major geological activity. The surface flux of tidal heat on HD 69830b would be yet an order of magnitude larger if it were a rocky planet. These heating rates are so large (especially for GJ 876d) that the extensive melting implied may not be consistent with the tidal dissipation parameters that we have assumed. Some melting might increase the rate of tidal heating as the tidal amplitude increases, but deep global melting would increase Q'_p and limit the heating to rates lower than what we have calculated. Another caveat is that the masses of these planets are minimum masses from radial velocity studies, so they may not be rocky, terrestrial-scale bodies after all. Finally, we emphasize that we have ignored the effects of mutual interactions among planets, which may affect orbital and tidal evolution in interesting ways.

Our results demonstrate the importance of using the coupled equations of tidal evolution of e and a. Some previous considerations of tidal evolution considered only the equation for de/dt, with semimajor axis held constant, which results in a simple exponential solution. The exponential damping (or "circularization timescale") found in that way can grossly underestimate the actual time that it takes to decrease the orbital eccentricity, as demonstrated in Jackson et al. (2008). Here we have seen that the slower circularization has likely resulted in significant heating rates at present and in the relatively recent past.

These results show that tidal heat may be a major factor in determining the character of extrasolar planets. The state of our understanding of tidal processes and of the relevant parameters for the planets is such that the specific results obtained here should be regarded as tentative at best. The tidal dissipation processes and their magnitude for these planets remain largely a matter of speculation. The extent to which a given amount of heat affects the physical state of the planet must depend on where the heat is dissipated. Heating near the surface may have less effect than if it is deep in the interior. Despite these uncertainties, the results presented here do demonstrate that tidal heat must be considered in theoretical modeling. The heating histories calculated here give a basis for a first cut at integrating tidal heat into physical models of extrasolar planets.

Planet TrES-4, discovered after initial preparation of this paper (Mandushev et al. 2007), was likely heated at a rate of $\sim 2 \times 10^{19}$ as recently as 2 Gyr ago, according to our calculation. These results may help explain the large observed radius.

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