

## STABILITY OF SATELLITES AROUND CLOSE-IN EXTRASOLAR GIANT PLANETS

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### ABSTRACT

We investigate the long-term dynamical stability of hypothetical moons orbiting extrasolar giant planets. Stellar tides brake a planet's rotation and, together with tidal migration, act to remove satellites; this process limits the lifetimes of larger moons in extrasolar planetary systems. Because more massive satellites are removed more quickly than less massive ones, we are able to derive an upper mass limit for those satellites that might have survived to the present day. For example, we estimate that no primordial satellites with masses greater than  $7 \times 10^{-7} M_{\oplus}$  ( $\sim 70$  km radius for  $\rho = 3 \text{ g cm}^{-3}$ ) could have survived around the transiting planet HD 209458b for the age of the system. No meaningful mass limits can be placed on moons orbiting Jovian planets more than  $\sim 0.6$  AU from their parent stars. Earthlike moons of Jovian planets could exist for 5 Gyr in systems where the stellar mass is greater than  $0.15 M_{\odot}$ . Transits show the most promise for the discovery of extrasolar moons—we discuss prospects for satellite detection via transits using space-based photometric surveys and the limits on the planetary tidal dissipation factor  $Q_p$  that a discovery would imply.

*Subject headings:* celestial mechanics — planetary systems — planets and satellites: general — stars: individual (HD 209458)

### 1. INTRODUCTION

Each of the giant planets in our solar system possesses a satellite system. Since the discovery of planets in other solar systems (Marcy, Cochran, & Mayor 2000b), the question of whether these extrasolar planets also have satellites has become relevant and addressable. Extrasolar planets cannot be observed directly with current technology and observing moons around them poses an even greater technical challenge. However, high-precision photometry of stars during transits of planets can detect extrasolar moons either by direct satellite transit or through perturbations in the timing of the planet transit (Sartoretti & Schneider 1999). Using these techniques, Brown et al. (2001) placed upper limits of 1.2 Earth radii ( $R_{\oplus}$ ) and 3 Earth masses ( $M_{\oplus}$ ) on any satellites orbiting the transiting planet HD 209458b based on the *Hubble Space Telescope* transit light curve.

The tidal bulge that a satellite induces on its parent planet perturbs the satellite's orbit (e.g., Burns 1986), causing migrations in the orbit's semimajor axis that can lead to the loss of the satellite. For an isolated planet, satellite removal occurs either through increase in the satellite's orbital semimajor axis until it escapes or by inward spiral until it impacts the planet's surface (Counselman 1973). In the presence of the parent star, stellar-induced tidal friction slows the planet's rotation, and the resulting planet-satellite tides cause the satellite to spiral inward toward the planet (Ward & Reid 1973; Burns 1973). This effect is especially important for a planet in close proximity to its star, and it has been suggested to be the reason for the lack of satellites around Mercury (Ward & Reid 1973; Burns 1973).

In this paper, we apply tidal theory and the results of numerical orbital integrations to the issue of satellites orbiting close-in extrasolar giant planets. We place limits on the masses of satellites that extrasolar planets may possess, discuss the implications these limits have for the detection of

extrasolar satellites, and apply our results to the issue of Earthlike satellites orbiting extrasolar giant planets.

### 2. TIDAL THEORY AND METHODS

According to conventional tidal theory, the relative values of the planetary rotation rate,  $\Omega_p$ , and the orbital mean motion of the moon,  $n_m$  (both in units of radians per second), determine the direction of orbital evolution (see, e.g., Murray & Dermott 2000). For a moon orbiting a planet slower than the planet rotates ( $n_m < \Omega_p$ ), the tidal bulge induced on the planet by the satellite will be dragged ahead of the satellite by an angle  $\delta$ , with  $\tan(2\delta) = 1/Q_p$ . Here  $Q_p$  is the parameter describing tidal dissipation within the planet (after Goldreich & Soter 1966), with  $1/Q_p$  equal to the fraction of tidal energy dissipated during each tidal cycle. Gravitational interactions between the tidal bulge and the satellite induce torques that transfer angular momentum and dissipate energy, slowing the planet's rotation and increasing the orbital semimajor axis of the satellite. Conversely, for satellites orbiting faster than their planet's rotation ( $n_m > \Omega_p$ ), the planet is spun up and the satellite's semimajor axis decreases. The same mechanism causes torques on the planet from its parent star that slow the planet's rotation (Murray & Dermott 2000).

The torque on the planet due to the tidal bulge raised by the moon ( $\tau_{p-m}$ ) is (Murray & Dermott 2000)

$$\tau_{p-m} = -\frac{3 k_{2p} G M_m^2 R_p^5}{2 Q_p a_m^6} \text{sgn}(\Omega_p - n_m), \quad (1)$$

where  $k_{2p}$  is the tidal Love number of the planet,  $R_p$  is the radius of the planet, and  $G$  is the gravitational constant. The term  $\text{sgn}(\Omega - n_m)$  is equal to 1 if  $(\Omega - n_m)$  is positive and is equal to  $-1$  if it is negative. We obtain the expression for the

stellar torque on the planet by replacing  $M_m$ , the mass of the moon, with  $M_*$ , the mass of the star; by replacing  $a_m$ , the semimajor axis of the satellite's orbit with  $a_p$ , the semimajor axis of the planet's orbit about the star (circular orbits are assumed); and by using the planet's mean orbital motion  $n_p$  instead of  $n_m$ :

$$\tau_{p-*} = -\frac{3k_{2p}GM_*^2R_p^5}{2Q_p a_p^6} \text{sgn}(\Omega_p - n_p). \quad (2)$$

The moon's semimajor axis,  $a_m$ , and the moon's mean motion,  $n_m$ , are related by Kepler's law,  $n_m^2 a_m^3 = GM_p$ . These torques affect both  $n_m$  and  $\Omega_p$ . The rate of change of  $\Omega_p$  is obtained by dividing the total torque on the planet by the planet's moment of inertia:

$$\frac{d\Omega_p}{dt} = \frac{\tau_{p-m} + \tau_{p-*}}{I_p}, \quad (3)$$

where  $I_p$  is the planet's moment of inertia.

Under the circumstances studied in this paper, where a planet is orbited by a much smaller satellite,  $\tau_{p-*}$  is much greater than  $\tau_{p-m}$  for most of the system's lifetime. Because the moon's orbital moment of inertia depends on  $n_m$ , the equivalent expression for  $n_m$  is less trivial to derive. We obtain it by setting the torque equal to the rate of change of the angular momentum and solving for  $dn/dt$  using the planet's mass,  $M_p$  (e.g., Peale 1988):

$$\frac{dn_m}{dt} = \frac{3\tau_{p-m}n_m^{4/3}}{M_m(GM_p)^{2/3}}. \quad (4)$$

Given appropriate initial and boundary conditions, integration of equations (3) and (4) determines the state of the system at any given time.

An important boundary condition for such an integration is the critical semimajor axis, or the location of the outermost satellite orbit that remains bound to the planet. This location must be within the planet's gravitational influence, or Hill sphere, and has been generally thought to lie between  $\frac{1}{3}$  and  $\frac{1}{2}$  the radius of the Hill sphere,  $R_H$  (Burns 1986), where

$$R_H = a_p \left( \frac{M_p}{3M_*} \right)^{1/3}. \quad (5)$$

Recently, Holman & Wiegert (1999) investigated the stability of planets in binary star systems, and their results are applicable to the planet-satellite situation as well. Through numerical integrations of a test particle orbiting one component of a binary star system, Holman & Wiegert (1999) found that for high mass ratio binaries, the critical semimajor axis for objects orbiting the secondary in its orbital plane is equal to a constant fraction ( $f$ ) of the secondary's Hill radius or

$$a_{\text{crit}} = fR_H. \quad (6)$$

We treat a star orbited by a much less massive planet as a high mass ratio binary system and deduce that the critical semimajor axis for a satellite orbiting the planet is  $0.36R_H$  ( $f = 0.36$ ) for prograde satellites (from Holman & Wiegert 1999, Fig. 1). This agrees closely with Burns (1986). In fact, none of the prograde moons of our solar system orbit outside this radius (see Table 1). Holman & Wiegert (1999) did not treat objects in retrograde orbits (which are expected to be more stable than prograde ones), so to treat possible cap-

TABLE 1  
SATELLITE SEMIMAJOR AXES

Planet	Satellite	$a_m/R_H$
Earth .....	Moon	0.257
Mars .....	Deimos	0.0216
Jupiter.....	Callisto	0.0354
	Elara	0.221
	Sinope	0.446R
Saturn.....	Titan	0.0187
	Iapetus	0.0545
	Phoebe	0.198R
	S/2000 S 9	0.283
Uranus.....	Oberon	0.00837
	Setebos	0.352R
Neptune.....	Triton	0.003R
	Nereid	0.0475

NOTES.—Orbital semimajor axes of selected solar system satellites are listed as a function of their parent planet's hill sphere radius,  $R_H$ . R=Retrograde.

tered satellites we take  $f_{\text{retrograde}} = 0.50$ , based on the solar system values for  $a_m/R_H$  in Table 1.

### 3. CONSTRAINTS ON SATELLITE MASSES

Satellites orbiting close-in giant planets fall into one of three categories based on the history of their orbital evolution. Satellites that either start inside the planet's synchronous radius (the distance from the planet where  $n_m = \Omega_p$ ) or become subsynchronous early in their lifetimes, as a result of the slowing planetary rotation, spend their lives spiraling inward toward the cloud tops. Eventually these moons collide with the planet or are broken up once they migrate inside the Roche limit. Moons that start and remain exterior to the synchronous radius evolve outward over the course of their lives and, given enough time, would be lost to interplanetary space as a result of orbital instability. In between these two is a third class of orbital history. In this case, a satellite starts well outside the synchronous radius and initially spirals outward, but its migration direction is reversed when the planet's rotation slows enough to move the synchronous radius outside the moon's orbit. These moons eventually impact the planet.

In order to determine which satellites might still exist around any given planet, we determine the maximum lifetime for a moon with a given mass in each orbital evolution category. Inward-evolving satellites should maximize their lifetime by starting as far from the planet as possible, at the critical semimajor axis  $a_{\text{crit}}$  (eq. [6]), and spiraling inward all the way to the planet. Outward-evolving satellites can survive the longest if they start just outside the synchronous radius of the planet, then spiral outward to the critical semimajor axis. The maximum lifetime for the out-then-in case occurs when a satellite reverses migration direction at the outermost possible point, the critical semimajor axis. In this case, the moon starts at the semimajor axis that allows for it to have reached  $a_{\text{crit}}$  by the time its planet's synchronous radius also reaches  $a_{\text{crit}}$ , thus maximizing the time for its inward spiral (see Fig. 1). For a given satellite mass, if the maximum possible lifetime is shorter than the age of the system, then such a satellite could not have survived to the

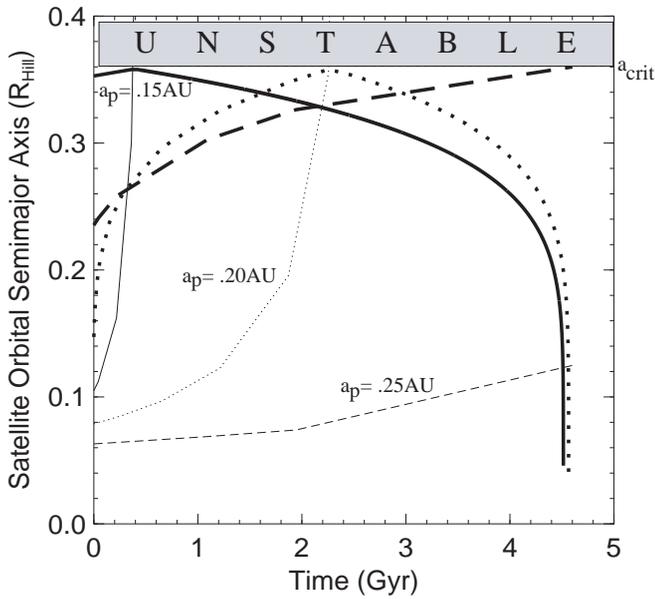


FIG. 1.—Satellite orbital semimajor axis vs. time for the maximum-mass moon in three different hypothetical 4.6 Gyr old,  $1 M_{\odot}$ ,  $1 M_{\text{Jup}}$  planetary systems. The solid lines represent a system with a planet-star distance of 0.15 AU, with the thick and thin lines corresponding to the satellite semimajor axis and planet synchronous radius, respectively. Tides between this planet and its star spin down the planet in short order, and the moon spends the majority of its lifetime evolving inward through tidal interactions with the planet. It is destroyed upon reaching the cloud tops of the planet. The dotted lines correspond to a system in which the planet-star separation is 0.20 AU; this planet is de-spun in just under half the age of the system. Thus, its maximum-mass moon initially moves outward because of tidal influences, but later it reverses direction because of the spin-down of the planet, eventually crashing into it. This moon reverses direction at the critical semimajor axis (the outermost stable orbit point) because doing so maximizes its orbital lifetime. The dashed lines indicate a planet orbital semimajor axis of 0.25 AU. The star's tidal torques on the planet have less influence at this distance, and the planet does not de-spin sufficiently over its lifetime to reverse the orbital migration of its maximum-mass satellite. This satellite is lost into interplanetary space because of orbital instabilities.

present. Because the orbits of higher mass satellites evolve more quickly than those of lower mass satellites (eq. [4]), an upper limit can be placed on the masses of satellites that could still exist around any given planet.

### 3.1. Analytical Treatment

For a given semimajor axis of a moon,  $a_m$ , the migration rate is the same whether the moon is moving inward or outward (with the assumption that  $Q_p$  is independent of the tidal forcing frequency  $\Omega_p - n_m$ ), and the migration rate is much faster for satellites close to their parent planets. For both the inward- and outward-migrating categories, the total lifetime of a satellite ( $T$ ) is well-characterized by the time necessary for a satellite orbit to traverse the entire region between the critical semimajor axis ( $a_m = a_{\text{crit}}$ ) and the planet's surface ( $a_m = R_p$ ; Murray & Dermott 2000):

$$T = \frac{2}{13} \left( a_{\text{crit}}^{13/2} - R_p^{13/2} \right) \frac{Q_p}{3k_{2p} M_m R_p^5} \sqrt{\frac{M_p}{G}}. \quad (7)$$

Since  $R_p \ll a_{\text{crit}}$  and the exponents are large, the  $R_p$  term inside the parenthesis can be neglected. Substituting  $a_{\text{crit}} = fR_H$  (eq. [6]), allowing  $T$  to be equal to the age of the

system, and solving for  $M_m$  collectively result in an analytical expression for the maximum possible extant satellite mass in both the inward and outward cases,

$$M_m \leq \frac{2}{13} \left[ \frac{(fa_p)^3}{3M_*} \right]^{13/6} \frac{M_p^{8/3} Q_p}{3k_{2p} TR_p^5 \sqrt{G}}, \quad (8)$$

which is the equation of the bottom dot-dashed line in Figure 2. In the case of satellites that evolve outward then inward, the spin-down of the planet is important. These moons can be saved temporarily by the reversal of their orbital migration. This reversal prolongs their lifetimes, but by less than a factor of 2 because the satellite traverses the region in which  $a_m < a_{\text{crit}}$  twice. The upper mass limit for these satellites is

$$M_m \leq \frac{4}{13} \left[ \frac{(fa_p)^3}{3M_*} \right]^{13/6} \frac{M_p^{8/3} Q_p}{3k_{2p} TR_p^5 \sqrt{G}}, \quad (9)$$

and this limit is plotted as the upper dotted line in Figure 2.

We obtain the boundaries between the in, out-then-in, and out cases by comparing the time necessary to de-spin the planet to the age of the system. The time necessary to spin down the planet to the point that the synchronous radius becomes exterior to the critical semimajor axis is equal to (Guillot et al. 1996)

$$T_{\text{spin-down}} = Q_p (\Omega_{p0} - \Omega_{p1}) \left( \frac{R_p^3 M_p}{GM_*^2} \right), \quad (10)$$

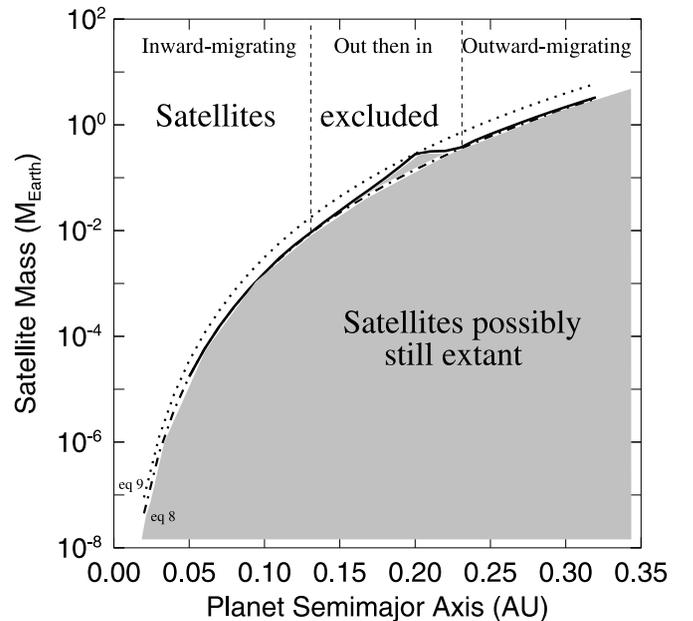


FIG. 2.—Stability diagram for satellites in a hypothetical 4.6 Gyr old  $1 M_{\odot}$ ,  $1 M_{\text{Jup}}$  planetary system as a function of the planet's orbital semimajor axis. The solid line represents the results from numerical integrations of eqs. (3) and (4), and the broken lines are the analytical approximations given in eq. (8) (lower, dot-dashed line) and eq. (9) (upper, dotted line). Satellites above this line are excluded, while those that lie below the line may or may not still exist depending on their specific orbital evolutionary histories. For this specific case, below  $a_p \sim 0.15$  AU satellite masses are limited by their inward migration, above  $a_p \sim 0.23$  AU by their outward migration, and in between by outward-followed-by-inward migration with the reversal being the result of slowing planetary rotation.

where  $\Omega_{p0}$  is the initial planetary rotation rate and  $\Omega_{p1}$  is the rotation rate at which the planet's synchronous radius is coincident with  $a_{\text{crit}}$ . At this point, from Kepler's law we infer that

$$\Omega_{p1} = n_{\text{crit}} = \left( \frac{GM_p}{a_{\text{crit}}^2} \right)^{1/3}. \quad (11)$$

For the case where  $T_{\text{spindown}} \ll T$  (where  $T$  is the system lifetime), the maximum-mass moon evolves inward and equation (8) should be used. When the system age is greater than this spin-down time ( $T_{\text{spindown}} \gg T$ ), moons evolve outward and again equation (8) is valid. However, when  $T_{\text{spindown}} \sim T$ , the reversal of satellite orbital migration is important and equation (9) provides a more robust upper mass limit for surviving satellites.

These results for the maximum  $M_m$  are limited by the requirement that the rate of angular momentum transfer between the planet and the satellite must be less than that between the planet and the star when  $a_m$  is relatively large (i.e.,  $\tau_{p-*} > \tau_{p-m}$  in eq. [3]) such that synchronization between the planet and moon does not occur. In the case of rocky satellites orbiting gaseous planets, this condition is met. For large moon-planet mass ratios or large  $a_p$ , this assumption breaks down, yielding a situation more closely resembling the isolated planet-satellite systems treated in Counselman (1973). In this case the planet and moon can become locked into a 1:1 spin-orbit resonance with each other, halting the satellite's orbital migration and extending its lifetime. For extrasolar Jovian planets ( $0.3 M_{\text{Jup}} < M_p < 13.0 M_{\text{Jup}}$ ) this occurs when satellite masses become very large, i.e., greater than  $8 M_{\oplus}$  for a  $1 M_{\text{Jup}}$  planet. Such a moon is large enough to accrete hydrogen gas during its formation, however, and in such a case the system is better treated as a binary planet, taking into account the tidal torques of each body on the mutual orbit. We do not address that situation here.

We assume prograde, primordial satellites, but objects captured into orbit by a planet late in its life could also remain in orbit. We do not treat the physics of satellite capture, but the lifetimes of such moons would be affected by the same processes described above if prograde, and limited by inward migration like Neptune's moon Triton (McCord 1966) if retrograde. In the case of retrograde, captured moons, the following upper limit on their survival lifetime can be placed by rearranging equation (8):

$$T_{\text{max}} = \frac{2}{13} \left[ \frac{(f_R a_p)^3}{3M_*} \right]^{13/6} \frac{M_p^{8/3} Q_p}{3k_{2p} M_m R_p^2 \sqrt{G}}. \quad (12)$$

Our analysis assumes a single satellite system. Inward-migrating moons could not be slowed significantly by entering into a resonance with another satellite farther in because the interior satellite would be migrating faster (due to the  $a_m^{-6}$  dependence of the torque in eq. [1]), unless its mass is less than  $0.08 M_m$  (assuming a 2:1 resonance). Slowly migrating moons exterior to the satellite in question cannot slow its orbital migration because objects in diverging orbits cannot be captured into resonances. However, outward-migrating satellites could have their lifetimes extended by entering into a resonance with an exterior neighbor through intersatellite angular momentum transfer (Goldreich 1965), similar to the resonances currently slowing the outward

migration of Io from Jupiter. Thus some outward-limited satellites above the mass limit derived in equation (8) may still survive because of resonances entered into earlier in their lifetimes.

### 3.2. Numerical Treatment

To verify the limits stipulated in equations (8) and (9), we integrate equations (3) and (4) numerically, from the initial rotation rate and semimajor axis until the satellite's demise through either impact with the planet or orbital escape. We use an adaptive stepsize Runge-Kutta integrator from Press et al. (1992) and have verified that it reproduces our analytical results for small satellite masses. We also assume that only  $\Omega_p$  and  $a_m$  change over time—other planetary parameters such as  $Q_p$ ,  $a_p$ ,  $R_p$ , and all others are taken to be constant for the length of the integration. The expected changes in the planet's orbital semimajor axis  $a_p$  over the course of the integration do not significantly affect the calculations, and larger planetary radii  $R_p$  in the past would only serve to further reduce the lifetime of a given satellite beyond what we have calculated here, pushing the upper surviving satellite mass lower.

For each planet, we determine the maximum satellite mass that could survive for the observed lifetime of the system by optimizing the initial semimajor axis of the satellite so as to maximize its lifetime and then tuning the satellite mass until this lifetime is equal to the system age. Sample evolutionary histories of this maximum mass satellite for a hypothetical  $1 M_{\odot}$ ,  $1 M_{\text{Jup}}$  system from each orbital evolutionary history category are shown in Figure 1. The numerically determined maximum mass as a function of planetary orbital semimajor axis is shown in Figure 2 as the solid line. These numerical results are consistent with our analytical upper mass limits from equations (8) and (9).

## 4. IMPLICATIONS

### 4.1. Known Extrasolar Planets

In applying these results to the specific test case of the transiting planet HD 209458b, we adopt the values  $M_* = 1.1 M_{\odot}$ ,  $M_p = 0.69 M_{\text{Jup}}$ ,  $a_p = 0.0468$  AU,  $T = 5.0$  Gyr (Mazeh et al. 2000), and  $R_p = 1.35 R_{\text{Jup}}$  (Brown et al. 2001) based on observational studies. We take  $k_{2p}$  for the planet to be 0.51, the value for an  $n = 1$  polytrope (Hubbard 1984). The least constrained parameter is the tidal dissipation factor  $Q_p$ ; for HD 209458b we adopt  $Q_p = 10^5$ , which is consistent with estimates for Jupiter's  $Q_p$  (Goldreich & Soter 1966). However,  $Q_p$  is not known precisely even for the planets in our own solar system, and the precise mechanism for the dissipation of tidal energy has not been established.  $Q_p$  for extrasolar planets, and especially for ones whose interiors differ from Jupiter's, such as close-in giant planets (Burrows et al. 2000), may differ substantially from this value.

Because HD 209458b was likely tidally spun-down to synchronous rotation very quickly (Guillot et al. 1996), satellites around it are constrained by the infall time, and we use equation (8) to obtain an upper limit of  $7 \times 10^{-7} M_{\oplus}$  for their masses. Assuming a density of  $\rho = 3 \text{ g cm}^{-3}$ , the largest possible satellite would be 70 km in radius—slightly smaller than Jupiter's irregularly shaped moon Amalthea. These limits are consistent with the those placed on actual satellites observationally by Brown et al. (2001). It is possi-

ble for captured satellites to exist around HD 209458b. Their lifetimes, however, would be exceedingly short—a  $1 M_{\oplus}$  satellite could survive for only 30,000 yr (eq. [12]), making the probability of detecting one low, unless such captures are common.

We also calculate the maximum masses for surviving moons around other detected extrasolar planets; the results are in Table 2. We take the planet masses to be equal to the minimum mass determined by radial velocity monitoring, as the orbital inclination has not been reliably determined for any planet except HD 209458b. We use the same  $k_{2p}$  and  $Q_p$  as we did for HD 209458b, but take  $R_p = R_{\text{Jup}}$  because the radii for these objects is unknown. For this table, we have only chosen planets whose orbital eccentricities are less than 0.10 because equation (6) applies only to planets in circular orbits. The critical semimajor axis for planets in non-circular orbits has not yet been determined, thus we leave the calculation of upper mass limits for satellites around these eccentric planets for future work.

#### 4.2. Earthlike Moons

Our approach can also shed light on the issue of Earthlike satellites, which we define to be moons capable of support-

ing liquid water. Low-mass satellites do not fit this definition because of their inability to retain volatiles (Williams, Kasting, & Wade 1997). Here we note that high-mass satellites may not survive for long periods around close-in planets because planets with low masses have smaller Hill spheres and therefore, for a given satellite mass, also have shorter maximum moon lifetimes. To calculate in general which giant planets might harbor Earthlike satellites, we use equation (8) and constrain  $a_p$  based on the insolation at the planet,  $F$ , relative to the Earth's insolation  $F_{\oplus} = 1370 \text{ W m}^{-2}$ . We use the rough approximation (Hansen & Kawaler 1994)

$$\frac{L_*}{L_{\odot}} = \left( \frac{M_*}{M_{\odot}} \right)^{3.5} \quad (13)$$

for the stellar luminosity,  $L_*$ , together with the insolation at the planet,

$$\frac{F}{F_{\oplus}} \frac{a_p^2}{a_{\oplus}^2} = \frac{L_*}{L_{\odot}}, \quad (14)$$

to fix the planet's semimajor axis by solving for  $a_p$ . By plugging the resulting value for  $a_p$  into equation (8), we can

TABLE 2  
CONSTRAINTS ON SATELLITES AROUND SELECTED EXTRASOLAR PLANETS

Name	Star Age (Gyr)	$M \sin i$ ( $M_{\text{Jup}}$ )	$a$ (AU)	Eccentricity	Maximum Moon Mass ( $M_{\oplus}$ )	Maximum Moon Radius (km)	Reference
HD 83443b .....	(5)	0.35	0.038	0.08	$8 \times 10^{-8}$	30	1
HD 46375b .....	(5)	0.25	0.041	0.04	$6 \times 10^{-8}$	30	2
HD 187123b.....	(5)	0.52	0.042	0.03	$6 \times 10^{-7}$	60	3
HD 209458b.....	5	0.69	0.045	0	$7 \times 10^{-7}$	70	4
HD 179949b.....	(5)	0.84	0.045	0	$3 \times 10^{-6}$	110	5
HD75289b.....	(5)	0.42	0.046	0.053	$6 \times 10^{-7}$	60	6
BD -10 3166 b.....	(5)	0.48	0.046	0.05	$7 \times 10^{-7}$	70	7
T Boo b.....	2	4.1	0.047	0.051	$5 \times 10^{-4}$	600	8
51 Pegasus b.....	(5)	0.44	0.051	0.013	$2 \times 10^{-6}$	90	9
U And b.....	2.6	0.71	0.059	0.034	$2 \times 10^{-5}$	190	10
HD 168746b.....	(5)	0.24	0.066	0	$2 \times 10^{-6}$	100	11
HD 130322b.....	(5)	1	0.088	0.044	0.0008	730	6
55 Cnc b.....	5	0.84	0.11	0.051	0.001	810	8
Gl86b.....	(5)	3.6	0.11	0.042	0.1	3950	12
HD 195019b.....	3.2	3.5	0.14	0.03	0.8	7090	13
GJ 876c.....	5	1.9	0.21	0.1	6	14050	14
$\rho$ CrB b.....	10	1.1	0.23	0.028	0.3	5310	15
U And c.....	2.6	2.1	0.83	0.018	...	...	10
HD 28185b.....	(5)	5.6	1	0.06	...	...	16
HD 27442b.....	(5)	1.4	1.2	0.02	...	...	17
HD 114783b.....	(5)	1	1.2	0.1	...	...	18
HD 23079b.....	(5)	2.5	1.5	0.02	...	...	19
HD 4208b.....	(5)	0.8	1.7	0.01	...	...	18
47 UMa b.....	6.9	2.5	2.1	0.061	...	...	4
47 UMa c.....	6.9	0.76	3.7	0.1	...	...	4

NOTES.—Upper satellite mass limits are determined with  $Q_p = 10^5$ ,  $R_p = R_{\text{Jup}}$ , and with  $M_p = m \sin i$ . Where no system lifetime was available in the literature, we have taken the system age to be 5 Gyr, and those cases are indicated by parenthesis. To obtain maximum moon radii, we assume  $\rho = 3 \text{ g cm}^{-3}$ . We cannot place useful limits for those planets whose maximum masses and radii are not listed. Planets with orbital eccentricities greater than 0.1 are excluded because of the difficulty in determining the proper value of  $f$ . The planet data used to generate this table have been formed into a World Wide Web accessible database of extrasolar planets, which is available at <http://c3po.lpl.arizona.edu/egpdb>.

REFERENCES.—(1) Mayor et al. 2000; (2) Marcy et al. 2000a; (3) Butler et al. 1998; (4) Fischer et al. 2002; (5) Tinney et al. 2001; (6) Udry et al. 2000; (7) Butler et al. 2000; (8) Butler et al. 1997; (9) Marcy et al. 1997; (10) Butler et al. 1999; (11) <http://obswww.unige.ch/~udry/planet/hd168746.html>; (12) Queloz et al. 2000; (13) Fischer et al. 1999; (14) Marcy et al. 2001; (15) Noyes et al. 1997; (16) Santos et al. 2001; (17) Butler et al. 2001; (18) Vogt et al. 2002; (19) Tinney et al. 2002.

exclude Earthlike moons around planets in systems that do not satisfy the inequality

$$M_p \geq \left[ \frac{39}{4} \left( \frac{f^3}{3} \right)^{-13/6} \frac{M_m k_{2p} T R_p^5 \sqrt{G}}{Q_p} \right]^{3/8} \times \frac{M_\odot^{273/64}}{M_*^{221/64}} \left( a_\oplus^2 \frac{F_\oplus}{F} \right)^{-39/32} \quad (15)$$

Equation (15) is plotted in Figure 3 for the same values of  $k_{2p}$ ,  $Q_p$ , and  $f$  as we use for HD 209458b, with  $R_p = R_{\text{Jup}}$  and  $T = 5$  Gyr.

Williams et al. (1997) found the lower limit  $M_m \geq 0.12 M_\oplus$  for moons that can retain volatiles over gigayear timescales. Using this mass, we find that Earthlike moons orbiting Jovian planets could survive for solar system lifetimes around stars with masses greater than  $0.15 M_\odot$  and that Earth-mass satellites that receive insolation similar to that of Earth are stable around all Jovian planets orbiting stars with  $M_* > 0.5 M_\odot$ . Planets with masses less than  $0.3 M_{\text{Jup}}$  differ in radius,  $Q_p$ , and interior structure from those with masses greater than  $0.3 M_{\text{Jup}}$ . In addition, for lower planet masses the planet/satellite mass ratio increases beyond the assumption of nonsynchronization between the planet and the moon. For these reasons, we do not treat here the question of Earthlike satellites of ice-giant planets ( $M_p < 0.3 M_{\text{Jup}}$ ).

The radial-velocity planet most likely to harbor Earthlike moons is HD 28185b because of its circular,  $a_p = 1$  AU, orbit around a star similar to the Sun with spectral type G5 V and  $L_* = 1.09 L_\odot$  (Santos et al. 2001). Because the calculated upper satellite mass for this planet is above  $8 M_\oplus$ , we cannot rule out any satellite masses for this object. Thus, Earthlike moons with any mass could plausibly be stable around HD 28185b.

#### 4.3. Future Discoveries

Several missions to search for extrasolar planet transits by high-precision space-based photometry are in the planning stages and will, if launched, have the capability of detecting satellites (Sartoretti & Schneider 1999). The probability that a given planet will transit across its parent star decreases with planetary orbital semimajor axis as  $1/a_p$ . Hence, these surveys will preferentially detect planets in orbits close to their parent stars. However, we have shown that it is unlikely that these close-in objects will harbor satellites. Therefore, satellite transits are most likely to be detected around planets orbiting at moderate distances from their parent star ( $0.3 \text{ AU} \leq a_p \leq 2 \text{ AU}$ ), even though

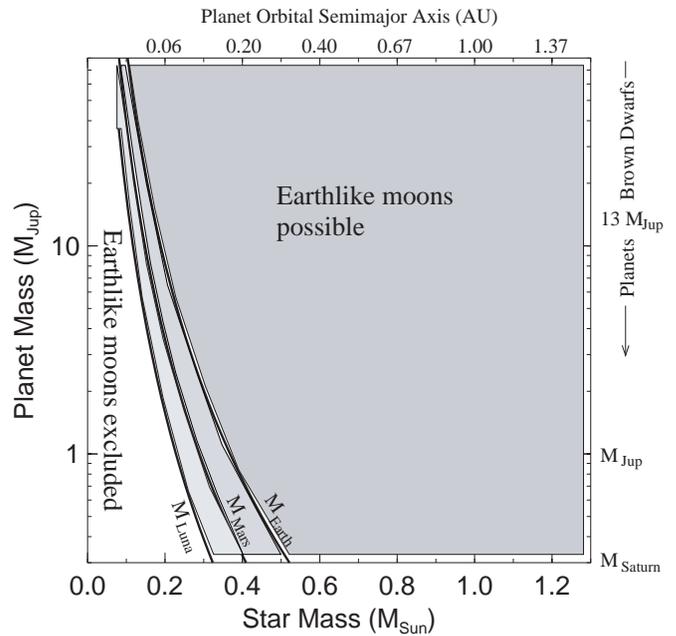


Fig. 3.—Stability of Earthlike moons. For stars of a given mass, we estimate a luminosity from eq. (13) and then calculate the limits on planet masses that allow for the stability of moons with insolation  $F = 1370 \text{ W m}^{-2}$  and mass  $1 M_{\text{Luna}}$  (solid line, left),  $1 M_{\text{Mars}}$  (solid line, center), and  $1 M_{\text{Earth}}$  (solid line, right). Planets with the proper  $a_p$  (top) and masses above the appropriate solid line might still harbor Earthlike satellites after 5 Gyr. For this plot, we have taken  $R_p = R_{\text{Jup}}$ , and as such the values are not valid for planets with masses less than  $0.3 M_{\text{Jup}}$ . Planet mass limits for very low mass stars where  $M_p \sim M_*$  are also suspect. From this plot we infer that Earthlike satellites of Jovian planets are plausibly stable for 5 Gyr around most stars with masses greater than  $0.15 M_\odot$ .

planet transits are most likely at small orbital distances. If a satellite were detected, equation (9) could be used to place limits on the planetary tidal dissipation parameter  $Q_p$ . By using extreme values of the lifetimes, masses, and possible values of  $Q_p$  that may exist, we estimate this process will not significantly affect planets more than 0.6 AU from their parent star, leaving intact any satellite systems they might possess.

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