Habitable Moons: *A New Frontier for Exobiology* *By Andrew J. LePage*

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The surface of habitable moons have served as a common setting for many science fiction stories. Until recently, conventional wisdom seemed to indicate that such places would be rare to nonexistent. Recent theories of planet formation dictated that the habitable zones around Sun-like stars would be populated by terrestrial planets such as Venus, the Earth, and Mars (1) whose natural satellites, if any, would usually be of asteroidal proportions. Only an unusual collision between the proto-Earth and a Mars-sized protoplanet is now believed by some scientists to cause the formation of our disproportionally large Moon (2). Unfortunately, this manner of formation has left the Moon totally depleted of most of the volatile compounds essential for life. Combined with its low mass, which does not permit it to retain an appreciable atmosphere, our sole natural satellite is a sterile rock despite its prime location in our solar system's habitable zone (HZ). Limited to such a formation scenario, the possibility that an unlikely collision could produce a still larger moon circling a terrestrial planet that just happens to be forming within another solar system's HZ and still somehow retains an adequate supply of volatiles seemed incredibly remote.

The recent flurry of brown dwarf and extrasolar giant planet discoveries add an additional twist to the limited view of the previously held conventional wisdom. These bodies have been found within a few AU of a few percent of the solar systems of nearby sun-like stars and several have now been located near and even inside the HZs of these systems, as shown in Figure 1. While these substellar companions are unlikely to harbor any sort of life as we know it, their moons may turn out to be habitable. If the sizes of the moons of these extrasolar companions scales with planet mass, one expects some of these moons to attain sizes similar to that of Mars or even the Earth.

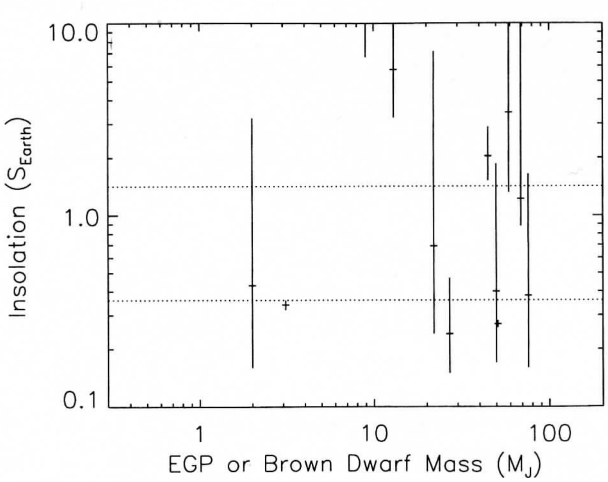

Figure 1: *This diagram shows the mass and insolation ranges of the EGPs and brown dwarfs that have been found to date near various stars Habitable Zones (HZ). The horizontal axis is the companion's probable mass (given since only the Msini values are known) and the vertical axis gives the insolation in terms of Earth units. Each vertical line gives the range of insolation values a companion experiences as it orbits its sun with the center tick giving its mean distance. From left to right they correspond to the companions orbiting 16 Cygni B, 47 Ursae Majoris, 70 Virginis, HD114762, BD+52 1650, BD-4 782, BD-9 3595, BD-25 1168, HD 29587, HD 140913, BD-14 3093, and BD-5 5804. The two dotted horizontal lines give the limits of one of the more liberal definitions of an HZ. In our solar system, this HZ would range from 0.84 to 1.67 AU.*

What's in a Name?

This spirit of discoveries challenges previous views of planet formation. Earlier theories of planet formation indicated that planets of Jovian proportions only form at a distance of 5 AU or greater from sun-like stars (1). Only at these great distances do ices condense so that they begin to serve as building blocks for giant protoplanetary cores. After these cores have grown to several Earth masses, they begin to obtain gas directly from the circumstellar disk surrounding a forming star and begin runaway growth until they reach sizes of tens to hundreds of $M_\oplus$. The discovery of epistellar planets (also known as "hot-Jupiters") and eccentric planets which can be found as close as 0.05 AU from their suns was totally unexpected based on this long held theory of planet formation. While the origin of these bodies is hotly debated, it now appears that planets ranging from Jovian to super-Jovian sizes, and their proportionally larger retinue of natural satellites, can be found in or near the HZs of a fair number of Sun-like stars.

Unlike planets, brown dwarfs are believed to form like stars by the direct collapse of a fragmenting cloud of gas. They differ from true stars only in that they do not possess enough mass to sustain the fusion of hydrogen in their cores. As a result, they do not radiate appreciable amounts of energy after their initial formation (3). However, like their heavier stellar siblings, they tend to form along with other stars in multiple star systems and it would not be unexpected to occasionally find one in the HZ of a Sun-like primary. Furthermore, like their smaller Jovian cousins, they are likely to be surrounded by a family of large natural satellites.

In addition to challenging our theories of planet and solar system formation, the discovery of these bodies causes some confusion over nomenclature. The dividing line between planets and brown dwarfs is quite fuzzy at this time and reflects our ignorance of the fine details of substellar companion formation. The more massive substellar companions discovered to date are almost certainly brown dwarfs in the classical sense. The less massive substellar companions with masses similar to Jupiter's that have been found in nearly circular orbits are more than likely planets despite their previously unexpected locations. The most hotly contested portion of parameter space is occupied by what Geoff Marcy and Paul Butler refer to as eccentric planets (4). These bodies have masses that range from less than a couple to possibly as high as a dozen $M_♃$ and therefore might be considered exceptionally large Jovian planets. Their orbits, on the other hand, are more eccentric than is normally expected for a planet formed by a dissapative process like accretion, but their eccentricities are in line with those expected for brown dwarfs. While the high masses of the first eccentric planets discovered led many astronomers to believe this class of planet marks the tail end of the brown dwarf mass spectrum (5), the recent discovery of an eccentric planet orbiting 16 Cygni B with a probable mass of only about 2 $M_♃$ has permanently complicated the situation for theoreticians (6).

With this confusion over the proper nomenclature for some of these substellar companions, additional confusion arises over the proper designation of any bodies that may orbit them. Small bodies circling planets found in our solar system are properly called "natural satellites" but are also colloquially referred to as "moons."

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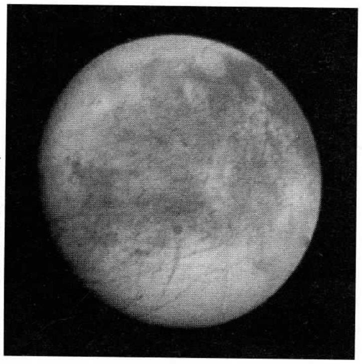

Figure 2: *The Jovian moon Europa is currently thought to possess an ocean tens of kilometers deep beneath its icy veneer. If there is enough heat generated in its interior from tidal flexing, this moon could support life near any hot springs that may develop. While this moon might support oases where life could thrive, it is not considered to be a habitable moon.*

This designation seems appropriate for the satellites of extrasolar planets of Jovian proportions found to date. Even though they do not shine by their own light, brown dwarfs form by the same process as stars. Consequently, perhaps the proper designation for any small bodies that circle them should be "planets." One cannot even begin to guess about the proper appellation that should be applied to the small bodies that may circle the "eccentric planets" discovered by Butler and Marcy at least until their status is clarified. In order to side step this battle over semantics in this article, I consistently refer to substellar companions less massive than roughly 12 $M_{♃}$ as extrasolar giant planets (EGP) and more massive bodies as brown dwarfs. The smaller bodies that orbit these substellar companions shall be referred to collectively as "moons" regardless of their primary's proper classification.

Location, Location, Location!

One of the first questions to tackle is what is meant by a habitable body. With the discovery of possible fossils in the Martian meteorite ALH84001 (7) and additional lines of evidence, it is believed by some that life was and may still be present today below the Martian surface or in limited oases on the surface. There is also speculation that life may exist in an ocean that is theorized to reside below the ice covered surface of the Jovian moon Europa shown in Figure 2 (8). Neither one of these bodies, however, is generally considered to be habitable by those interested in SETI. In general terms, a habitable body is one whose surface is not only capable of supporting life, but also offers conditions such that these life forms eventually evolve into higher forms as has happened here on Earth. In order for this to occur, the surface temperatures of a habitable body must be such that liquid water can permanently exist over most if not all of its surface.

A necessary condition for habitability is that the body must reside in a star's habitable zone (HZ). Many definitions of this exist but based on detailed models, the HZ of the Sun is now conservatively estimated to span from 0.95 to 1.37 AU (9). The actual inner edge of the HZ may lie as close as 0.84 AU where a runaway greenhouse effect occurs, thus transforming a planet into a Venus-like hell. The outer edge lies as far out as 1.67 AU. At that distance, the addition of more carbon dioxide (believed to be the primary greenhouse gas of a mature planetary body) to an atmosphere will not increase the surface temperature due to the opacity of such an increasingly dense atmosphere. While these models assume that the only important greenhouse gases are carbon dioxide and water vapor, other gases such as methane may play an important role early in the atmospheric evolution of a planet or moon. Such a geologically short-lived enhancement in the greenhouse effect early in a planet's history helps explain the evidence of marginally habitable conditions on Mars even though it lies at the edge of our Sun's current HZ (10).

As an added complication, the location of the HZ slowly moves outward as a solar system's sun ages. This is the result of the star's luminosity increasing with time which, according to existing stellar models, is a natural consequence of stellar evolution. As a result, a star's HZ is not static and bodies can move into or out of the HZ over the course of the star's main sequence lifetime. There is some question as to whether it is possible for a cold body initially beyond the HZ to thaw out and become habitable (9). If this is not possible, the initial outer edge of the HZ stays fixed with time and the inner edge, inside of which a body experiences a runaway greenhouse effect, moves outward with time. The region outlined by these boundaries is referred to as the Continuously Habitable Zone (CHZ). Its proportions vary with time and, depending on the rate of stellar evolution, it can disappear completely in just a few billion years. If this view proves accurate, habitable planets are more common around younger stars.

How to Hold an Atmosphere

While being located in a star's HZ is a necessary condition for habitability, it is not a sufficient one as we can see in the case of the Moon. The Moon, with a mass of 0.012 $M_{\oplus}$, does not have enough mass to retain an appreciable atmosphere. So the first criterion for a habitable moon that will be examined is the minimum mass needed to retain an atmosphere. One of the important atmospheric loss processes is thermal or Jean's escape. With this escape mechanism, a gas molecule in the upper atmosphere that moves faster than the moon's or planet's escape velocity will permanently leave that body. Assuming a moon with a Mars-like density (i.e. 3.94 grams per cubic centimeter) has a 1,000 kilometer high exobase with a temperature of 2000 K (as is typical for the Earth during solar maximum), it could retain an appreciable fraction of its atmospheric nitrogen and oxygen for 4.5 billion years if it has a mass greater than 0.07 $M_{\oplus}$ (11). Oxygen loss might not prove fatal to a moon's biosphere if a replacement mechanism is available. On Earth, photosynthesis acts as a means of replacing any lost oxygen since is converts plentiful water into oxygen.

Unlike oxygen loss, nitrogen loss seems to be irreversible. Unfortunately there is another nonthermal loss mechanism that can decrease a moon's nitrogen allotment known as dissossociative recombination (12). In this mechanism, positively charged molecular nitrogen combines with a free electron to form two atoms of nitrogen. The kick these atoms receive during this process is enough to increase the now-neutral atomic nitrogen to velocities high enough to escape a large body. On Mars, with a mass of 0.11 $M_{\oplus}$, nitrogen is lost at the rate of 5×10^{9} atoms per square meter per second by dissossociative recombination (13). Scaling this loss rate to a nitrogen dominated atmosphere only 1 AU from the Sun results in a loss rate of about 4×10^{11} atoms per square meter per second. An Earth-like planet loses only 17% of its nitrogen over the course of 4.5 billion years. This nonthermal loss mechanism is estimated to become negligible for a moon with a mass greater than 0.12 $M_{\oplus}$ (11).

Another nonthermal process that is potentially a greater threat to any moon's atmosphere is sputtering. In this process high energy charged particles collide with a molecule and the resulting rebound kicks the molecule clear of the moon. On Mars, the solar wind striking the upper atmosphere sputters carbon dioxide and oxygen at a rate of about 2×10^{10} molecules per square meter per second (14). Inside the magnetosphere of a Jovian planet, the charged particle flux is up to three orders of magnitude higher. Under such conditions, an Earth-like planet loses all of its nitrogen in only half a billion years (11).

One way to curb this loss rate is having a strong magnetic field to act as a shield. The Galileo spacecraft, presently in orbit around Jupiter, has detected a magnetosphere around the largest Jovian moon Ganymede (shown in Figure 3) which has a mass of about 0.025 $M_\oplus$ (15). The Hubble Space Telescope has also detected tentative evidence of aurora in the thin atmosphere of Ganymede again hinting that the shielding powers of a magnetosphere are present (16). The situation with another Jovian moon, Io with a mass of 0.015 $M_\oplus$, is a bit more ambiguous but still promising. A large core, possibly composed of iron, has already been detected (17) and there are indications that this moon also has its own magnetic field (18). Additional study of the data in hand is necessary to disentangle the effects of plasma flowing past Io on the magnetic environment so that the actual strength of Io's magnetic field can be determined (19). In any case, it seems likely that massive moons could possess a magnetic field with sufficient magnitude to shield their atmospheres from the eroding effects of the powerful radiation environments that probably exist around other substellar companions.

One other loss mechanism that may have to be taken into account is impact erosion. In this mode of atmospheric loss, highly energetic cratering events that form large impact basins literally blast away significant portions of a small body's atmosphere. One proposed example of this loss process is the planet Mars which has only a trace of its original atmosphere today (20). The Saturnian moon Titan, with a mass of 0.022 $M_\oplus$, was probably able to retain its atmosphere despite its diminutive size because of the lower relative velocities of impactors at Saturn's orbit. There are a number of parameters, some of which may currently be unknown or unrecognized, that may affect the importance of this process on habitability. As a result, habitability presently can not be ruled out by this loss mechanism alone.

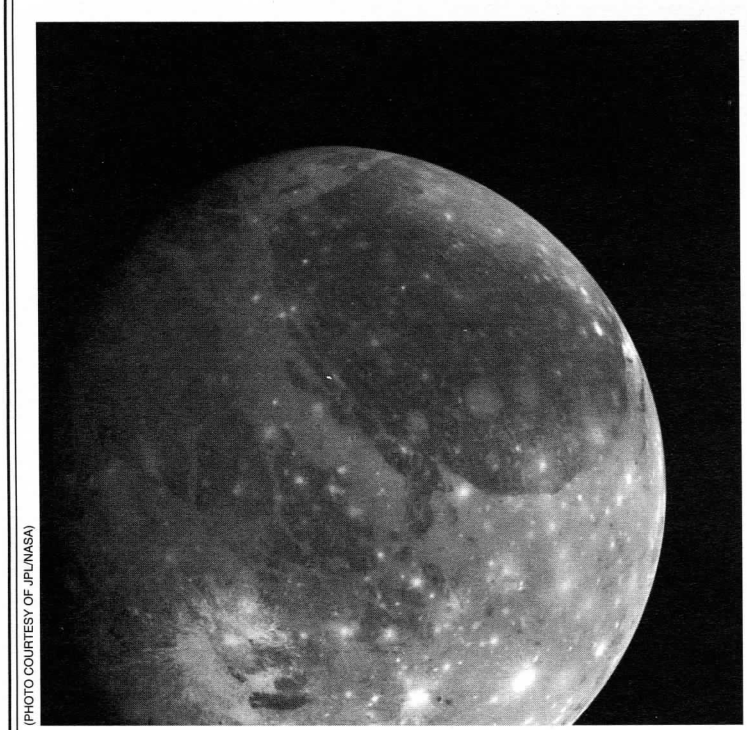

Figure 3: *The largest moon in our solar system, Ganymede, has been found to possess a magnetic field that provides some shielding from Jupiter's powerful radiation belts. More massive moons found orbiting EGPs and brown dwarfs could very well have more intense magnetic fields that could shield a moon's atmosphere from the potent erosion effects of the intense radiation environments that likely exist around substellar companions.*

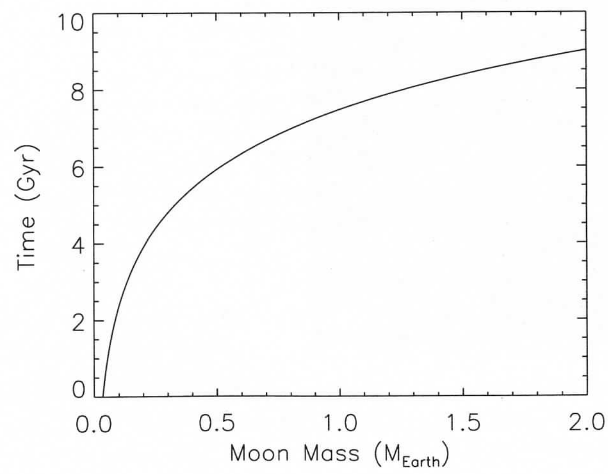

Figure 4: *This plot shows the amount of time a moon or planet can remain geologically active using internal radiogenic heat sources such as uranium-238. A threshold heat flux of 35 milliwatts per square meter is assumed to be needed to drive geologic activity.*

Geologic Activity and the Atmospheric Thermostat

Another condition necessary for habitability is the existence of a sustained carbonate-silicate cycle. This cycle controls the amount of atmospheric carbon dioxide in such a way that maintains surface temperatures in a narrow range that allows liquid water to exist on the surface (21). In addition to requiring water to dissolve carbon dioxide and to act as a medium to allow dissolved gases to react with other ions to produce deposits of insoluble carbonates, the cycle also requires some form of geologic activity that recycles these carbonate deposits back into the atmosphere via some form of plate tectonics and volcanism. A body that lacks sufficiently active geologic cycles eventually ends up with its allotment of carbon dioxide permanently tied up in carbonate deposits. The steady decline in the atmospheric concentration of this important greenhouse gas eventually results in a fatal drop in surface temperatures that causes any surface water to freeze. The fact that Mars lost this capability about two billion years ago may be one reason it is the cold, desolate planet that it is today (22).

The geologic activity, such as plate tectonics, necessary to maintain the carbonate-silicate cycle requires heat from the body's interior. The critical flux of heat needed to drive the required level of geologic activity must lie somewhere between that of the Earth (which has the needed level of activity) with a flux of 70 milliwatts per square meter and Mars (which does not have the needed level of activity) with an estimated heat flux of 30 milliwatts per square meter (23). If the primary means of internal heating is assumed to be from the decay of uranium-238 and we assume that Mars was geologically active until about 2.0 billion years ago (24), the critical heat flux is roughly 35 milliwatts per square meter. For a body with the density of Mars, a mass of about 0.26 $M_\oplus$ is required to maintain the needed level of geologic activity for 4.5 billion years (11).

The minimum mass needed for a body with a Mars-like density of four grams per cubic centimeter to sustain geologic activity as a function of time is plotted in Figure 4. It should be stressed that there are many unknowns surrounding the minimum heat flux needed to maintain the carbonate-silicate cycle and that this plot is a rough estimate. Some studies suggest the minimum heat flux needed to sustain our planet's plate tectonics is as high as 60 milliwatts per square meter (25). This suggests that a planet with an Earth-like mass is required to sustain habitable conditions for 4.5 billion years if only radiogenic heat sources are available.

Moon Orbit Limits

A natural question to consider for a brown dwarf or EGP orbiting only about one or two AU from its sun is whether there are stable orbits for any moons it might have. A number of definitions and criteria exist for orbit stability yet they all seem to indicate that such orbits do exist. One of the more general definitions of stability is plotted in Figure 5 (26). It can be seen that the orbits of all the major satellites circling either Jupiter or Saturn would remain bound to these planets if they were moved to one AU from the Sun. As expected, the more massive the EGP or brown dwarf, the larger the zone of stable orbits.

The inner edge where moons could exist is defined by the Roche limit. Named after the French astronomer Edouard Albert Roche who developed the concept in 1847 (27), this limit defines the point where a large moon is torn apart by the tidal forces produced by its parent. The fact that only ring systems and tiny moons exist inside the Roche limits of all the Jovian planets in our solar system attests to the reality of this limit. The Roche limit for a moon with a Mars-like density is plotted in Figure 5. As can be seen, there is plenty of real estate for large moons to exist between the Roche limit and the orbit stability limit.

However, it is unlikely that any large moon remains in orbit this close to its parent for any length of time. A moon orbiting at the Roche limit has its orbit enlarged fairly quickly due to tidal interactions with its parent, just as our moon continues to recede from the Earth (28). Such tidal evolution is believed to have affected the satellite systems of our Jovian planets and the details

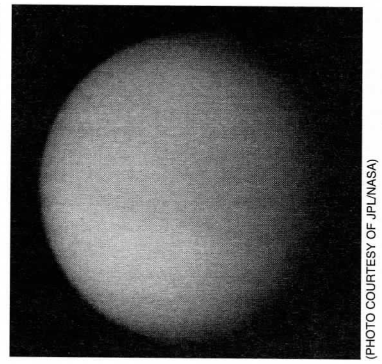

Figure 6: *Titan, Saturn's largest moon, possesses an atmosphere of nitrogen with twice the surface pressure of Earth's atmosphere. This dense atmosphere allows this moon to maintain a nearly constant surface temperature despite its 17 Earth-day long solar day.*

of a close moon's orbital evolution is dependent on the sizes and locations of any other moons that exist in the system.

The Length of Day

There also exist other orbital limitations that affect the habitability of any moon. One of these is the orbital period. Because of the tidal effects of its parent, all closely orbiting moons in our solar system have their rotation rates tidally locked so that their "day" is equal to their respective orbital periods. It can be easily shown that any Earth-size moon orbiting within the orbit stability limit of an EGP or brown dwarf at one AU will have its rotation tidally locked in only a few hundred million years (29). Since the time needed to have the rotation become tidally locked varies only with the cube root of the moon's mass, it is safe to assume that all large, potentially habitable moons experience synchronous rotation.

Having a day equal to the orbital period can have severe consequences on the habitability of a moon especially if the period is very long. If today's Earth were to have its rotational period lengthened beyond 96 hours, the large temperature swings between night and day would render its surface uninhabitable (30). While this 96 hour long day was long thought to be the limit for habitability, recent computer simulations indicate that a planet remains habitable even if one hemisphere is perpetually locked towards the sun, provided the atmosphere is dense enough. An atmosphere containing one to two bars of carbon dioxide is dense enough to carry heat from the permanently lit hemisphere to the permanently dark atmosphere so that both hemispheres maintain temperatures allowing liquid water to exist (31).

A couple of examples of slowly rotating bodies whose temperatures are equalized by their dense atmospheres exist in our own solar system. An extreme case is Venus whose 100 bar atmosphere maintains a globally constant, albeit sweltering, temperature despite a 117 Earth day long solar day. At the other temperature extreme, Titan's cold 2-bar nitrogen atmosphere (shown in Figure 6) is sufficient to essentially equalize its surface temperatures and it has a 17 Earth-day long solar day. For otherwise habitable planets or large moons inside the HZ, a sufficiently thick carbon dioxide atmosphere is produced as a natural consequence of the carbonate-silicate cycle in the outer portions of the HZ. While the exact location in the HZ where such an atmosphere forms depends on the size of the moon, the arrangement of its continents, the parent body's orbital eccentricity, and obliquity, for an Earth-size body it should form when the insolation drops below about 0.53 $S_\oplus$ or at a distance of about 1.37 AU in our present day solar system (9). The location of this 96-hour rotation/orbital period limit is plotted in Figure 5. While the exact relationship between minimum day length versus atmospheric density remains to be mod-

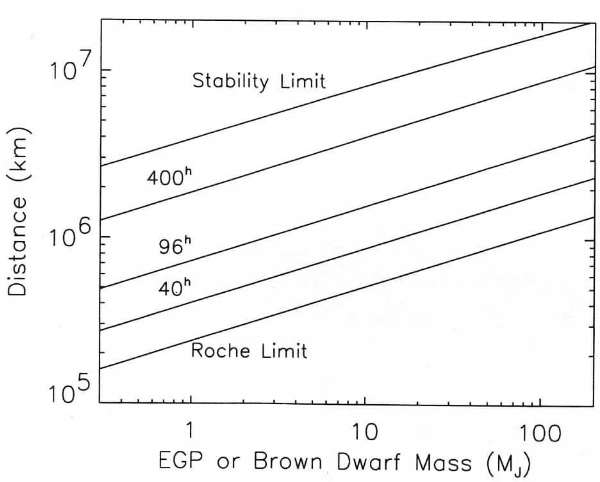

Figure 5: *This plot shows various orbit limits as a function of EGP or brown dwarf mass and distance. The lower line represents the Roche limit below which any moon would be torn apart. The upper line gives the orbit stability limit (for a distance of 1 AU from a Sun-like star) above which any moon would escape due to perturbations from its sun. The three other lines give the size of an orbit with periods of 40, 96, and 400 hours.*

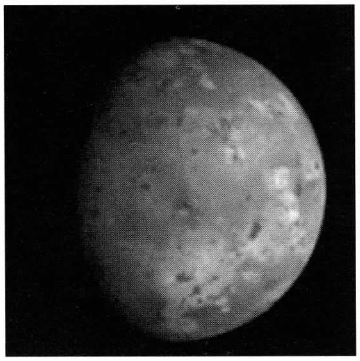

Figure 7: *The Galilean satellite Io is the most volcanically active body known in our solar system. Instead of relying on radiogenic heat sources to maintain geologic activity, this small moon generates heat from lithospheric flexing induced by tides as the moon moves along its slightly eccentric orbit around Jupiter. Tidal heating should be a major source of energy that could supplement or perhaps replace radiogenic heating to drive the geologic activity needed to keep large moons habitable.*

eled, in general moons whose orbits lie much beyond this 96 hour limit could only remain habitable if they lie in the outer portion of the HZ. Those moons inside the limit rotate quickly enough to maintain habitable conditions anywhere in the HZ.

Tidal Heating

In addition to synchronous rotation, tides raised on moons by their parent body can generate considerable amounts of heat under the proper circumstances. A moon in a perfectly circular orbit has a static tidal bulge and could not produce any heat. The small amount of lithospheric flexing that results from even a slightly eccentric orbit, however, produces geologically significant amounts of heat. Io, a Jovian moon (shown in Figure 7) with a tidally produced heat flux estimated to be 40 milliwatts per square meter, is the best known example in our solar system (32). Because Io's orbit is in a 4:2:1 mean-motion resonance with its siblings Europa and Ganymede, its orbital eccentricity remains at a constant 0.004 despite the effects of tidal damping that otherwise circularizes the orbit in short order. It seems likely that such resonances are a natural byproduct of the moon formation process or the tidally induced orbital evolution that subsequently occur (33). Even if there were only one major moon in a satellite system, perturbations from its sun only an AU or two away may be enough to drive up the orbital eccentricity of the moon. In either case, the orbits of moons around their parent body are likely to possess at least enough eccentricity to produce a significant amount of tidal heating.

If the tidally generated heat flux is greater than the previously described minimum limit needed to maintain the carbonate-silicate cycle, a moon probably remains habitable even after its radiogenicly produced heat flux falters. As a result, properly placed moons remain habitable indefinitely so long as they are massive enough to retain an atmosphere and remain in their sun's CHZ. The upper limits where tidal heating can totally replace radiogenic heating, assuming a 35 milliwatt per square meter minimum, for moons of various masses is plotted in Figure 8. In this plot it is assumed that the moons have an orbital eccentricity, internal rigidity, and tidal dissipation factor that is the same as Io's and that they have a Mars-like density. Moons of a given mass whose orbits lie significantly above these lines must rely on their limited supply of radiogenic heat sources to maintain the carbonate-silicate cycle and hence habitability.

Of course there is also too much of a good thing. With the tidal heat flux inversely proportional to the cube of the orbit's semimajor axis, the amount of tidal heat generated quickly rises with decreasing orbital distance. In some cases, the tidally induced heat flux might soar to the point where extreme geologic activity renders the surface uninhabitable. Exactly what this critical heat flux should be is currently unknown. A guess might be somewhere around 1 watt per square meter. Besides being a nice round number, this heat flux is 14 times Earth's current heat flux but might be about what it was from all radiogenic sources (including relatively short lived sources such as aluminum-26 and potassium-40) combined with heat left over from formation when the Earth was a few hundred million years old and life first arose. The inner tidal limits for this assumed tidal heat flux is about 33% of the outer tidal limit. This inner limit is plotted in Figure 8 along with the outer limit for several moon masses. Despite these limits, there is still plenty of room for large moons to reside and generate heat fluxes sufficient to maintain geologic activity almost indefinitely.

The Big Problem: Orbit Eccentricity

One of the biggest potential problems for the habitability of moons is the eccentricity of their parent bodies' orbits around their suns. Because of their great mass, brown dwarfs are more likely to have large moons but brown dwarfs typically have very eccentric orbits (5). Unfortunately, the more eccentric the orbit, the larger the temperature extremes any moon experiences over the course of a year. Earlier work indicated that the maximum tolerable eccentricity is roughly 0.2 (30). Recent work on the temperature evening effects of a dense atmosphere on slowly rotating planets (31) as well as those with extreme obliquities (34) hint that higher eccentricities are tolerable for bodies that possess atmospheres significantly denser than Earth's. Although detailed calculations have yet to be performed, it seems that the atmospheric density of a body in a highly eccentric orbit critically depends on its mass, the obliquity and rate of precession of its orbit, the arrangement of its continents, and possibly other factors.

Based on the distribution of the eccentricities for the orbits of brown dwarfs and their closely related cousins, small stellar companions, only about one third of all brown dwarfs in or near the

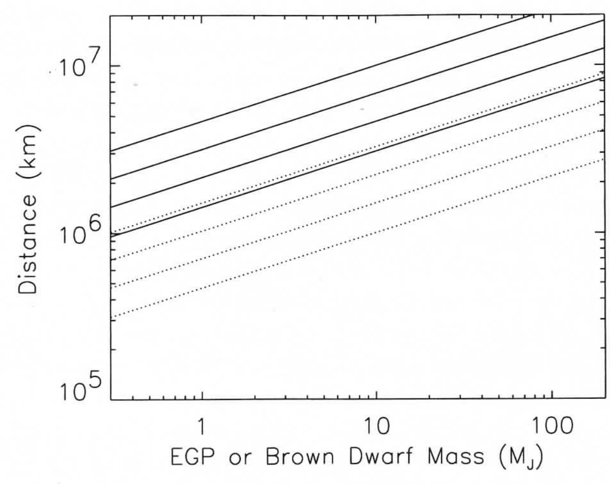

Figure 8: *This plot shows tidal heating limits for moons of various masses as a function of EGP or brown dwarf mass and distance. The solid lines show the outer bounds below which tidal heating can totally replace radiogenic heat sources to drive geologic activity (with an assumed heat flux threshold of 35 milliwatts per square meter). The dotted lines give the estimated lower bounds below which tidal heating will become too vigorous (with an assumed maximum heat flux of 1,000 milliwatts per square meter). From top to bottom, each group of lines corresponds to a moon with a mass of 1.0, 0.5, 0.25, and 0.12 $M_\oplus$. For this plot it is assumed that the moons have a density of 4 grams/cubic centimeter and possess the same orbital eccentricity, internal rigidity, and tidal dissipation factor as Io.*

HZ are expected to have a small enough eccentricity to possess habitable moons given what is currently known (35, 36). Considering the small number of EGPs discovered to date and the uncertainties of how they formed, it is difficult to estimate what fraction of them have small enough eccentricities to aid in their moons habitability. It seems likely, as with brown dwarfs, that maybe only about one third of EGPs in or near the HZ possess orbits circular enough to allow habitability.

Another potentially fatal side effect of having a parent body in an eccentric orbit is excessive eccentricity induced in the moon's orbit. While the stability of a moon's orbit was addressed previously, the regular perturbative pumping caused by an eccentric orbit around a sun certainly increases a moon's orbital eccentricity. Such a scenario has been proposed to explain the eccentric orbit of the planet orbiting 16 Cygni B which may have its orbit regularly perturbed by 16 Cygni A (37). Depending on the exact interplay between perturbative pumping, the interactions between moons, and tidal damping, a moon's orbit could become so eccentric that tidal heating soon exceeds tolerable levels. Since tidal heating is directly proportional to the square of a moon's orbital eccentricity, an orbit only a few times more eccentric than Io's almost circular path could increase tidal heating by an order of magnitude. In extreme cases, an otherwise habitable body becomes a planet-sized ball of molten rock by an overly eccentric orbit. This is another problem that awaits further detailed study before definitive limits are determined.

As Bright as the Sun

Another potential problem for the formation of a habitable moon is the thermal history of its parent body. Even 4.6 billion years after its formation, Jupiter radiates twice as much heat as it receives from the Sun. The source of this heat is the slow contraction of Jupiter that has been turning gravitational potential energy into heat since it formed. Theoretical models for the formation of giant planets indicate that they cool almost linearly with time (38). These same models indicate that the luminosity of EGPs of a given age is proportional to almost the square of the mass. The effects of EGP luminosity, especially very massive ones, on the formation and early evolution of their moons has yet to be addressed in detail. The clear trend of decreasing water ice content with decreasing orbital distance seen among the Galilean moons of Jupiter hints that such effects may be important (39).

The situation with brown dwarfs is even more extreme. While by definition brown dwarfs are incapable of sustained fusion of normal hydrogen, bodies with an initial mass greater than about 12 to 15 $M_{♃}$ are able to briefly fuse their limited stores of deuterium and attain rather respectable luminosities of as much as a few percent of $L_\odot$ (3). Fortunately this deuterium burning phase takes place between one to ten million years after the formation of the brown dwarf after which the brown dwarf starts to contract and cool like their lighter EGP cousins. During this early phase of formation, any moons that form are deeply shrouded in insulating dust and probably experience temperatures not much above those they might otherwise experience in isolation (1). At some point, however, the dust clears and the moons have to contend with the heat radiated by their parent.

Figure 9 shows a plot of the location at three points in the evolution of brown dwarfs where a moon receiving 1 $S_\oplus$ from its sun experiences a runaway greenhouse effect from the combined insolation of its sun and cooling parent (3). The three curves shown represent 70 million, 600 million and 10 billion years after the formation of the parent body. The dividing line between brown dwarfs and small stars at about 80 $M_{♃}$ is especially apparent in the 10 billion year curve where minimal size stars are able to maintain their luminosities due to hydrogen fusion. Almost certainly any large moon found under the 10 billion year curve in Figure 9 will be permanently incapable of being habitable. As a result of this and episodes of flaring, most if not all of the space available for planets around M dwarfs that closely orbit sun-like stars will be incapable of supporting habitable planets. Detailed modeling is required before a definitive statement can be made about the borderline where a brown dwarf boils off too much of a moon's initial allocation of volatiles and renders it a sterile cinder.

Even the initial allocation of volatiles a moon might possess is open to debate. If an EGP forms several AU from its sun and then subsequently migrates into the HZ (40), its system of moons (assuming they survive the migration) might retain a trend in water content similar to that seen in the Galilean satellite system. In such a case, an EGP could have its inner moons with an almost Earth-like allotment of water allowing the existence of not only oceans but dry land. The outer moons, formed from water-rich materials and ices found beyond the water condensation limit around an EGP or brown dwarf, could possess global oceans tens if not hundreds of kilometers deep. In such a situation it might be impossible to initiate the carbonate-silicate cycle needed to maintain habitable conditions on these moons.

If eccentric planets form by some sort of dynamic instability resulting in the merger of EGPs (41, 42), the effect on any existing moons or moons that subsequently form out of the impact debris is totally unknown. In a situation analogous to the formation of our Moon, it may be possible that a larger than normal system of moons might form as a result of some of these mergers. But if EGPs or brown dwarfs near the HZ have formed where they are presently found, the effects of the water condensation limit might not be as important or could be ignored completely. Much more information on the origin of a planet's or moon's

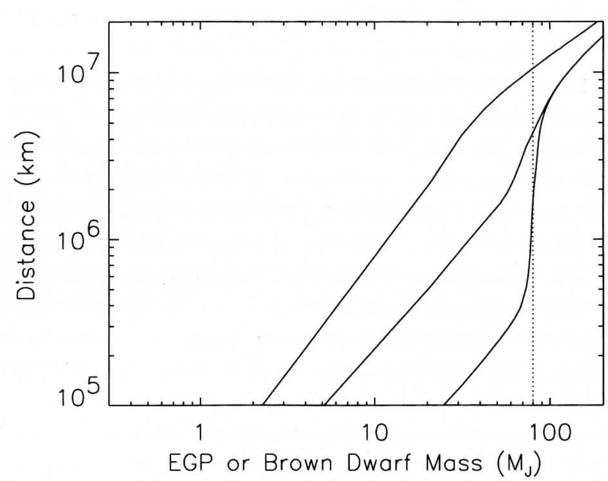

Figure 9: *This plot shows the lower limit below which a moon receiving 1 $S_\oplus$ insolation from its sun will experience a runaway greenhouse effect (which occurs above 1.42 $S_\oplus$) due to the additional heat received from its slowly cooling parent. The tree curves, from left to right, represent the limits for EGPs or brown dwarfs 70 million, 600 million, and 10 billion years after their formation. The vertical dotted line corresponds roughly to the 80 $M_{♃}$ mass limit where brown dwarfs become small stars.*

allotment of volatiles, the timing of their arrival, and the origin and evolution of its parent body as well as the surrounding environment is needed to resolve these questions.

Where Can We Find Habitable Moons?

After all this discussion, looking at Figure 1 there do not seem to be any immediately promising sites for habitable moons currently known. The orbits of the substellar companions circling 47 Ursae Majoris (43) and HD 29587 (36) have very low eccentricities but they both lie just outside these systems' current HZs. Given 47 Ursae Majoris' estimated age of 7 billion years (44), its Jupiter-like EGP likely lies well outside of this system's CHZ lessening its chances further.

Other possibilities include the recently discovered eccentric planet found orbiting 16 Cygni B and the brown dwarfs found around BD+51 1650 (HD 110833), BD-4 782, BD-25 1168 (HD 18445), and BD-5 5804 (HD 217580) (36). While all five of these bodies have orbits with high eccentricities ranging from 0.28 to 0.69, on average they spend more of their time in the outer portions of these systems' estimated HZ. As a result it is possible that some of them have moons with atmospheres dense enough to lessen the temperature extremes that might otherwise be expected from such large variations in insolation.

While these substellar companions may not perfectly fit the bill for potential sites for habitable moons, some will eventually be found. If brown dwarfs have the same distribution of orbital periods as small stellar companions, 19% of those orbiting within 4 AU of a sun-like star can be found in the HZ (35). If one brown dwarf in three have small enough eccentricities, about 6% of all brown dwarfs within 4 AU of their suns will be properly positioned to possess habitable moons. We presently have no way of knowing for sure but comparable figures might also apply to EGPs. When such a substellar companion is found, what are the chances of it having a habitable moon? At this time, not only is the planet formation process poorly understood but also the way systems of moons form. This makes a definitive statement on the chance of finding habitable moons currently impossible. But if we are willing to extrapolate from the satellite systems of the Jovian planets in our solar system, we might be able to make an educated guess.

Looking at the regular satellite systems of Jupiter, Saturn, and Uranus, some trends seem to emerge. First, the total masses of not only these three regular satellite systems but even Neptune's irregular system seem to scale linearly with the planets' mass. It also appears that all the major satellites in these systems have periods of no less than 40 hours but no more than 400 hours (or almost 17 Earth-days). These two observations imply that the total angular momentum for these systems scales with the cube root of planet mass just as the orbit size does for a given period of revolution. It may just be a coincidence that such trends appear to be present, but the fact they seem to exist over a factor of 20 in planetary mass leads me to think it might be real and that it might continue to extend into the realm of super-Jovian EGPs and brown dwarfs.

Assuming for the moment that we can extrapolate from our regular Jovian satellite systems to those of other EGPs and brown dwarfs, we can estimate the possible locations and masses of any moons and determine which, if any, are likely to be habitable. First we will tackle the location of these moons around their parent: It

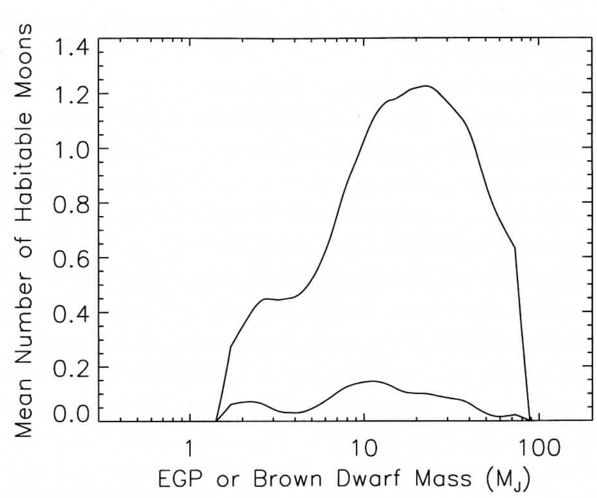

Figure 10: *This plot gives the mean number of moons per EGP or brown dwarf as a function of mass. The upper curve corresponds to a 4.5 billion year old body in a circular 1.4 AU orbit from a Sun-like star while the lower one represents a body in a circular 1.0 AU orbit. Both curves have been smoothed to soften any jaggedness caused by the limited statistics in the model moon mass spectrum derived from our solar system's regular satellite systems.*

can be seen in every Jovian satellite system that rings and small moons are found close to the planet, the large satellites are found in the middle, and small moons in irregular orbits lie far beyond. Previous investigations have already noted this trend in terms of satellite orbit size versus the ratio of its angular momentum to that of the whole satellite system (33). As a result it seems plausible to use the mass invariant 40 to 400 hour range in orbital periods as the place most likely to contain large moons. For the calculations to follow, we use the mass spectrum of moons with orbital periods of 40 to 400 hours for the satellite systems of Jupiter, Saturn, and Uranus and assume that the results can be placed at random in this zone. These limits on period are plotted in Figure 5.

Other limits to consider in our calculation include the effects of tidal heating shown in Figure 8. Considering our present assumption that moons form with periods between 40 and 400 hours, it can be seen that moons with minimal to moderate masses will, by and large, be capable of maintaining the heat flux needed to sustain geologic activity much longer (if not indefinitely longer) than if they were solely dependent on radiogenic heating. Clearly, moons approaching or exceeding the mass of the Earth are affected by excessive—if not fatal—levels of tidal heating throughout much of this region, making it unlikely that habitable moons will possess a mass equal to or greater than that of the Earth. If the 96-hour limit is taken into account, it appears that only moons slightly larger than Mars are able to have low enough levels of tidal heating and short enough orbital periods to remain habitable in the inner portion of a star's HZ.

The pyrolyzing effects of the parent body's early luminosity, demonstrated in Figure 9, must be taken into account. For the sake of this calculation we will assume that moons receiving more than 1.43 $S_\oplus$ from their young sun and parent at 600 million years of age are permanently rendered sterile due to runaway greenhouse effects. A simplified stellar evolution model previously developed is used to estimate the changes in solar luminosity as a function of time (45). This pyrolyzing limit effectively eliminates any possibility of having habitable bodies once the 80 $M_{♃}$ stellar limit is passed. An optimistic assumption is made that all moons larger than 0.12 $M_{\oplus}$ that do not violate any of the limits discussed here have an initial Earth-like volatile abundance and are habitable.

The results of two sets of calculations for a sun-like star with an age of 4.5 billion years are shown in Figure 10. The upper curve represents the average number of habitable moons per substellar companion as a function of mass for EGPs or brown dwarfs in the outer HZ at 1.4 AU while the lower curve represents a distance of 1 AU. It is immediately apparent that habitable moons are about an order of magnitude more common in the outer third of the HZ than close in. This is primarily the result of the 96 hour orbital period limit that removes many more distantly orbiting moons from consideration for habitability in the inner HZ. The effects of tidal heating on more massive moons orbiting inside this limit eliminates still more. The roll over in the curves in the vicinity of 15 to 30 $M_{♃}$ is the result of increasing numbers of moons attaining the masses needed to suffer from excessive tidal heating. Even if the limit for geologic heating were increased, excessive heat from the brown dwarfs with masses starting around 50 $M_{♃}$ begins to kill off any potentially habitable moons early in their history. Both of these effects are even more important for moons circling inside of the 96 hour limit.

Assuming that the mass spectrum for brown dwarfs is relatively flat (which is a reasonable model given the presently limited population statistics) (46), the one third of brown dwarfs of the assumed age with circular orbits at 1.4 AU will have an average of 0.9 habitable moons while those at 1.0 AU will have only 0.05 habitable moons. It should be remembered that these are only averages and that habitable moons can be present in pairs, threes, or even larger sets especially among brown dwarfs near the peak of the curve in the outer HZ. Naturally the cases of systems with multiple habitable moons are offset by those without any.

In the case of EGPs, only those with masses greater than about 2 $M_{♃}$ appear to have any possibility of possessing habitable moons. Optimistically, assuming a flat mass spectrum for EGPs in the 2 to 12 $M_{♃}$ range, the average number of habitable moons for super-Jovian EGPs in circular orbits is approximately 0.8 at 1.4 AU and 0.1 at 1.0 AU. Since the actual mass spectrum of EGPs (which is currently unknown) likely makes less massive examples more common, the actual averages are probably much smaller but still appreciable.

How Many Habitable Moons Are There?

These two calculations, however, are just a snapshot in time at two distances. As explained previously, Sun-like stars steadily brighten during their life on the main sequence. Once a brown dwarf's insolation rises above 0.53 $S_{\oplus}$ at any particular distance from its sun, only the much smaller number of moons with orbital periods less than 96 hours will be habitable. As a result, the mean number of habitable moons will plummet quite quickly after this threshold is reached as can be seen in the difference in the two curves in Figure 10. Using the presently assumed distribution of brown dwarf orbital periods, the mean number of habitable moons averaged over all brown dwarf masses, their distances in the initial HZ, and the lifetime of their sun is about 0.12 moons.

Assuming that this average is typical for all stars of spectral types F, G, and K and that habitable bodies of any sort are most likely to be found around stars of this type, we can make a rough estimate of the total number of habitable moons in our galaxy: Stars of the appropriate spectral types make up about 22% (47) of our galaxy's 400 billion stars. Based on surveys to date, about 1% of these stars will have brown dwarfs orbiting within 4 AU (36), 19% of these will be in the HZ (35), and one third of these will have orbital eccentricities low enough to allow habitability. Combined with a mean number of habitable moons for brown dwarfs just calculated, the estimated number of habitable moons orbiting brown dwarfs in our galaxy is about 7 *million.*

The number of uncertainties concerning EGPs makes a similar calculation even more speculative. But if we assume that the mass spectrum of EGPs in the 2 to 12 $M_{♃}$ mass range is flat and that the distribution of orbital periods for EGPs is similar to brown dwarfs (which is probably not a valid assumption given the totally different ways each class of body is formed), the mean number of habitable moons circling super-Jovian EGPs is about 0.14. Current surveys estimate that super-Jovian EGPs with masses greater than 2 $M_{♃}$ orbit maybe 5% (36) of sun-like stars. Using this information along with the other numbers for brown dwarfs (which is admittedly a real0 stretch), maybe as many as 40 million habitable moons circle EGPs in our galaxy. If we use 2.6% as an estimate for the prevalence of habitable terrestrial planets around stars (45), there are 10 billion habitable terrestrial planets in our galaxy. The estimate of 47 million habitable moons represents only about 0.5% of all the habitable bodies in our galaxy but a number of arguments could be made that these abodes may have a significance disproportionate to their numbers.

Considering the Possibilities

As mentioned earlier, habitable moons will frequently be found in pairs, threes, or larger groupings especially around mid-sized brown dwarfs. Assuming that terrestrial planets have logarithmic orbital spacings similar to those found in our solar system, at best maybe only two habitable terrestrial planets will be present in any one solar system. Even then, the slowly increasing luminosity of this system's primary will allow both of them to remain habitable for only a couple of billion years at best. Since an entire group of habitable moons in orbit around a single brown dwarf might remain habitable for two or three times this length of time, some very interesting possibilities begin to emerge.

First, even if life manages to arise only on one moon early in the history of a system with multiple habitable moons, it is likely to spread to the neighboring moons from the exchange of impact generated debris in the form of lithospermia (48). Such exchanges of material are known to occur in our solar system (49) and were likely to happen early in our solar system's history when life is known to have first started on the Earth and large impacts were commonplace. In a compact satellite system with habitable moons, such exchanges become more common and the transit times are measured in years or decades instead of hundreds of thousands or millions of years as is the case in our solar system. Such quick and easy exchanges of materials greatly increases the chances that viable life forms will spread throughout a system of moons in its early history.

With significantly greater chances that all the large moons in this system will have life, there is also a greater chance that more advanced, multicellular life forms will eventually arise on one or more of the geologically less volatile moons. And with this greater chance of higher forms of life, there is also a greater chance that intelligent life capable of producing a technologically advanced civilization will arise. Imagine for a moment if our civilization arose on one of these moons. The cultural and scientific impact of the sight of several large, close worlds is interesting in light of the development of our species' views of the universe especially since the beginning of the Copernican revolution.

Travel between these worlds requires technology no more advanced than what we have acquired in this century. With transit times via Houghman transfer orbits of only a few days, travel between these life-bearing worlds is much easier than our current scenario. One need only imagine the impact on a Space Age society like our own from the opportunities for exploration, discovery, and exploitation in such a small system of habitable worlds. If a particularly advanced society inhabited one of the more slowly rotating moons with its environment degrading as its sun brightens, it is likely that species might be motivated to pull up stakes and move to a neighboring moon with better conditions only a couple of days away. One could easily build a case that a civilization in a system such as this offers much greater opportunity and reason to be an aggressively space-faring society than one like ours with the closest nearly-habitable world (i.e., Mars) months away at best. With this in mind, it might not come as a surprise if the first extraterrestrials with the space travel technology needed to visit our world are from a system of habitable moons instead of from a solitary habitable planet like our own.

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1) A.P. Boss, "Proximity of Jupiter-Like Planets to Low Mass Stars," ***Science***, Vol. 267, pp. 360-362, January 20, 1995

2) Paul D. Spudis, "The Moon," ***The New Solar System***, Third Edition, J. Kelly Beatty and Andrew Chaikin (eds.), Cambridge University Press & Sky Publishing Corp., pp. 41-52, 1990

3) A. Burrows, W.B. Hubbard, D. Saumon, and J.I. Lunine, "An Expanded Set of Brown Dwarf and Very Low Mass Star Models," ***The Astrophysical Journal***, Vol. 406, pp. 158-171, March 20, 1993

4) G.W. Marcy and R.P. Butler, "A Planetary Companion to 70 Virginis," ***The Astrophysical Journal***, Vol. 464, pp. L147-L151, June 20, 1996

5) T.Mazeh, M. Mayor, and D.W. Latham, "Eccentricity Versus Mass for Low-Mass Companions and Planets," submitted to ***The Astrophysical Journal***, 1996

6) W.D. Cochran, A.P. Hatzes, R.P. Butler, and G.W. Marcy, "The Discovery of a Planetary Companion to 16 Cygni B," submitted to ***The Astrophysical Journal***, 1996

7) David S. McKay, Everett K. Gibson Jr., Kathie L. Thomas-Keptra, Hojatollah Vali, Christopher S. Romanek, Simon J. Clemett, Xavier D.F. Chillier, Claude R. Maechling, and Richard N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001," ***Science***, Vol. 273, no. 5277, pp. 924-930, August 16, 1996

8) "Jupiter's Europa Harbors Possible 'Warm Ice' or Liquid Water," NASA Press Release 96-164, August 13, 1996

9) James F. Kasting, Daniel P. Whitmire, and Ray T. Reynolds, "Habitable Zones Around Main Sequence Stars," ***Icarus***, Vol. 101, pp. 108-128, 1993

10) J.F. Kasting , "CO2 Condensation and the Climate of Early Mars," ***Icarus***, Vol. 94, pp. 1-13, 1991

11) Darren M. Williams, James F. Kasting, and Richard A. Wade, "Habitable Moons Around Extrasolar Giant Planets," Submitted to ***Nature***, 1996

12) M.B. McElroy, "Mars: An Evolving Atmosphere," ***Science***, Vol. 175, pp. 443-445, 1972

13) J.L. Fox, "The Production and Escape of Nitrogen Atoms on Mars," ***Journal of Geophysical Research***, Vol. 98, No. E2, pp. 3297-3310

14) D.M. Kass and Y.L. Yung, "Loss of Atmosphere from Mars Due to Solar Wind-Induced Sputtering," ***Science***, Vol. 268, No. 5211, pp. 697-699, May 5, 1995

15) "Galileo Spacecraft Makes New Discoveries at Ganymede," NASA Press Release 96-133, July 10, 1996

16) "Jupiter's Largest Moon Has Thin Oxygen Atmosphere," Space Telescope Science Institute Press Release, October 23, 1996

17) J.D. Anderson, W.L. Sjogren, and G. Schubert, "Galileo Gravity Results and the Internal Structure of Io," ***Science***, Vol. 272, No. 5262, pp. 709-712, May 3, 1996

18) M.G. Kivelson, K.K. Khurana, R.J. Walker, C.T Russell, J.A. Linker, D.J. Southwood, and C. Polanskey, "A Magnetic Signature at Io: Initial Report from the Galileo Magnetometer," ***Science***, Vol. 273, No. 5273, pp. 337-340, July 19, 1996

19) M.G. Kivelson, K.K. Khurana, R.J. Walker, J. Warnecke, C.T Russell, J.A. Linker, D.J. Southwood, and C. Polanskey, "Io's Interaction with the Plasma Torus: Galileo Magnetometer Report," ***Science***, Vol. 274, No. 5286, pp. 396-398, October 18, 1996

20) H.J. Melosh and A.M. Vickery, "Impact Erosion of the Primordial Atmosphere of Mars," ***Nature***, Vol. 338, pp. 487-489, April 6, 1989

21) J.C.G. Walker, P.B. Hays, And J.F. Kasting, "A Negative Feedback Mechanism for the Long-Term Stabilization of Earth's Temperature," ***Journal of Geophysical Research***, Vol. 86, pp. 9776-9782, 1981

22) J.F. Kasting, O.B. Toon and J.B. Pollack, "How Climate Evolved on the Terrestrial Planets," ***Scientific American***, Vol. 256, pp. 90-97, 1988

23) Sean C. Solomon and James W. Head, "Heterogeneities in the Thickness of the Elastic Lithosphere of Mars - Constraints on Heat Flow and Internal Dynamics," ***Journal of Geophysical Research***, Vol. 95, pp. 11073-11083, July 10, 1990

24) P.W. Francis and C.A. Wood, "Absence of Silicic Volcanism on Mars - Implications for Crustal Composition and Volatile Abundance," ***Journal of Geophysical Research***, Vol. 87, pp. 9881-9889, November 30, 1982

25) K.C. Condie, "Origin of the Earth's Crust," ***Paleogeography, Paleoclimatology, Paleoecology*** (Global and Planetary Change Section), Vol. 75, pp. 57-81, 1989

26) David C. Black, "A Simple Criterion for Determining the Dynamical Stability of Three-Body Systems," ***The Astronomical Journal***, Vol. 87, No. 9, pp. 1333-1337, September 1982

27) Edouard Roche, Acad. Sci. Lett. Montpilier, pp. 243-363, 1847

28) James A. Burns, "Orbital Evolution," ***Planetary Satellites***, Joseph A. Burns (ed.), University of Arizona Press, pp. 113-156, 1977

29) Staton J. Peale, "Rotation Histories of Natural Satellites," ***Planetary Satellites***, Joseph A. Burns (ed.), University of Arizona Press, pp. 87-112, 1977

30) S.H. Dole, "Habitable Planets for Man," Blaiisdell Publishing Co., 1964

31) M. Joshi and R. Haberle, "The Atmospheres of Synchronously Rotating Planets," Paper 12.18 presented at the 28th DPS Meeting, October 23-26, 1996

32) S.J. Peale, P. Cassen, and R.T. Reynolds, "Melting of Io by Tidal Dissipation," ***Science***, Vol. 203, pp. 892-894, March 2, 1979

33) Jack J. Lissauer and Jeffrey N. Cuzzi, "Rings and Moons: Clues to Understanding the Solar Nebula," ***Protostars and Planets II***, David C. Black and Midred Shapley Matthews (eds.), University of Arizona Press, pp. 920-956, 1985 (and references therein)

34) Darren M. Williams and James F. Kasting, "Habitable Planets with High Obliquities," submitted to ***Icarus***, 1996

35) A. Duquennoy and M. Mayor, "Multiplicity Among Solar-Type Stars in the Solar Neighbourhood. II. Distribution of the Orbital Elements in an Unbiased Sample," ***Astronomy and Astrophysics***, Vol. 248, p. 485, 1991

36) Michel Mayor, Dider Queloz, Stephane Udry, and Jean-Louis Halbwachs, "From Brown Dwarfs to Planets," To appear in ***Astronomical and Biochemical Origins and the Search for Life in the Universe***, IAU colloquim 161, 1996

37) T. Mazeh, Y. Krymolowski, and G. Rosenfeld, "The High Eccentricity of the Planet Around 16 Cygni B," submitted to ***The Astrophysical Journal***, 1996

38) A. Burrows, D. Saumon, T. Guillot, W.B. Hubbard, and J.I. Lunine, "Prospects for Detection of Extra-Solar Giant Planets by Next-Generation Telescopes," ***Nature***, Vol. 375, pp. 299-301, May 25, 1995

39) R.G. Prinn and B. Fegley Jr., "Kinetic Inhibition of CO and N2 Reduction in Circumplanetary Nebulae - Implications for Satellite Composition," ***The Astrophysical Journal***, Vol. 249, pp. 308-317, October 1, 1981

40) D.N.C. Lin, P. Bodenheimer, and D.C. Richardson, "Orbital Migration of the Planetary Companion of 51 Pegasi to its Present Location," ***Nature***, Vol. 380, pp. 606-607, April 18, 1996

41) Frederic A. Raio and Eric B. Ford, "Dynamical Instabilities and the Formation of Extrasolar Planetary Systems," ***Science***, Vol. 274, No. 5289, pp. 954-956, November 8, 1996

42) D.N.C Lin and S. Ida, "On the Origin of Massive Eccentric Planets," submitted to ***The Astrophysical Journal***, 1996

43) R.P. Butler and G.W. Marcy, "A Planet Orbiting 47 Ursae Majoris," ***The Astrophysical Journal***, Vol. 464 pp. L153-L156, June 20, 1996

44) G.W. Henry, A.L. Baliunas, R.A. Donahue, W.H. Soon, and S.H. Saar, "Properties of Sun-Like Stars with Planets," To appear in January 1, 1997 issue of ***The Astrophysical Journal.***

45) Martyn J. Fogg, "An Estimate of the Prevalence of Biocompatible and Habitable Planets," ***Journal of the British Interplanetary Society***, Vol. 45, No. 1, pp. 3-12, January 1992

46) Geoffrey W. Marcy and R. Paul Butler, "Brown Dwarfs and Planets Around Solar-Type Stars: Searches by Precise Velocities," The Bottom of the Main Sequence and Beyond, C. Tinney (ed.), 1995

47) W. Gliese and H. Jahreiss, Preliminary Version of the ***Third Catalogue of Nearby Stars***, Astronomischen Rechen-Instituts, Heidelberg, 1991

48) C.A. Tobias and P. Todd, ***Space Radiation Biology and Related Topics***, Academic Press Inc., 1974

49) Brett J. Gladman, Joseph A. Burns, Martin Duncan, Pascal Lee, and Harold F. Levinson, "The Exchange of Impact Ejecta Between Terrestrial Planets," ***Science***, Vol. 271, No. 5254, pp. 1387-1392, March 8, 1996