THE POTENTIAL FOR TIDALLY HEATED ICY AND TEMPERATE MOONS AROUND EXOPLANETS

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ABSTRACT

Moons of giant planets may represent an alternative to the classical picture of habitable worlds. They may exist within the circumstellar habitable zone of a parent star, and through tidal energy dissipation they may also offer alternative habitable zones, where stellar insolation plays a secondary, or complementary, role. We investigate the potential extent of stable satellite orbits around a set of 74 known extrasolar giant planets located beyond 0.6 AU from their parent stars—where moons should be long-lived with respect to removal by stellar tides. For this sample, the typical stable satellite orbital radii span a band some \(\sim 0.02\) AU in width, compared to the \(\sim 0.12–0.15\) AU bands for the Jovian and Saturnian systems. Approximately 60% of these giant planets can sustain satellites or moons in bands up to \(\sim 0.04\) AU in width. For comparison, the Galilean satellites extend to \(\sim 0.013\) AU. We discuss how the actual number and characteristics of satellites will depend strongly on the formation pathways. We investigate the stellar insolation that moons would experience for these exoplanet systems and the implications for sublimation loss of volatiles. We find that between 15% and 27% of all known exoplanets may be capable of harboring small, icy moons. In addition, some 22%–28% of all known exoplanets could harbor moons within a “sublimation zone,” with insolation temperatures between 273 and 170 K. A simplified energy-balance model is applied to the situation of temperate moons, maintained by a combination of stellar insolation and tidal heat flow. We demonstrate that large moons (>0.1 \(M_\oplus\)), at orbital radii commensurate with those of the Galilean satellites, could maintain temperate, or habitable, surface conditions during episodes of tidal heat dissipation of the order 1–100 times that currently seen on Io.

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1. INTRODUCTION

Based on the example of our own solar system, giant planets appear to be excellent candidates for playing host to significant satellite and moon systems. Of particular interest is the possibility that moons may share characteristics with terrestrial type worlds, in terms both of composition and size and of thermodynamic conditions favorable to life. If a host giant planet orbits within the so-called circumstellar habitable zone, then moons of mass greater than approximately 0.1 \(M_\oplus\) may be able to retain a long-lived atmosphere and sustain temperate surface conditions (Williams et al. 1997).

Moons may also represent an entirely new class of habitable environment owing to the potential for them to form beyond the planetary snow line in a system and hence accumulate a significant icy mantle, and the potential for them to enter into orbital resonance conditions favorable for driving significant tidal heating and sustainable subsurface liquid oceans (e.g., Reynolds et al. 1987). The latter is a direct consequence of the dynamically dense nature of moon systems. The Galilean moon Europa has served as a prototype for such objects, and it appears possible that a liquid-water ocean, perhaps as deep as 100 km (e.g., Melosh et al. 2003) currently exists beneath an outer icy crust. This state is consistent with vigorous tidal heating by Jupiter due to the maintenance of an eccentric orbit \((e \approx 0.01)\) by the mean-motion 4:2:1 Laplacian resonance between Io, Europa, and Ganymede. Other moons in our solar system, which would otherwise be inert, also show evidence for dynamically driven heating. For example, the recent detection of water “geysers” on Enceladus in the Saturnian system (e.g., Porco et al. 2006) points toward a remarkably active geology, even on such a small moon. In the case of Enceladus, although it is known to be in a 1:2 mean-motion orbital resonance with the moon Dione (with a resultant orbital eccentricity of 0.0045), it appears unlikely that the resultant tidal heating by Saturn is sufficient to maintain a subsurface ocean, although the tides may contribute to localized heating. Proximity to a librational resonance (Wisdom 2004), together with radiogenic heating and a variety of possible internal compositions may provide the additional boost required to explain its activity (Porco et al. 2006).

Nonclassical habitable zones such as that proposed for Europa could greatly extend the potential for biota in planetary systems by essentially decoupling from the stellar energy output (e.g., Reynolds et al. 1987) and circumventing the mass requirement for atmospheric retention. In addition, the classical circumstellar habitable zone could conceivably be extended when the surface temperature of a satellite or moon is maintained by a combination of stellar insolation and tidal heating. In the broader context of life within a planetary system such potential habitats are of enormous interest in seeking both the origins of life and the capacity for life to survive through unfavorable circumstances. For example, not only could moons like Europa offer potential “incubators” for life, they might—through forward contamination (e.g., Gladman et al. 2006)—offer a relatively safe haven for microbial life set adrift due to cataclysmic events on inner, terrestrial-type worlds.

It is not unreasonable to speculate that moon and ring systems will eventually be detected using more sensitive instrumentation and current and future observational techniques. Indeed, such detections appear plausible even with current transit methods (Sartoretti & Schneider 1999; Barnes & Fortney 2004), especially when applied to future missions such as Kepler or COROT, which may even be able to detect the signature of equivalent systems to Jupiter-Europa using eclipse timing (e.g., Doyle & Deeg...
2. SATELLITE ORBITAL TERRAIN

Previous works have investigated the longevity of satellite systems due to tides and migrations, and in particular of Earth-mass moons around giant planets on close orbits to the parent star (Kokubo & Ida 1998; K. A. Mikkola & Tremaine 1999; Benz & O’Neill 2002). Kuiper & Dell (1999) and Benz & O’Neill (2002) note that for parent stars with $M_\star > 0.15 M_\odot$, Earth-sized moons of Jovian planets can remain in stable orbits for some 3 Gyr; they also point out that beyond approximately $\sim 0.6$ AU, there are essentially no meaningful dynamical constraints on moon masses and survival times. Moons around such planets could therefore be both massive and long lived. In this work we therefore restrict our investigation to the potential orbital ranges of stable satellite systems around known planets whose semimajor axes are $a_p > 0.6$ AU.

A simple consideration of the Hill sphere radius; $R_H = a_p (M_p/3M_\star)^{1/3}$ (Burns 1986) from the restricted three-body problem, leads to a broad constraint on the outer physical extent of any system in terms of the satellite semimajor axis $a_s$. The critical semimajor axis—the location of the outermost satellite orbit that remains bound to the planet—has been estimated to be a fraction between $1/4$ and $1/6$ of $R_H$. We use the numerical result of Holman & Wiegert (1999) for prograde satellites, which suggests a critical semimajor axis of $0.36R_H$. For the majority of the exoplanet systems we consider below, the planets also have significant orbital eccentricity. We therefore modify our Hill radius estimate by conservatively considering the perihelion star-planet separation [i.e., $(1-e)a_p$, in calculating the allowed satellite orbits. Similarly, a consideration of the Roche limit, $a_{Roche} = R_\star (2M_p/M_\star)^{1/3}$, where $R_\star$ and $M_\star$ are the satellite orbital radius and mass, respectively, provides a constraint on the inner radius of a viable satellite system, such that

$$\left(\frac{3M_p}{2\pi\rho_s}\right)^{1/3} < a_s < \frac{0.36(1-e_p)M_p}{M_\star} \left(\frac{M_\star}{3M_p}\right)^{1/3},$$

where $M_p$ is the planet mass, and $M_\star$ is the parent star’s mass. In other words, a moon can only survive if it is far enough from the planet that it is outside the satellite-planet Roche limit (which we subsequently label $a_{Roche}^{inner}$), is not entirely disrupted, and is close enough to the planet that it is within some fraction of the planet-star Hill radius (which we subsequently label $a_{Roche}^{outer}$). These limits are somewhat conservative, since the Roche limit is strictly true only for liquid or “rubble-like” objects, and solid objects can in principle survive closer in to the host planet. It is interesting to note that, given the observables $M_p$, $a_p$, $e_p$, and $M_\star$ (from stellar modeling), the only variable that remains to determine the range of $a_s$ is the satellite density $\rho_s$.

3. THE PLANET SAMPLE

The sample used here has been compiled from both the online catalog from the Geneva Extrasolar Planet Search Programmes \(^1\) and that of the Extrasolar Planets Encyclopaedia, \(^2\) both of which are themselves compilations of detections. We have extracted planet candidates (including multiple systems) with semimajor axes $>0.6$ (see above) and measured eccentricities. We have then compiled the planet orbital data with the parent-star masses estimated from stellar models, as cited in the online catalog. The final sample used here (at the time of writing) consists of 74 planets, 13 of which are known to be in multiple planet systems, whereby excluding these objects does not alter our conclusions.

For all planets we use the estimated $M \sin i$ as a direct surrogate for true mass, ignoring therefore any systematics that bias the sample toward low-inclination systems or the scatter introduced by the (presumed) random distribution of inclinations. Even allowing for a 50% ($i = 30^\circ$) underestimate of $M_p$, our conclusions are not significantly altered.

In Figure 1 we plot the number of systems with a given range of $a_p$: $a_{Roche}^{inner}$, which we refer to as the allowed satellite orbital radii or band, estimated from equation (1). We have assumed here a mean satellite density ($\rho_s$) of $3$ g cm$^{-3}$, commensurate with the upper-mid range of densities seen in the Galilean satellites (Io: $3.55$ g cm$^{-3}$; Europa: $3.04$ g cm$^{-3}$; Ganymede: $1.93$ g cm$^{-3}$; Callisto: $1.83$ g cm$^{-3}$).

For this sample the most frequently occurring band is $\sim 0.02$ AU, and $\sim 60\%$ of the giant planets have bands less than $0.04$ AU in width. For comparison we also indicate in Figure 1 the allowed bands for the Jovian and Saturnian systems: $0.122$ and $0.148$ AU, respectively. We also note that, for example, the Galilean moons actually occupy only the inner 10% of the allowed Jovian orbital terrain and that it is the irregular, smaller, satellites that occupy the outermost stable orbits. The narrowest allowed band in our sample is approximately $0.0088$ AU (for the planet HD 4350b, which has $M \sin i = 0.98M_\oplus$, $a_p = 1.77$ AU, and the highest eccentricity in our sample: $e = 0.78$).

These results should not be surprising, the exoplanet sample is strongly biased toward planets with semimajor axes smaller than

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\(^1\) At: http://obswww.unige.ch/~udry/planet/planet.html.

\(^2\) At: http://vo.obspm.fr/exoplanetes/encyclo/encycl.html.
those of the giant planets in our own solar system. It does raise the issue, however, of what the impact on moon populations is of a reduced total orbital terrain. We discuss this in § 7.

4. TIDAL HEATING, STELLAR INSOLATION, AND BOOSTED TEMPERATURES

We address three questions. First, what is the potential for the existence of Europa-analog moons in the current exoplanet sample, i.e., icy moons beyond the water sublimation line, which are tidally heated to levels commensurate with the presence of subsurface liquid oceans? Second, what is the present stellar insolation for hypothetical moons in this exoplanet sample, and what are the implications for the surface environments and retention of volatiles. Third, since we find that ~50% of the sample could harbor moons warmer than 170 K, but not in the liquid-water zone, we investigate the requirements for boosting temperatures through tidal heating to attain surface equilibrium temperatures $T_{eq} < 373$ K. For this latter issue we assume that the moons must be massive enough to retain a significant atmosphere.

4.1. Potential Tidal Heating

Here we consider in very simple terms the potential tidal heating for moons due to the smallest type of mean-motion orbital resonance. For a satellite or moon in a nonzero eccentricity orbit (maintained by orbital resonances with other moons, e.g., Io, Europa, and Ganymede, or via resonances with the host planet orbit; see § 8) the rate of tidal dissipation ($\dot{E}$), assuming Keplerian motion, synchronous rotation, and zero obliquity, can be written in terms of the surface heat flow ($H_T$),

$$
H_T = \frac{\dot{E}}{4\pi R_s^2} = \frac{21}{38} G^{5/2} \frac{\rho_s^2 R_s^5}{\mu Q} \varepsilon_s^2 \left( \frac{M_p}{a_s^3} \right)^{5/2},
$$

where $\mu$ is the satellite elastic rigidity (assumed uniform), $Q$ is the satellite specific dissipation function, $R_s$ the satellite radius, and $\varepsilon_s$ the satellite orbital eccentricity, which is assumed to be small (see, e.g., Peale et al. 1980). This can be rewritten in terms of the satellite mass $M_s$ as

$$
H_T = \frac{21}{38} \frac{G^{5/2}}{\mu Q} \left( \frac{3}{4\pi} \right)^{5/3} \varepsilon_s^2 \frac{\rho_s^{1/3}}{a_s^{1/2}} M_s^{5/3} M_p^{5/2}.
$$

For a given $H_T$ it is therefore possible to place a constraint on the maximum satellite orbital radius where such heating might occur, given the planet mass and the satellite mass, density, orbital eccentricity, and composition. In order to calibrate this relationship in a large potential parameter space, we first choose a specific question, namely, what is the potential extent of the zone around the planet candidates within which an icy, Europa-mass moon ($\sim 0.008 M_\oplus$) might be heated to levels commensurate to those estimated for Europa. These levels are therefore assumed to be reasonable for maintaining and/or generating subsurface liquid-water oceans.

We assume that such a moon has an orbital eccentricity commensurate with that of Europa $e \approx 0.01$, an icy composition and rigidity $\mu \approx 4 \times 10^{10}$ dyne cm$^{-2}$ (appropriate to ice at temperatures near 100 K; see Peale et al. 1980), and $Q \approx 100$, similar to that of solid materials on Earth. We note that the rigidity of a solid, silicate rock is a few times $10^{11}$ dyne cm$^{-2}$. If a rocklike rigidity were assumed, then the results presented in this section and those following would not be altered beyond factors of 1.4–4, due to lower values of $H_T$ for a given configuration. In no case would our conclusions be significantly altered. Given both the very considerable uncertainty in other factors and the varying values of $\mu$ used in the literature, we choose the lower, ice rigidity in what follows.

We further assume a density $\rho_s = 3$ g cm$^{-3}$. Estimates of the actual tidal dissipation in Europa are, of course, subject to significant uncertainty; nevertheless, surface heat flows of between $H_T \approx 300$ ergs s$^{-1}$ cm$^{-2}$ and $H_T \approx 50$ ergs s$^{-1}$ cm$^{-2}$ have been estimated in the literature (Cassen et al. 1979, 1980). Such flows are broadly consistent with the known system parameters and with the hypothesis of a tidally sustained subsurface liquid ocean. For comparison, on Io the surface heat flow due to tides is estimated to be $\sim 1500$ ergs s$^{-1}$ cm$^{-2}$.

The orbital radii at which such a moon would have to be located in order to experience tidal heating greater than or equal to $50-300$ ergs s$^{-1}$ cm$^{-2}$ is then estimated. The number of systems versus the difference between these radii and the innermost stable orbit ($a_s^{inner}$) is plotted in Figure 2. For the outer exoplanet sample it is clear that the physical orbital range for such a moon is commensurate with that of the Jovian system, despite the range of host planet masses, although in some cases it can be a factor 2 larger. In all cases the inner allowed orbit ($a_s^{inner}$) is less than 0.001 AU. Furthermore, in all systems these levels of tidal heating can be achieved for orbital radii well within the allowed maximum orbits of Figure 1. For a given surface heat flow the required satellite orbit $a_s \propto M_s^{2/9}$. Clearly, then, even an Earth-mass moon would reside only a factor ~3 times farther from the host planet (assuming all other parameters remain fixed) to attain the same levels of heating as assumed in Figure 2. Only a small fraction of the exoplanet sample used here (~3%) would not be able to retain such a moon in a stable orbit. In addition, as described in § 5, those systems are also the ones within stellar insolation zones that are likely unsuitable for icy covered moons with subsurface oceans. Thus, the reduced satellite orbital terrain in this exoplanet sample (compared to that of the Jovian systems) does not appear to limit the potential tidal heating required to sustain putative subsurface oceans on icy moons. Nor does it
force such moons to be heated to greater levels, which might result in the loss of volatiles (e.g., $\text{CO}_2$).

However, if the reduced stable satellite terrain results in a lower likelihood of the presence of large, icy moons, then it remains an open question whether the exoplanets in the sample are more or less likely to harbor tidally heated moons. We discuss some of these issues in more detail in § 7.

5. STELLAR INSOLATION AND MOON CONDITIONS

Hayashi (1981) introduced the idea of a planetary snow line in a protostellar protoplanetary disk as the distance from the system center at which the local disk gas temperature drops below 170 K, which is the characteristic, zero-pressure sublimation temperature for water ice. Icy moons must almost certainly form beyond this snow line in a protoplanetary disk system and beyond the local snow line within the circumplanetary disk of the forming host planet. The precise location of the planetary snow line in our own solar system is still unclear; indeed, it has been suggested that it may have been as small as $\sim 1$ AU for a dusty disk, compared to the often quoted distance of 4 AU (Sasselov & Lecar 2000).

However, a giant planet hosting formed or forming moons with significant icy mantles may migrate inward to a final orbit that passes within the planetary snow line, and/or the later main-sequence evolution of the parent star may result in the water sublimation line (so called to distinguish it from the snow line in a protoplanetary disk), eventually intersecting the planet/moon orbit. In this context it is appropriate to evaluate the present conditions experienced by potential moon systems around known exoplanets.

Specifically there are several classes of conditions that “water-rich” exomoons could experience, based on sublimation temperatures (170 K) and temperatures commensurate with liquid surface water at 1 atm pressure (273–373 K), which are typically considered representative of “habitable” conditions. These classes can be defined as:

1. An orbit, or incursions, within the vapor line, where stellar insolation would produce a mean surface temperature in excess of 373 K.

2. An orbit, or incursions, within a stellar insolation zone resulting in mean surface temperatures between 273 and 373 K, where for a massive moon retaining a significant atmosphere (Williams et al. 1997), liquid surface water could exist, or for a less massive moon, volatile loss would be rapid. We label this the “liquid-water” zone, rather than the circumstellar habitable zone.

3. An orbit, or incursions, within a stellar insolation zone resulting in mean surface temperatures between 170 and 273 K, where significant water ice sublimation will occur, with subsequent volatile loss for lower mass moons unable to retain an atmosphere.

4. An orbit, or incursions, within a stellar insolation zone resulting in mean surface temperature less than 170 K, where water-ice sublimation is significantly reduced.

By limiting our exoplanet sample to systems with $a_p \geq 0.6$ AU, we naturally avoid planets that spend substantial time within the inner vapor line (see below).

In order to make an initial estimate of the orbital radius at which stellar insolation produces a given surface temperature, we follow the classical prescription for estimating the equilibrium surface temperature of a fast-rotating body, namely,

$$ T_{\text{eq}} = \left( \frac{(1 - A_B)L_\star}{16\pi\sigma a^2} \right)^{1/4}, $$

where $A_B$ is the Bond albedo, $L_\star$ the parent stellar luminosity, and $a$ the distance from the parent star. The factor $\epsilon$ is a crude, first-order correction for the case in which an atmosphere is assumed (for zero atmosphere $\epsilon = 1$). It incorporates the infrared optical depth, and for a present-day Earth-type atmosphere $\epsilon \approx 0.62$ (e.g., McGuffie & Henderson-Sellers 2005). The fast-rotating approximation should be a fair one when applied to moons of giant planets aligned with the system orbital plane, since while they should have synchronous spin orbits (as is the case for the Galilean satellites), the combination of their orbital period with that of their host planet will typically result in rapidly changing and generally uniform insolation across the moon surfaces. For moon systems at significant inclination to the system plane there is the potential for much more static stellar insolation; we have not considered this situation but note that the slowly rotating $T_{\text{eq}}$ is only a factor of $\sqrt{2}$ larger than that for a rapidly rotating body.

We have also examined the potential eclipse, or shadowing, times of moons by the host planet, assuming all moon orbits lie in the planetary system plane. These range from $\sim 12\%$ to $\sim 0.1\%$ of the total moon orbital period, for close-in ($\alpha_{\text{inner}}$) and outer ($\alpha_{\text{outer}}$) moons, respectively. In the case of close-in moons (as defined by eq. [1]) the actual shadow time is typically $\sim 20$ minutes, compared to $\sim 5$ hr for the outermost allowed moons in the sample. We therefore ignore this effect in considering the first-order, long-term impact of stellar insolation on moon and satellite systems.

A major source of uncertainty is whether or not an atmosphere is included in the estimation of surface conditions. Since we are concerned here first with the potential vacuum sublimation of surface volatiles and the impact on moon characteristics, we assume zero-atmosphere conditions and set $\epsilon = 1$.

Stellar luminosities are compiled for our exoplanet sample from the online catalog and sources described in § 2. Where luminosities are not directly available we have estimated them using the reported optical magnitudes and distances. The total range is $0.29 < L_\star/L_\odot < 4.59$ with a mean of $1.66 L_\odot$. We then compute the orbital ranges for $T_{\text{eq}} < 170$ K, $170 < T_{\text{eq}} < 273$ K, $273 < T_{\text{eq}} < 373$ K, and $T_{\text{eq}} > 373$ K, assuming albedos of either $A_B = 0.68$, commensurate with that of Europa, or 0.3 commensurate with that of a mixed surface, such as Earth. As described above, we have not included the effect of an atmosphere on $T_{\text{eq}}$.

The orbital parameters ($a_p$, $e$, $P$) of the sample exoplanets are used to evaluate the amount of time each planet spends within a given zone and to evaluate time-averaged fluxes and temperatures. In both cases we are effectively assuming no time latency in reaching an equilibrium surface temperature as the stellar insolation varies.

The situation is summarized in Figures 3 and 4. In Figure 3 the number of systems spending a given fraction of their orbital period within the three inner zones is plotted for an assumed $A_B = 0.68$. For the zone with $170 < T_{\text{eq}} < 273$ K, exoplanets are not counted if they enter a zone with $T > 273$ K during any part of their orbit. In Figure 4 the number of systems as a function of time-averaged equilibrium temperature for objects with $A_B = 0.3$ and 0.68 are plotted.

With an assumed moon albedo $A_B = 0.68$ then 22 of the 74 sample planets spend time within the zone of $273 < T < 373$ K. Of these, two also spend time inside this zone, i.e., within the vapor line. Beyond this, approximately 53% of the systems never enter the liquid-water zone and remain with $T_{\text{eq}} < 273$ K.

For those planets passing into or through the liquid-water zone, there is a significant range in the amount of time actually
spent in this zone, or within the vapor line. Only one system spends its entire orbital period with the liquid-water zone (depending on assumed albedo), and many spend less than 30% of their orbit within this zone, with actual times varying from a few days to ~100 days. Of the systems, 73% spend some time in the outer sublimation zone (170 < $T_{eq}$ < 273 K), and 63% of those do not enter the liquid-water zone. Beyond these zones there are only 18 planets (24% of the sample) that always remain beyond their system sublimation lines.

In terms of time-averaged equilibrium temperatures, between 5% and 18% of systems (for albedos of 0.68 and 0.3, respectively) attain 273 < $T_{eq}$ < 373 K, and between 51% and 28% of systems remain at or below the sublimation temperature at all times (Fig. 4). The remaining 43% or 54% of systems have surface temperatures that place them in what might be best termed the sublimation zone (170 < $T_{eq}$ < 273 K)—a similar number to that determined from the simple zoning criteria above.

Allowing for atmospheres ($\epsilon < 1$) in equation (4) would shift all insolation zone radii outward (e.g., by a factor ~1.27 for $\epsilon = 0.62$). However, our primary purpose here is to evaluate the impact of insolation on the icy mantle of small moons, where atmospheres may be hard to retain. We do note, however, that for those systems that may remain within the liquid-water zone at all times or with an equivalent time-averaged temperature, one would expect that if an atmosphere can be retained by a moon, then substantial liquid surface water could potentially exist (Williams et al. 1997).

5.1. Sublimation Rates and Volatiles Loss

As described above, in vacuum the sublimation temperature for pure water ice is ~170 K, and this is the physical criterion used to define the sublimation line in a planetary system. A significant number of the exoplanets in our chosen sample spend between 10% and 100% of their orbital periods within this sublimation line but outside of the liquid-water line. To first order...
we can evaluate the effect of this on an icy mantle on associated moons by considering the upward sublimation rate of water ice at these temperatures. Following Spencer (1987), we plot in Figure 5 the rate of surface lowering due to sublimation for water ice as a function of temperature. The water vapor pressure over ice, following Spencer (1987), we plot in Figure 5 the rate of surface lowering due to sublimation for water ice as a function of temperature. The water vapor pressure over ice is estimated using the water vapor pressure over ice, following Spencer (1987).

![Figure 5](image)

**Fig. 5.**—Upward sublimation rate of water ice in vacuum as a function of temperature expressed in terms of the lowering of a surface in kilometers per $10^6$ yr. The rate is estimated using the water vapor pressure over ice, following Spencer (1987).

What is immediately apparent is that for $T > 170$ K sublimation—depending on local surface temperature variations (e.g., latitudinal variation on Galilean satellites; Spencer 1987). What is immediately apparent is that for $T_{eq} > 170$ K sublimation loss rates are extremely quick—with 100 km depth of water ice sublimating in only a few $10^6$ yr at 170 K—if there is no redeposition.

The escape velocity from the surface of a Europa-mass moon ($\sim 0.0082 M_\oplus$) is $\sim 2$ km s$^{-1}$, compared to a mean velocity of a water molecule in a gas at 170 K of $\sim 0.4$ km s$^{-1}$. Applying the thermal (Jeans) escape methodology (e.g., Lammer et al. 2004), the typical flux of escaping gas particles at these temperatures is at least a factor $10^4$ lower than that for gas in the exosphere of a large moon with 1000 K temperatures (e.g., similar to the Martian exosphere). Thus, thermal escape appears unlikely to be a dominant mechanism for material loss in cold moons beyond the sublimation line and even up to the ice line at 273 K. However, as Williams et al. (1997) describe, sputtering by charged particles trapped in the magnetosphere of the giant planet host is likely to be a highly efficient loss mechanism for moons—if they do not have protective magnetic fields. Williams et al. (1997) further suggest that moons of mass $<0.1 M_\oplus$ without magnetic fields, at any distance from the parent star, will have a hard time retaining an atmosphere for as long as a billion years.

Thus, it appears reasonable to speculate that small ($<0.1 M_\oplus$), icy moons that spend significant time within the sublimation line are likely to lose sublimated material and eventually all surface volatiles over relatively short timescales. The major caveat to this statement is that if a small moon with a host planet in such an orbital configuration has a strong magnetic field, it might retain a cold atmosphere of volatiles and their dissociated atomic species over longer timescales.

For our current sample of exoplanets and the zones occupied as described in § 5, between 49% and 72% of these systems are such that small moons are unlikely to have retained any surface water from an icy mantle—if they initially had one. Thus, we can reevaluate our estimate of the potential for small, tidally heated “Europa-like” moons to restrict ourselves to those beyond the sublimation line. As seen in § 5, this would result in some 28%–51% of our current sample of exoplanets being capable of harboring small, icy moons with the potential for tidally heated subsurface oceans. In terms of all currently known exoplanets (i.e., including those within 0.6 AU of their parent star) this corresponds to 15%–27% of the total population.

### 5.2. Tidally Boosted Temperatures

An intriguing possibility, raised by Reynolds et al. (1987), is that a combination of stellar insolation and tidal heating act to raise the surface temperature of a moon to within the classically habitable range. The range of stellar insolation seen around the above sample of exoplanets is also motivation for examining this possibility, since many planets are only just beyond the liquid-water zone of their parent stars. To examine this possibility we make a very naive assumption, that the equilibrium temperature of an object’s surface—where we define the surface as some ad hoc layer of outer material—is that of a pure blackbody receiving both an input radiation flux and an input flux from tidal heating. This condition can be written as a form of a zero-order energy-balance equation,

$$
\epsilon \sigma T_{eq}^4 = \frac{1}{4} A_B f_{rad} + H_T,
$$

where $f_{rad}$ and $H_T$ are the stellar flux and tidal surface heat flow, respectively. An implicit assumption is that the tidal surface heat flow (which is really just the net rate of tidal energy dissipation divided by the moon surface area) acts exactly like a radiation field. In other words, the energy flux is assumed to be entirely thermalized by the object’s surface. This is extremely crude by comparison with Reynolds et al. (1987), who employed a radiative-convective equilibrium code to examine the impact of tidal heating on a hypothetical object similar to Titan (i.e., with a thick atmosphere). However, the differential adjustment to $T_{eq}$ as $f_{rad}$ is varied is quite similar (within an order of magnitude) between the more sophisticated model with an atmosphere and our simplistic model, where a “greenhouse” atmosphere is incorporated via the atmospheric infrared transparency factor $\epsilon$ in equation (5). We note as well that neither model allows for nonthermal energy dissipation—e.g., the tidally surface energy flow could equally power the bulk rearrangement of an object’s surface. We therefore use the above argument to illustrate in the broadest terms the potential for tidal boosting.

In Figure 6 we present some of the constraints and potential environments discussed here in terms of the parameters $M_*$ and $a_p$, the satellite or moon mass, and the distance from the parent star, respectively. Major limits on $M_*$ and $a_p$ are indicated by shaded regions. The approximate minimum mass for retention of an atmosphere is indicated at $M_* = 0.1 M_\odot$ (e.g., Williams et al. 1997). The limiting orbital semimajor axis below which moons will be tidally stripped on relatively short timescales is also indicated at $a_p = 0.6$ AU (e.g., Barnes & O’Brien 2002). Immediately beyond this line is the ice line ($T_{eq} = 273$ K) for an assumed 1 $M_\oplus$ parent star, an albedo $A_B = 0.68$, and $\epsilon = 0.62$, which occurs at 0.75 AU. The related vapor and sublimation lines are also plotted. We also plot a hypothetical upper mass limit based on the minimum mass subnebula postulated for the Jovian system (Canup & Ward 2002). The subnebula has been estimated at $\sim 2\%$ of the final mass of Jupiter, or $\sim 6$ $M_\oplus$, and we
therefore treat this as a zero-order estimate of the maximum possible mass for a single moon.

Given the expression for tidal heating in equation (3), we can substitute for \( a_i \) by either the minimum allowed satellite orbital radius (\( a_{\text{inner}} \)) or the outer one (\( a_{\text{outer}} \)). In both cases the host planet mass \( M_p \) cancels out, and we can rearrange for \( M_s \), namely,

\[
M_s^{\text{inner}} = \left( \frac{38}{21} \right)^{3/5} \left( \frac{6}{\pi} \right)^{1/2} (\mu Q)^{3/5} \left( \frac{H_T}{\varepsilon_s^2 \rho_s^{1/3}} \right)^{17/6}.
\]

(6)

where we have assumed \( \mu Q = 4 \times 10^{12} \text{ dyne cm}^{-2} \) in what follows. Similarly for the outer allowed satellite orbital radius, we obtain:

\[
M_s^{\text{outer}} = \left( \frac{38}{21} \right)^{3/5} \left( \frac{4\pi (\mu Q)^{3/5}}{3} \right)^{2/3} \left( \frac{H_T}{\varepsilon_s^2 \rho_s^{1/3}} \right)^{1/3} (3M_p^{2/3})^{1/2}.
\]

(7)

\( M_s^{\text{inner}} \) and \( M_s^{\text{outer}} \) are therefore the required moon masses at the inner and outer allowed orbital radii to generate a given \( H_T \), assuming all other parameters are fixed. It is immediately apparent that \( M_s^{\text{inner}} \) will be small for most interesting choices of parameters. Equation (7) can also be scaled for moons at arbitrary radii within the outer allowed orbital radius. Three sets of curves are plotted in Figure 6 (dashed and solid lines), corresponding to loci of constant \( T_{\text{eq}} \) (373 and 273 K, respectively) for moons at radii 0.1(\( a_{\text{inner}} \)) including the effects of stellar insolation according to equation (5) and \( A_{0} = 0.68, \epsilon = 0.62 \). This orbital radius scaling is chosen to correspond with the approximate relative location of the Galilean satellites in the Jovian system (Fig. 1). As described above, we choose \( \rho_s = 3 \text{ g cm}^{-3} \) and (left to right) increasing values of moon eccentricity: \( e_s = 0.001, 0.01, \) and 0.1. Zero eccentricity, \( e_s = 0 \), is assumed for the planet. The

\section{6. TIDAL BOOSTING AND KNOWN EXOPLANET SYSTEMS}

The outer stable orbit (eq. [1]) provides a natural scaling for a moon system architecture. A given hypothetical moon must have a semimajor axis of \( \beta a_{\text{outer}}^{\text{inner}} \) (assuming small eccentricities), where \( \beta \leq 1 \) and \( \beta a_{\text{outer}}^{\text{inner}} \geq a_{\text{inner}}^{\text{inner}} \). We can also write this in terms of tidal heat flow:

\[
\beta a_{\text{outer}}^{\text{inner}} = \left( \frac{21}{38} \right)^{2/15} \left( \frac{3}{4\pi} \right)^{2/9} \frac{G^{1/3}}{(\mu Q)^{2/15}} \left( \frac{\varepsilon_s^2 \rho_s^{1/3} (3M_p^{2/3})^{1/2}}{H_T} \right)^{2/15}.
\]

(8)

Thus, for a given exoplanet in the sample used here we can estimate the time-averaged \( H_T \) required to attain a given \( T_{\text{eq}} \) (eq. [5]), and for an assumed set of moon properties, such as mass, orbital eccentricity, density, rigidity, dissipation, and atmosphere, we can then evaluate the required orbital radius of the moon \( \beta a_{\text{outer}}^{\text{inner}} \).

We have applied this calculation to the subset of known exoplanets considered above. Figure 7 summarizes the results for regions between the pairs of curves for a given \( e_s \), therefore represent the temperate (habitable) zone produced by the combination of stellar insolation and tidal heating—which clearly extends this zone to greater distances (by as much as a factor \( 2 \)) in planet-star radius for an Earth-mass moon with \( e_s = 0.01 \) from the parent star than the classical, stellar insolation zone alone.

However, in addition to the major caveat that the energy balance represented by equation (5) is extremely approximate, it should be noted that the actual levels of tidal heating required in these zones can be as high as \( \sim 10^6 \text{ ergs s}^{-1} \text{ cm}^{-2} \)—which is a factor \( \sim 10^1 \) larger than the surface heat flow estimated for Io. It is an interesting question whether or not levels this high would create such an unstable surface environment that habitability would be compromised. More modest heating levels are required to boost temperatures that are already close to temperate.
the example of a 0.1 $M_\oplus$ moon (the minimum mass moon likely capable of retaining a terrestrial type atmosphere) with an orbital eccentricity of $e_s = 0.01$, density $\rho_s = 3$ g cm$^{-3}$, and albedo, rigidity, and dissipation commensurate with that estimated for Europa. We have assumed an atmosphere with $\epsilon = 0.62$. To attain a moon surface temperature $T_{\text{eq}} = 273$ K, then (as described above) 46 of the exoplanets would require a moon to have $H_T > 0$ to boost the stellar insolation; for $T_{\text{eq}} = 373$ K, 70 of the exoplanets would require a moon to have $H_T > 0$. In Figure 7 we plot the distribution of both the absolute orbital semimajor axis required for such moons and the ratio of this orbital axis to the inner ($a_s^{\text{inner}}$) stable orbital semimajor axis. The latter plot confirms that such moons would reside comfortably outside of the inner Roche limit.

For the range of habitable surface temperatures the required orbital range is ~0.002–0.007 AU, corresponding to ~4–10 times the innermost stable orbital radius. Since $a_s^{\text{outer}}$ only scales as $M_s^{2/3}$, a larger moon of mass 1 $M_\oplus$ would shift these ranges outward by approximately 67%. In either case, the relevant orbital terrain is very similar in absolute terms to that occupied by the Galilean moons (as explicitly indicated in Fig. 7) and does not therefore raise any immediate concerns that this would be an unusual configuration for a giant planet.

The tidal surface heat flow $H_T$ required in Figure 7 ranges from $\sim 10^3$ to $10^5$ ergs s$^{-1}$ cm$^{-2}$, compared to (for example) the $1.5 \times 10^3$ ergs s$^{-1}$ cm$^{-2}$ estimated for Io. In Figure 8 the distribution of total energy dissipation rates for the case of 0.1 $M_\oplus$, $e_s = 0.01$ and $T_{\text{eq}} = 273$ K is shown, and it ranges from $\sim 10^{21}$ to $10^{23}$ ergs s$^{-1}$. By comparison, for Io the total dissipation rate is $\sim 6 \times 10^{20}$ ergs s$^{-1}$. These levels of energy dissipation for the boosted moons therefore raise a number of questions. First, very basic order-of-magnitude energy estimates suggest that dissipation at a level of $10^{23}$ ergs s$^{-1}$ may not provide enough longevity to be of interest for habitability. The total energy of a planet-moon system consisting of a Jupiter mass planet and a 0.1 $M_\oplus$ moon with 0.003 AU orbital semimajor axis is dominated by the rotational energy of the giant planet. In the case of Jupiter this total energy is at least $10^{40}$ ergs, modulo uncertainties in internal rotation and composition. This energy could be dissipated completely in $\sim 3$ Gyr at a rate of $10^{23}$ ergs s$^{-1}$—assuming tidal heating was sustained at this level—whereas in reality the moon might well move out of the assumed mean-motion resonance on a shorter timescale. It is also not yet known whether Jupiter’s apparently fast rotation rate is actually typical for giant planets—others may spin much more slowly. For the lower end of dissipation energies the maximum lifetime could be 1 or 2 orders of magnitude larger, although the issue remains that the mean-motion resonances may not last that long and indeed may come and go over a moons lifetime. Second, as discussed in the previous section, it is unclear exactly how these levels of tidal heating would manifest themselves in terms of surface environment. For a liquid-ocean-dominated moon, the bulk motions would be considerable. For a moon where tidal heating results in significant tectonic and volcanic activity, the surface environment might be rendered less hospitable as a result.

7. SATELLITE FORMATION AND ORBITAL TERRAIN

We discuss briefly the relationship of surviving moon or satellite systems to the formation and early history of a given planetary system in general. There is currently no clear consensus on the precise formation mechanisms for satellites of giant planets—even if it is essentially very different from the mechanism likely responsible for producing the Earth-Moon system (Peale 1999). The standard model (e.g., see the review by Pollack et al. 1991) for the Galilean satellites follows an analog to the core-accretion model for giant planets but invokes a minimum mass sub-nebula—where the total observed mass in circumplanetary solid material is added to sufficient gas to match solar element abundances. However, dynamical timescales in satellite systems are much shorter than their planetary analogs, and it is not clear that such a model can succeed in reproducing the known Galilean satellites and their often icy compositions. Alternatives include the model of Canup & Ward (2002), which invokes a gas-starved circumplanetary accretion disk in which satellites form late relative to the growth of the giant planet (specifically Jupiter). In both scenarios the migration of satellites within the circumplanetary disk can proceed much as it does for the planets themselves.

Based on the above results, while we have shown that the orbital terrain suitable for significant tidal heating due to planet-moon interaction in the existing exoplanet sample is physically comparable to that in the Jovian system, the actual total stable satellite orbital terrain is typically much smaller, by a factor $\sim 5$–6. This raises the question: does this reduced terrain also reduce the number of potential satellites/moons and therefore reduce the net likelihood of tidally heated moons?

As already noted (Fig. 1), the actual occupancy of the stable satellite orbital terrain in the Jovian system is small for the Galilean satellites, which span only the inner $\sim 10\%$ of the total allowed range. The lesser satellites, which are a factor 10–100 smaller in radius, do however occupy the terrain out to $a_s^{\text{outer}}$.

However, the bigger issue is whether an analogous system of large moons could form around a planet with, for example, a total stable orbital terrain some $\sim 16\%$–20% of the Jovian range. In order to answer this question we need to know (among other factors) whether or not a planet has undergone significant migration toward the parent star, thereby reducing the stable satellite terrain, and how the timing of such a migration compares to the formation time of a satellite system. Two basic, and undoubtedly simplistic, scenarios can be considered that more or less bracket the range of possible models. In the first the satellite system of a giant planet forms essentially contemporaneously with the planet and, in the case of a migrating planet, during the period of either type I or II migration. In the second the satellite system forms “late” in a largely gas-free environment due to N-body accretion (e.g., Canup & Ward 2000) and at a time when the host planet has ceased migration. In the first scenario,
although the planet-star Hill sphere radius shrinks as the planet migrates inward, the circumplanetary disk continues to receive inflowing material (e.g., Lubow et al. 1999)—thus, forming satellites can continue to accrete material even if the stable orbital terrain is shrinking. In the second scenario the formation of satellites is potentially constrained by the amount of material retained according to the Hill sphere criterion (e.g., eq. [1]). If the first scenario occurs, we can argue that a reduced final stable orbital terrain compared to, for example, the Jovian system, does not necessarily reduce the likelihood of the formation of an equivalent number of large moons. In this case then, it will be correct to state that there is at least an equal potential for tidally heated moon systems in the current exoplanet sample compared to the Jovian system—as summarized by Figure 2. This is also clearly dependent on the actual subnebula mass, which we have assumed scales with the final host-planet mass. However, in the second scenario it may well be the case that fewer moons can be formed, in which case certain exoplanets may represent a more barren terrain for significant moons, heated or otherwise. It should be noted that a third scenario exists, which is that moons are captured bodies that did not participate in the evolution of the subnebula.

The issue of moon composition, in particular the presence of an icy mantle, has been briefly described in § 5.1. In addition to issues of sublimation rates, a full treatment would necessarily include discussion of the chemical/elemental structure of the protoplanetary nebula, and subnebula. The distribution of water in protoplanetary systems is clearly relevant in this case.

8. SUMMARY AND DISCUSSION

We present an initial investigation of the potential for and possible scenarios of moons around giant exoplanets that are subject to tidal heating and may therefore provide a distinct class of habitable environment beyond that of the classical “habitable zone.” For the majority of $a_p > 0.6$ AU planetary systems discovered thus far, we make a clear prediction that any associated, long-lived satellite systems will occupy a significantly narrower range of orbital semimajor axes than the examples of the Jovian or Saturnian systems. Despite this finding, the potential for tidal heating to levels sufficient to sustain subsurface liquid-water oceans does not appear to be impacted, even for Earth-sized moons—if the formation pathways to large moons is not effected by the narrower stable orbital terrain.

We have also explored the zonal and time-averaged stellar insolation that hypothetical moon systems around known exoplanets might experience. In many cases it seems likely that if ice shrouded moons had at some time existed around these planets, then sublimation processes will have likely removed this material. For small moons the volatiles will have been lost; for moons more massive than some 0.1 $M_\oplus$ (Williams et al. 1997) an atmosphere may have been retained. Between 28% and 51% of the exoplanet systems studied here are expected to be capable of harboring small moons with intact icy mantles. This translates to between 15% and 27% of the total population of known exoplanets at this time.

We consider the possibility of a combination of stellar insolation and tidal “boosting” raising the surface temperature of a moon into the temperate range ($273 < T_{eq} < 373$ K). A very general set of constraints is presented, demonstrating how this can lead to an extended temperate, or habitable, zone of as much as a factor $\sim 2$ greater distance from the parent star for massive ($\sim 1 M_\oplus$) moons. We also find that the relevant orbital terrain around the known exoplanets for tidally boosted, temperate, massive moons is essentially the same as that of the Galilean satellites in the Jovian system. However, the required tidal heating energy budgets range from the level seen in Io to as much as 100 times greater. At this upper extreme it is not clear whether such dissipation could be either long lived (more than a few 100 million yr) or compatible with a habitable surface environment.

We have ignored a multitude of possible additional factors in making our estimates—for example, there are likely significant resonance conditions that may occur for moons orbiting planets that are themselves in eccentric orbits about the parent star, and there are also likely influences from other, as yet undetected, planets in the system. We have also not considered resonances beyond simple orbital mean motions—for example, spin-orbit librational resonances, such as is likely in the case of Enceladus (Wisdom 2004). Such effects are interesting and should be explored further. We have also not included any estimate of the likelihood that moons will enter into resonance conditions that will drive orbital eccentricity and hence moon-planet tidal dissipation—or of the dynamical timescales of such situations. This will require a more extensive study, which should include modeling of the origin of a satellite or moon system and the potential orbital migration of major satellites within such a system. Such a study should also include an evaluation of any variation in the composition and structural properties of the satellites resulting from different circumstellar/circumplanetary formation distances.

However, taken at face value, one of the implications of the above observations is that the potential for subsurface oceans in icy moons, or even ocean moons (for those systems that lie close enough to the parent star for significant surface temperatures to develop, boosted by tidal dissipation) suggests that broad questions of habitability may need to be revisited to include such environments as significant potential biospheres. As the parameter space for exoplanet detection expands to include lower mass, larger orbital-radii systems, and if future missions and instruments begin to detect the presence of moons around giant planets, we will be able to extend the evaluation of such potential habitats.

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REFERENCES

Barnes, J. W., & Fortney, J. J. 2004, ApJ, 616, 1193
Barnes, J. W., & O’Brien, D. P. 2002, ApJ, 575, 1087
Burns, J. A. 1986, IAU Colloq. 77, Satellites, ed. J. A. Burns & M. S. Matthews (Tucson: Univ. Arizona Press), 117
Canup, R. M., & Ward, W. R. 2000, BAAS, 32, 5501
Burns, J. A. 1986, IAU Colloq. 77, Satellites, ed. J. A. Burns & M. S. Matthews (Tucson: Univ. Arizona Press), 117
Canup, R. M., & Ward, W. R. 2000, BAAS, 32, 5501
Cassen, P., Peale, S. J., & Reynolds, R. T. 1980, Geophys. Res. Lett., 7, 987
Cassen, P., Reynolds, R. T., & Peale, S. J. 1979, Geophys. Res. Lett., 6, 731
Burns, J. A. 1986, IAU Colloq. 77, Satellites, ed. J. A. Burns & M. S. Matthews (Tucson: Univ. Arizona Press), 117
Canup, R. M., & Ward, W. R. 2000, BAAS, 32, 5501
Cassen, P., Peale, S. J., & Reynolds, R. T. 1980, Geophys. Res. Lett., 7, 987
Cassen, P., Reynolds, R. T., & Peale, S. J. 1979, Geophys. Res. Lett., 6, 731
Doyle, L. R., & Deeg, H. J. 2003, in IAU Symp. 213, Bioastronomy 2002: Life among the Stars, ed. R. Norris & F. H. Stootman (San Francisco: ASP), 80
Ehrenreich, D., Tinetti, G., Lecavelier Des Etangs, A., Vidal-Madjar, A., & Selvis, F. 2006, A&A, 448, 379
Gladman, B., Dones, L., Levison, H., Burns, J., & Gallant, J. 2006, Lunar Planet. Sci. Conf., 37, 2165
Hayashi, C. 1981, Prog. Theor. Phys. Suppl., 70, 35
Holman, M. J., & Wiepert, P. A. 1999, AJ, 117, 621
Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Bauer, S. J., & Weiss, W. W. 2004, Stellar Structure and Habitable Planet Finding (ESA SP-538; Noordwijk: ESA), 339
Lubow, S. H., Seibert, M., & Artymowicz, P. 1999, ApJ, 526, 1001
McGuffie, K., & Henderson-Sellers, A. 2005, A Climate Modelling Primer (New York: Wiley)
Melosh, H. J., Ekholm, A. G., Showman, A. P., & Lorenz, R. D. 2003, Icarus, 168, 498
Peale, S. J. 1999, ARA&A, 37, 533
Peale, S. J., Cassen, P., & Reynolds, R. T. 1980, Icarus, 43, 65
Pollack, J. B., Lunine, J. I., & Tittenmore, W. C. 1991, Uranus (Tucson: Univ. Arizona Press), 469
Porco, C. C., et al. 2006, Science, 311, 1393
Reynolds, R. T., McKay, C. P., & Kasting, J. F. 1987, Adv. Space Res., 7, 125
Sartoretti, P., & Schneider, J. 1999, A&AS, 134, 553
Sasselov, D. D., & Lecar, M. 2000, ApJ, 528, 995
Spencer, J. R. 1987, Icarus, 69, 297
Ward, W. R., & Reid, M. J. 1973, MNRAS, 164, 21
Williams, D. M., Kasting, J. F., & Wade, R. A. 1997, Nature, 385, 234
Wisdom, J. 2004, AJ, 128, 484