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The Extremes of Habitability

by Andrew J. LePage

A habitable zone, also referred to as an ecosphere, is the region around a star where a habitable planet or moon can exist. While there are a number of definitions for what constitutes a "habitable" world, today it is generally considered to be one that has surface temperatures that allow for the existence of liquid water over a substantial portion of its surface (1).

Since the Earth is such a planet, the current conventional wisdom considers these worlds to be the most likely place for life to arise and technological intelligence to develop. This is not to suggest that this is the only type of world where life can exist. There could be biocompatible environments below the Martian surface or in the tidally heated ocean that might reside beneath the icy crust of Europa. While admittedly this is an anthropocentric conceit, most scientists today do not consider these locales as likely sites for the development of a technologically advanced civilization.

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Figure 1: *Over the past quarter century, planetary scientists have found ample evidence that Mars had a much warmer and wetter climate billions of years ago. One of the latest pieces of evidence for this more habitable epoch is this high-resolution image of Nanedi Vallis which cuts through the Xanthe Terra region of Mars. Taken on January 8, 1998, by the Mars Orbiter Camera on NASA's Mars Global Surveyor, this image indicates that a sustained flow of water was responsible for cutting this canyon. These sorts of channels would have replenished open bodies of water that probably existed on Mars more than three billion years ago.*

Candidate Stars

Studies of the life cycles of stars indicate that there are only certain types that have any chance of harboring habitable worlds. First of all, a planet's sun must be a main sequence star that is fusing hydrogen into helium. Such stars are relatively stable, allowing for long uninterrupted periods of habitability. In addition a star must be no more massive than about 1.8 $M_\odot$ since more massive stars evolve too quickly and leave the main sequence in less than one billion years (2). Such stars would not have enough time for the planet formation process to complete itself and for life to become firmly established on a suitable planet.

Calculations made by James Kasting of Penn State and his colleagues indicate that potentially habitable planets with oxygen in their atmospheres can produce enough shielding ozone for suns ranging from at least type F to K (3). Cooler M stars produce insignificant amounts of ultraviolet radiation and would not require any ozone. Despite these limits, main sequence stars cooler than A2 (which comprise the vast majority of stars in the galaxy) could potentially sustain habitable planets.

One criterion for determining the habitability of a world is the amount of sunlight it receives, its insolation. Using present-day Earth as a guide, early researchers concluded that a star's habitable zone would be very narrow and range only from about 0.93 to 1.02 AU from the Sun. Any closer and a runaway greenhouse effect would set in (4). Any farther out and the Earth would freeze (5,6,7). With such narrow limits, habitable planets would be relatively rare.

But according to accepted models of stellar evolution, the Sun should have had a luminosity of only 0.7 $L_\odot$ at the beginning of its history and subsequently slowly brightened as helium, the byproduct of hydrogen fusion, built up in its core (8). This fact implies that the location of a star's habitable zone moves outward as it ages.

The vast body of geologic evidence gathered over the years indicates that Earth has had liquid water present throughout its history and that temperatures were actually higher a couple of billion years ago than they are today. As a result, the habitable zone of the Sun today should extend at least as far as 1.2 AU from the Sun. This problem has become known as the early faint Sun paradox (9).

One of the results of recent exploration of Venus has been the discovery that surface temperatures are also affected by the amount of greenhouse gases like carbon dioxide and water vapor present in the atmosphere. While present-day Earth has only a mild greenhouse effect, its atmosphere might have contained much more of these greenhouse gases in its early history to make the climate warmer.

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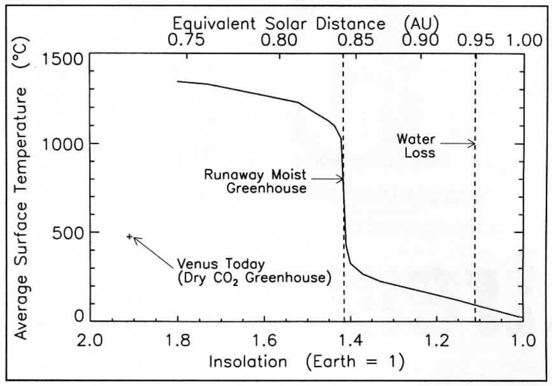

Figure 2: *The average surface temperature of a water-rich, Earth-like planet orbiting a Sun-like star increases with insolation. Locations where water loss and a runaway greenhouse effect occur are indicated. The present-day temperature of Venus shown in this plot is below this temperature curve because Venus has lost all of its water and is now dominated by a dry carbon dioxide greenhouse effect.*

Investigations over the past decade have discovered geochemical processes that take place on geologically active terrestrial bodies that keep just enough carbon dioxide in the atmosphere to stabilize the climate and maintain habitable conditions over a wide range of insolation values. The most important of these processes is the carbonate-silicate cycle (10).

The Carbonate-Silicate Cycle

The carbonate-silicate cycle begins with carbon dioxide being removed from the atmosphere by rain. The rain water with its dissolved carbon dioxide then reacts with magnesium- and calcium-bearing silicate minerals in a process called weathering. The dissolved products of weathering are then carried by rivers to a world's oceans where they are concentrated. Eventually the insoluble carbonates precipitate out of solution in the shallows to form vast deposits.

On the Earth the formation of carbonates is facilitated by various forms of life that produce protective shells. But carbonate deposits can still form abiotically on a lifeless world (11). On a geologically active planet like Earth, these carbonate deposits are eventually carried into the mantle by the subduction of tectonic plates or similar process. As the carbonate deposits are heated and metamorphose, the carbonates break down and the carbon dioxide gas is thus liberated and vented back into the atmosphere, via volcanism, thus completing the cycle.

Assuming that geologic activity remains vigorous, there are temperature-sensitive feedback mechanisms in this cycle that control the amount of carbon dioxide removed from the atmosphere on time scales of hundreds of thousands of years (1). On a world that is too hot, the rate of weathering increases due to enhanced meteorological activity and chemical reaction rates. The result is more carbon dioxide being removed from the atmosphere and turned into climatically inert carbonates. This lessens the greenhouse effect and allows surface temperatures to fall. When it becomes too cold, the weathering process slows down and the carbon dioxide that is constantly being released from volcanoes builds up in the atmosphere. This enhances the greenhouse effect which in turn raises surface temperatures.

As a result, the carbonate-silicate cycle acts as a negative feedback mechanism which maintains temperatures that allow for the continued existence of liquid water despite changes in insolation (1).

The Inner Limit

James Kasting of Penn State University and his colleagues have developed a one-dimensional radiative-convective climate model to study the changes to a habitable planet's climate brought about by increasing insolation (1). Once the carbonate-silicate cycle has eliminated most of the atmospheric carbon dioxide, temperatures will inevitably start to rise with increased insolation as in Figure 2. This temperature increase in turn raises the amount of water vapor in the atmosphere through evaporation. Since water vapor itself is a potent greenhouse gas, temperatures climb still further.

According to Kasting's model, when the average surface temperature exceeds 87 degrees C, changes in the atmospheric temperature structure brought about by this moist greenhouse effect now allow water vapor to reach high into the atmosphere where it can be broken down by solar ultraviolet light in a process called photolysis (1). With the escape of the light, water-derived hydrogen from the planet, water is permanently lost and the planet starts to become desiccated. Such water loss is prevented on the Earth and cooler planets by cold stratospheric temperatures that cause water vapor to freeze before it gets too high in the atmosphere where it can be destroyed. When water loss sets in, it would take only a few hundred million years for an Earth-like planet to lose all of its oceans (12). While any life that managed to arise before water loss started might continue to survive these hot and arid conditions, such a planet would not be considered habitable.

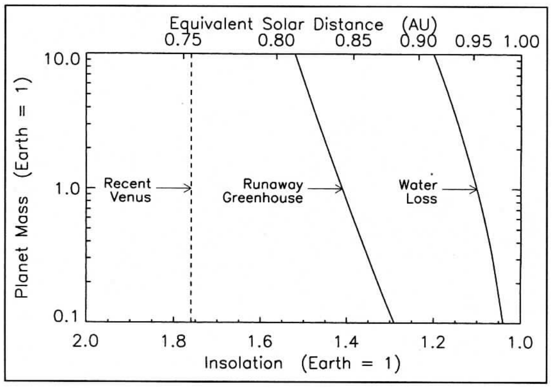

Figure 3: *The location of the water loss and runaway-greenhouse limits around a Sun-like star as a function of planetary mass are shown. The "recent Venus" line is the most optimistic inner limit of the habitable zone based on recent studies of Venus.*

The point where water loss drastically increases is considered the first limit for the habitable zone. For an Earth-sized planet this occurs at an equivalent solar distance of about 0.95 AU where the planet's insolation equals 1.10 $S_\oplus$ (1). With the Sun's ever-increasing luminosity, this inner boundary of the habitable zone will reach Earth in about one billion years (2). Once this occurs, water loss will render the Earth uninhabitable in a geologically brief period of time. As can be seen in Figure 3, for a planet with a mass of 10 $M_\oplus$, this happens at the slightly closer equivalent solar distance of 0.91 AU while for a Mars-sized world water loss starts at 0.98 AU (1).

This slight planetary mass dependence happens because the increased gravity of a more massive planet holds the atmosphere closer to the surface than a less massive planet does. This compresses the column height of the atmosphere which decreases the greenhouse effect (1). Planets that are more massive than 10 $M_\oplus$ are not expected to be habitable at all. When planets this large form, they are massive enough to start feeding directly from the gases in a protoplanetary nebula. At this stage they inevitably experience runaway growth to become gas giants (13). Planets less massive than Mars could not remain habitable for long because they are unable to hold on to an appreciable atmosphere for any length of time (14). (For a more thorough discussion on the minimum size of habitable bodies, see "Habitable Moons: A New Frontier for Exobiology" in *SETIQuest* Vol. 3, No. 1, pp. 8-16.)

According to Kasting's model, the next limit for a planet that manages to retain its water is reached when the insolation surpasses 1.41 $S_\oplus$ (1). At this equivalent solar distance of 0.84 AU, a moist runaway greenhouse effect sets in and surface temperatures start to skyrocket uncontrollably as shown in Figure 2. For planets with a mass of 10 $M_\oplus$ and 0.1 $M_\oplus$ the onset of a runaway greenhouse effect starts at an equivalent solar distance of 0.81 and 0.88 AU, respectively, as can be seen in Figure 3. Once this runaway greenhouse effect takes hold, the surface would be rendered sterile (1). After a few million years when all the planet's water is lost to photolysis, temperatures would slacken somewhat but carbon dioxide will now begin to accumulate in the atmosphere unchecked. Eventually a dry, carbon dioxide-based runaway greenhouse effect will set in, resulting in a hot and arid planet like present-day Venus (15).

Just as planetary mass affects the insolation value where severe water loss and the runaway greenhouse effect begin, so does the spectrum of a planet's sun. A star that is hotter than the Sun emits less of its energy in the infrared where greenhouse gases have their greatest effect. For a cooler star, which radiates much more of its energy in the infrared, the opposite is true. As a result, a habitable planet orbiting an F0 star begins to experience water loss, then a runaway greenhouse effect, when the insolation reaches 1.25 $S_\oplus$ and 1.90 $S_\oplus$, respectively (1). For a cooler M0 red dwarf the corresponding insolation values are a much lower 1.00 $S_\oplus$ and 1.05 $S_\oplus$.

Kasting and his collaborators caution that these inner boundaries of the habitable zone may be overly pessimistic due to the limitations of their simple model. In particular their model maintains an Earth-like fraction of cloud cover regardless of the atmosphere's water vapor content. Admittedly with increased concentrations of water vapor, the cooling effects of greater cloud cover would push these estimated limits closer to the Sun.

But recent studies of the geologic history of Venus set a firm limit to how close the actual inner boundary of the habitable zone can be (16). The present-day surface of Venus, which is no older than one billion years, shows no indication that water existed on the surface. Taking into account the Sun's increase in luminosity during this time and assuming water loss occurred on Venus just before its oldest existing landforms came into being, the maximum possible insolation for a habitable planet is about 1.76 $S_\oplus$, which corresponds to an equivalent solar distance of 0.75 AU. The actual inner boundary of the Sun's current habitable zone must lie somewhere between this overly optimistic "recent Venus" estimate and Kasting's pessimistic 0.95 AU water-loss limit.

Search for the Outer Limit

As we move outward from the inner edge of the habitable zone, the amount of carbon dioxide in the atmosphere slowly starts to rise in response to decreasing insolation as shown in Figure 4. While these enhanced levels of atmospheric carbon dioxide would be fatal to humans and most of the animals found on Earth today, life forms native to such an environment should have no problem thriving. Darren Williams and James Kasting have developed a more sophisticated two-dimensional, energy-balance climate model that explicitly incorporates the temperature-sensitive effects of weathering as well as the placement of continents and oceans to predict carbon dioxide levels and planetary temperatures. They found that for an Earth-sized planet the first possible impediment to habitability is the formation of carbon dioxide ice clouds as the upper atmosphere becomes very cold. According to Williams's and Kasting's model, carbon dioxide clouds begin to form over the polar regions at an equivalent solar distance of 1.30 AU and become widespread between 1.40 and 1.45 AU (17).

What happens after these clouds form depends critically on their optical properties. If the clouds are thick and their particles are very small, they will be very efficient reflectors of visible light. At the same time, they would allow infrared radiation from the planet to pass through unimpeded, thus radiatively cooling the planet's surface. From this point on, the result would be a drop in surface temperatures with decreasing insolation. An equivalent solar distance of 1.40 AU, where the insolation is 0.51 $S_\oplus$, is considered to be the most conservative definition for the outer limit of the habitable zone (17).

According to Kasting's earlier one-dimensional model, the distance where these carbon dioxide clouds form is dependent on planetary mass as shown

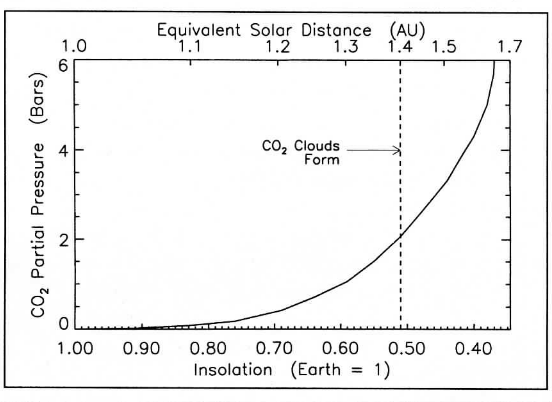

Figure 4: *The carbonate-silicate cycle increases the partial pressure of carbon dioxide in the atmosphere of an Earth-like planet orbiting a Sun-like star in response to decreasing insolation. The location where clouds of frozen carbon dioxide become widespread is also indicated. Assuming that these clouds have no significant effect on a planet's radiation budget, the maximum carbon dioxide greenhouse limit is reached at a solar equivalent distance of 1.67 AU, where the partial pressure of carbon dioxide is in the 5- to 10-bar range.*

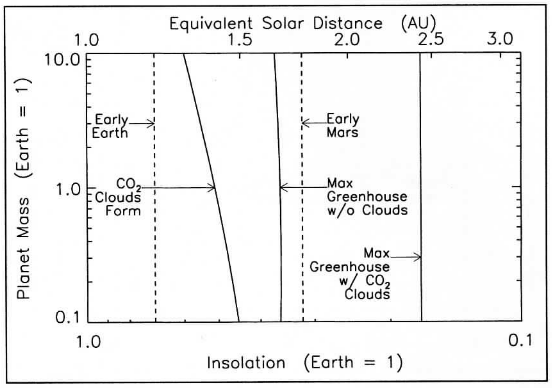

Figure 5: *The locations of the various outer limits of the habitable zone are detailed in the text as a function of planetary mass. Also indicated are the insolation levels that Earth and Mars experienced early in the history of the Solar System when both bodies experienced habitable conditions.*

in Figure 5. For planets with a mass of 10 $M_\oplus$ and 0.1 $M_\oplus$, these clouds form at an equivalent solar distance of 1.29 and 1.49 AU, respectively (1).

But if the clouds that cover the planet at 1.40 AU are too thin to significantly affect the radiation balance, the amount of carbon dioxide will continue to increase with decreasing insolation to keep the mean surface temperature above freezing, as in Figure 4. For planets with a mass equal to or less than Earth's, the next limit is reached when the insolation drops to 0.36 $S_\oplus$ at an equivalent solar distance of 1.67 AU (1,17). For a 10 $M_\oplus$ planet, the solar equivalent distance would be 1.64 AU where the insolation is 0.37 $S_\oplus$. At this level of insolation, the partial pressure of carbon dioxide in the atmosphere is between 5 and 10 bars, depending on the details of the planet models used. Such an atmosphere is so optically dense that the addition of any more carbon dioxide will actually result in a decrease in surface temperature. This is the maximum greenhouse limit.

Investigations with the one-dimensional model show that the spectral type of a planet's sun also has an effect on the position of the outer limit of the habitable zone. For a hot F0 star, carbon dioxide starts to freeze in the atmosphere at 0.61 $S_\oplus$ while the maximum greenhouse effect is encountered with an insolation of 0.46 $S_\oplus$ (1). For a cool M0 red dwarf star, these limits are reached at insolation values of 0.46 $S_\oplus$ and 0.27 $S_\oplus$, respectively. The resulting limits of the habitable zone as a function of a star's mass or spectral type are shown in Figure 6.

Pushing the Limit: Mars

But what about Mars? With a mean distance of 1.52 AU, Mars is just inside this outer limit of the Sun's current habitable zone. Why is it not habitable? One reason is because its level of geologic activity has waned to the point where the carbonate-silicate cycle has broken down (18). When this first happened, Martian surface temperatures would have steadily fallen as more atmospheric carbon dioxide was converted into carbonates. Eventually surface temperatures dropped so low that the atmosphere collapsed as its constituents began to be adsorbed by surface materials and finally freeze. All that would remain from this series of catastrophic events is the extremely thin atmosphere seen today. The only possible way for Mars, or any other habitable planet whose geologic activity is fading, to avoid this deep freeze is to be within about 1.05 AU of the Sun so that habitable conditions can be maintained with little atmospheric carbon dioxide.

But Martian history hints that even the 1.67 AU maximum greenhouse limit for the habitable zone might be too conservative. There is ample evidence for large bodies of liquid water on the surface of Mars early in its history when the Sun was much dimmer (19), as in Figure 1. With an insolation of 0.32 $S_\oplus$ 3.8 billion years ago, the outer edge of the habitable zone is now pushed out to an equivalent solar distance of at least 1.77 AU (16). One of the more frequently proposed means of resolving the early faint Sun paradox for a juvenile Mars is with the addition of methane or ammonia to the atmosphere to augment the greenhouse effect of carbon dioxide (10,20).

Ammonia and methane are generally expected to exist in trace amounts in the primordial atmospheres of terrestrial planets. Because of its extreme opacity in the thermal infrared, ammonia is an especially potent greenhouse gas and need be present only in the 1 to 100 parts per million level to significantly raise early Martian surface temperatures (21,22). But the problem with ammonia is that it is easily destroyed by exposure to solar ultraviolet light. Once the ammonia is broken up into its constituent elements of nitrogen and hydrogen, the light hydrogen quickly escapes, resulting in the permanent loss of ammonia. While a photochemical smog produced by ultraviolet light reacting with traces of methane in the upper atmosphere might shield atmospheric ammonia (9), there are still many uncertainties (23).

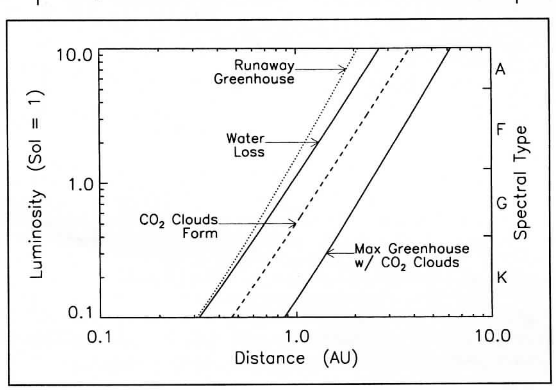

Figure 6: *The locations of the various inner and outer bounds of the habitable zone for an Earth-sized planet as a function of a sun's luminosity are demonstrated in the diagram above. The axis on the right gives the approximate ranges of luminosity for each spectral type.*

Another way to increase Martian surface temperatures is by means of the previously dreaded clouds of frozen carbon dioxide. In a recent paper, François Forget of the Laboratoire de Meteorologie Dynamique du CNRS in Paris and Raymond Pierrehumbert of the University of Chicago explored the possibility that the presence of such clouds might actually raise surface temperatures (24). Their studies suggest the size of the frozen carbon dioxide particles in these clouds could be much larger than originally supposed. With particles as large as 0.1 millimeters, these clouds would still be efficient scatterers of visible light but they would be even better reflectors of thermal infrared radiation. As a result, carbon dioxide clouds would augment the carbon dioxide–based greenhouse effect by reflecting heat back toward the planet.

There is some evidence to support the position that carbon dioxide clouds would be good reflectors in the infrared. Such clouds could explain enhanced Martian polar temperatures (25) as well as certain features in the infrared spectra of Mars (26), Venus (27), and even Titan (28).

According to Forget and Pierrehumbert, the incorporation of their carbon dioxide ice-cloud model in simulations of a planet's radiation balance would now allow the edge of the habitable zone to reach as far as 2.4 AU from the Sun where the insolation is only 0.17 $S_\oplus$ (24). Such clouds could easily maintain above-freezing temperatures on Mars with only a few hundred millibars of carbon dioxide in its atmosphere.

The Continuously Habitable Zone

But all of these estimates for outer limits are for the Sun's current habitable zone. As mentioned above, stars brighten as they age, resulting in the boundaries of the habitable zone moving outward with time. One can easily imagine a situation where a planet that was initially beyond the outer edge of the habitable zone finds itself within this limit after a matter of a billion years or more. There are some concerns whether or not these frozen worlds can thaw to become habitable (1).

One argument against these "cold starts" centers on the enhanced albedo of such an icy world which will keep temperatures low despite the increased insolation. Another argument against cold starts deals with these planets' atmospheric carbon dioxide content. Without any liquid water to drive the carbonate-silicate cycle, virtually all of a frozen terrestrial planet's carbon dioxide eventually will be released into the atmosphere, resulting in a dense atmosphere with several tens of bars of carbon dioxide. At these concentrations and temperatures, carbon dioxide's albedo overcomes its greenhouse capabilities and the planet's surface is actually cooled by its presence. With a 60-bar carbon dioxide atmosphere (Earth's estimated allotment of this gas), a planet would need an insolation of about 0.5 $S_\oplus$ before it would begin to thaw (1). A star will only brighten enough to allow a planetary cold start at the end of its life when it evolves off the main sequence. Based on this, cold starts are probably not common.

Without cold starts, the outer edge of the habitable zone stays fixed in its initial position as the inner edge slowly moves out with time. As a result, the width of the habitable zone decreases with time. To take this effect into account, the concept of a continuously habitable zone has been introduced to describe the size of a zone that has remained habitable for a given length of time (1,29). A consequence of this is that younger stars have wider continuously habitable zones as shown in Figure 7. If we accept Forget's and Pierrehumbert's 0.17 $S_\oplus$ definition for the outer edge of the habitable zone (24), that would place the outer edge of the Sun's continuously habitable zone at about 2.0 AU.

While much work is still required to better define the role of clouds of all types in determining the location of the habitable zone's edges, present estimates hint that it can be wide enough to accommodate two or three habitable planets if they are suitably positioned and sized. In fact, if our Solar System, instead of adorning a G-type star, existed around a slightly dimmer K-type star with a luminosity of about 0.5 $L_\odot$ and a mass of 0.8 $M_\odot$, our Solar System would probably have two habitable planets today: Venus and Earth.

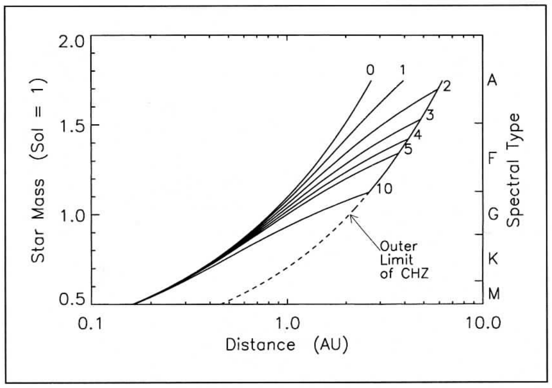

Figure 7: *The positions of the boundaries of the continuously habitable zones (CHZ) for various ages of stars (in billions of years) are shown as a function of stellar mass. The axis on the right gives the approximate ranges of mass for each spectral type. The inner limits are defined by the water-loss limit while the outer limit stays fixed at the maximum greenhouse limit with carbon dioxide clouds at the beginning of a star's life on the main sequence. The assumption is that planetary "cold starts" are not possible.*

Strange New Worlds Beyond the Edge: Titan

The terrestrial planets of our Solar System, and presumably those in other solar systems, formed in the warm inner regions of a protoplanetary disk where the environment is predominantly oxidizing. As a result the atmospheres of such worlds are dominated by carbon dioxide (30). But in the cooler outer regions of the solar nebula, reducing conditions which favor the formation of ammonia and especially methane existed (31).

The Saturnian moon Titan, with its haze-shrouded nitrogen and methane atmosphere, is an example of such a world. Being so distant from the Sun, however, Titan is too cold to allow for life to develop because its ammonia and water are frozen solid. Since the temperature structure of a protoplanetary disk is largely insensitive to a wide range of stellar luminosity, the demarcation between planets with oxidizing and reducing environments would be fixed at a few astronomical units (32).

But with the discovery of extrasolar giant planets (EGPs) orbiting within a few astronomical units of their suns, habitable bodies with reducing atmospheres might be possible after all. One of the theories to explain the origin of EGPs calls for these planets to migrate toward their sun as a result of gravitational interactions between a forming EGP and the protoplanetary disk (33). The result is that the EGP and any smaller planets with interior orbits can move from the outer part of a solar system where they formed and into the inner solar system. If the migration stops before the planets reach their sun, an EGP with its family of moons or an Earth-sized planet with a reducing atmosphere might now be close enough to its sun to be habitable.

A habitable planet with a reducing atmosphere would be much different from the ones examined so far. First of all, the ocean of such a world would be a highly alkaline ammonia-water mixture. While such an environment would be lethal to any terrestrial life forms, ammonia water is a viable solvent for prebiotic and protobiotic chemistry. Like pure water, ammonia water is strongly polar and allows for hydrogen bonding. As a result, such a mixture has good protein-folding properties and can dissolve charged molecules common in biochemistry (34). Ammonia can also stabilize the environment because it remains liquid over a large range of temperatures and has a high latent heat. Ammonia is also a potent antifreeze that can depress the freezing point of water to as low as 176 degrees K (35). While this is extraordinarily cold by terrestrial standards, it does allow a liquid ammonia water ocean to exist with only a minimal greenhouse effect.

At a temperature of 176 degrees K, ammonia and water have vapor pressures on the order of 10^{-4} and 10^{-7} bars, respectively (36). At such low concentrations these normally powerful greenhouse gases will play only a minor role in determining surface temperatures. But with so little oxygen-bearing water vapor in the atmosphere, methane will remain stable for long periods of time and could serve as the primary greenhouse gas.

Little theoretical work has been done to define the boundaries of the habitable zone of a planet with a reducing atmosphere. But studies of Titan's potential as a habitable body, once the Sun begins to evolve into a much brighter red giant star, give us some tantalizing hints of the issues involved (37).

The atmosphere of an Earth-sized Titan-like world would be predominantly primordial molecular nitrogen with several percent of methane (31). If this world orbits a Sun-like star, the stratosphere will also contain a dense photochemical smog produced by the action of ultraviolet radiation bathing this nitrogen-methane atmosphere. While the products of these reactions would be an important source of organic compounds for any life that develops on the surface, the resulting haze layer would have potent antigreenhouse properties because of its transparency in the thermal infrared and its ability to scatter visible light (38). On Titan, for example, methane produces a 21 degree K greenhouse effect that is partially offset by its haze layer's 9 degree K antigreenhouse effect.

According to detailed radiative-convective models of Titan's atmosphere, surface temperatures would be relatively insensitive to increases in insolation because the haze layer becomes thicker and puffs up the outer atmosphere with increasing insolation (37). This results in an even more potent antigreenhouse effect that largely offsets the increase in insolation. Simple models of Titan's response to much higher insolation levels estimate that the 176 degree K melting point of a saturated ammonia-water mixture would be reached at an insolation level of 0.15 $S_\oplus$ or an equivalent solar distance of 2.6 AU (37).

While not yet investigated, a hotter sun which has a greater ultraviolet flux would probably have an effect on the position of the outer boundary. More ultraviolet light should produce an even thicker haze layer producing enhanced antigreenhouse properties. As a result, the outer limit for the habitable zone of a reduced planet could be much closer than a solar equivalent distance of 2.6 AU. This is indicated schematically in Figure 8.

The situation with a star significantly cooler than the Sun would be very different. The ultraviolet output of a star drops dramatically with photospheric temperature. This in turn leads to a significantly thinner haze layer and consequently a much diminished antigreenhouse effect. According to models predicting Titan's surface temperature when the Sun evolves into a red giant, the insolation at the outer limit of the habitable zone of a K-type star is 0.06 $S_\oplus$, which corresponds to an equivalent solar distance of 4.0 AU (37).

The location of the inner limit of the habitable zone for planets with reduced atmospheres has yet to be studied. Nonetheless, many of the factors that will come into play can be identified. As the surface temperature slowly increases, the vapor pressure of ammonia will begin to increase as well as its role as a greenhouse gas. This will accelerate the rise in surface temperatures with increasing insolation, invalidating the assumptions made with the current simple models of Titan used to estimate its response to increased insolation. The rate at which ammonia is destroyed by photolysis, despite the shielding effects of the haze layer, now could become an issue to this compound's long-term role in affecting surface temperatures especially around Sun-like and hotter stars.

As the surface temperatures rise even more, enough water will eventually be present in the atmosphere to begin to convert methane into carbon dioxide and hydrogen. Water-derived oxygen could also start to destroy atmospheric ammonia even around cool K- or M-type stars that have low ultraviolet fluxes. Detailed investigation will be required before the ultimate fate of such planets as they experience increased insolation levels can be predicted. It is almost certain that data returned by the European Space Agency's Huygens probe, scheduled to land on Titan in 2004 as part of NASA's Cassini mission, will shed light on the nature of these worlds and their potential habitability.

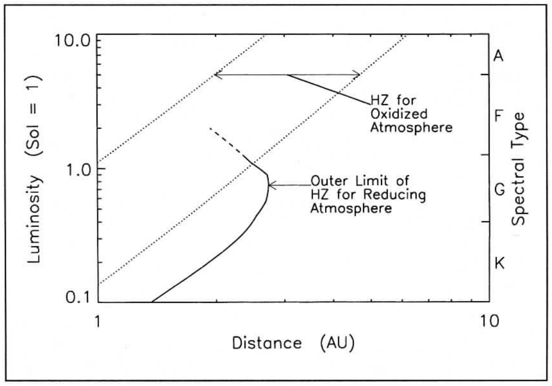

Figure 8: *The estimated outer boundary of the habitable zone (HZ) of a planet with a reducing environment as a function of stellar luminosity is shown above. The axis on the right gives the approximate ranges of luminosity for each spectral type. The sharp bend in the curve at about 0.75 $L_\odot$ is the result of a significant increase in a star's ultraviolet flux which produces a stratospheric haze layer with strong antigreenhouse properties. How this haze layer responds to ultraviolet fluxes significantly greater than the Sun's has yet to be investigated. The size of the habitable zone for an Earth-like planet (defined by the limits of water loss and the maximum greenhouse with carbon dioxide clouds) is shown for comparison.*

Where the Sun Never Sets: A New Model

Dim red dwarfs account for 75 percent of all the stars in the galaxy (39). But because of their extreme dimness compared to the Sun, the distance from a red dwarf corresponding to an Earth-like insolation level ranges from 0.4 to less than 0.03 AU. Any terrestrial planet this close to a red dwarf would quickly have its rotation tidally braked to become a synchronous rotator with one hemisphere always facing its sun while the other experiences perpetual darkness (40). According to conventional wisdom, such a planet would be in radiative equilibrium and quickly experience atmospheric collapse as carbon dioxide, water vapor, and possibly other atmospheric gases permanently freeze and form thick deposits on the planet's cold darkside. Such a situation would be fatal to most, if not all, life forms that managed to arise on such a planet (1). Based on this, red dwarfs are rarely considered candidates for targeted SETI.

But recent calculations and computer simulations performed by Robert Haberle and Monj Joshi of NASA Ames Research Center and their colleagues now suggest that conventional wisdom may be wrong. Early calculations first showed that horizontal atmospheric circulation from a synchronous rotator's lit hemisphere to the dark one was more than strong enough to move the darkside away from radiative equilibrium over a wide but reasonable range of planetary conditions. As a result, atmospheric collapse could easily be avoided. A simple energy balance model produced by Haberle and others hinted that a pure carbon dioxide atmosphere with an estimated surface pressure of 150 millibars was dense enough to avoid atmospheric collapse (41).

With this promising start, a three-dimensional global circulation model was developed to study heat transport on a synchronous rotator in greater detail (42). This model could then be used to verify earlier estimates and study the effects of various parameters in more detail. While the temperature moderating effects of a global system of oceans were not taken into account, this model does provide insights into the climate of synchronous rotators.

The results of this more sophisticated simulation indicate that an Earth-sized planet with a water-saturated carbon dioxide atmosphere can avoid atmospheric collapse with a surface pressure as low as 30 millibars when the insolation is at Earth-like values (42). According to the new model, transient decreases in insolation caused by the passage of starspots would only threaten atmospheric collapse when the pressure is lower than about 100 millibars. These simulations also showed that an atmosphere with 1 to 1.5 bars of carbon dioxide would not only avoid atmospheric collapse but it allows for the existence of liquid water over the entire planet. Despite an Earth-like amount of insolation, this large amount of atmospheric carbon dioxide would likely be present as a natural consequence of the carbonate-silicate cycle which tries to maintain above-freezing temperatures over most of a planet's surface (42).

These simulations found that the temperature differences between the lit and dark hemispheres was quite sensitive to the size of the planet. A planet with a radius of 2 $R_\oplus$ and a mass of 12.6 $M_\oplus$ exhibited much greater hemispheric temperature differences than an Earth-sized planet (42). Even with Earth-like values of insolation, such an atmosphere is close to collapse with a one-bar of carbon dioxide atmosphere. While the increased radius of a larger planet requires the atmosphere to circulate further to transport heat between the hemispheres, much of this difference results from the three-times increase in surface gravity which compresses the atmospheric column height and allows the darkside to radiate heat more effectively.

An investigation of a smaller Mars-sized planet with a radius of 0.53 $R_\oplus$ and a mass of 0.11 $M_\oplus$ shows that the hemispheric temperature differences are much lower than for an Earth-sized planet. For such a planet with an Earth-like insolation level, a carbon dioxide atmosphere with a pressure as low as 10 millibars can avoid collapse (42). As long as this world can remain geologically active enough to support the carbonate-silicate cycle, it is more likely to experience habitable conditions than a larger planet.

While their simulations were not specifically designed to do so, Joshi, Haberle, and their collaborators also explored the effects of synchronous rotation on the bounds of a red dwarf's habitable zone (see Figure 9). Because of the three-dimensional atmospheric temperature structure of synchronous rotators, carbon dioxide will begin to freeze on the surface of the darkside before carbon dioxide clouds form on the lit side. As a result, the formation of such clouds (whether they cool or heat a planet's surface) will not be a factor in determining the location of the outer edge of the habitable zone. In the case of an Earth-sized planet with a one-bar carbon dioxide atmosphere, the outer limit of the habitable zone is estimated to occur when the insolation drops to about 0.3 $S_\oplus$

(42). Based on earlier results, this distance is expected to decrease rapidly with increasing planetary mass.

The inner limit for habitable synchronous rotators is a bit more difficult to define. Water loss from photolysis would not be a concern with a red dwarf because of its low flux of ultraviolet light. In such a case the inner limit of the habitable zone could correspond to the level of insolation required to keep water from freezing on the darkside with a planet possessing minimal amounts of atmospheric carbon dioxide. For an Earth-sized planet with a 0.1-bar carbon dioxide atmosphere, this would occur with an insolation of about 3 $S_\oplus$ (42). While the surface temperature at the subsolar point of such a planet would exceed 200 degrees C, the planet's terminator and darkside could still support life. This inner limit is much smaller than that for Sun-like stars where water loss by photolysis is a concern.

All of these results are very preliminary and vary considerably depending on assumptions made about atmospheric properties. Future computer models, which incorporate the transport of heat by ocean circulation, can take into account the effects of clouds and properly handle carbon dioxide atmospheres denser than a couple of bars, will be required to accurately determine the possible extent of the habitable zones of synchronous rotators orbiting red dwarfs.

Further investigations into the carbonate-silicate cycle will also be required to determine if it can sustain the concentration of atmospheric carbon dioxide needed to avoid atmospheric collapse and maintain habitability. Nonetheless, these initial investigations seem to disprove the previously held conventional wisdom: Apparently dim red dwarfs can have habitable planets over a wide but reasonable range of conditions.

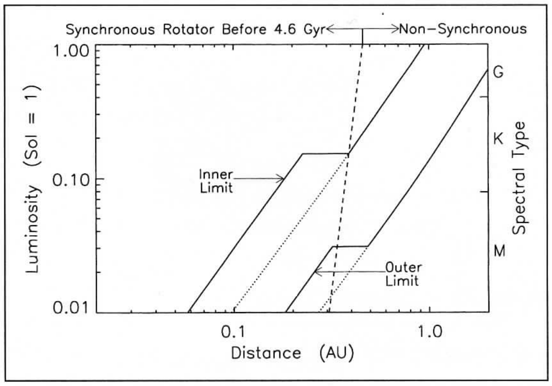

Figure 9: *The estimated locations of the inner and outer bounds of the habitable zone of a synchronously rotating Earth-sized planet are a function of stellar luminosity. The axis on the right gives the approximate ranges of luminosity for each spectral type. The nearly vertical dashed line shows the distance from a sun where a planet would become a synchronous rotator after 4.6 billion years. The boundaries of the habitable zone for a nonsynchronous rotating Earth-sized planet (defined by the limits of water loss and the maximum greenhouse with carbon dioxide clouds) are also shown. The sharp transition in the location of these boundaries in this schematic would probably be much more gradual as a planet's rotation rate slowly decreases.*

Extremes in Obliquity

More than three decades ago, Stephen Dole was the first to explore the effect on planetary habitability of one of the most basic of a planet's properties, the tilt of its rotational axis to the plane of its orbit. This property is called a planet's obliquity. According to his calculations, the polar regions of a planet with a tilt of 55° or greater would receive more light on average than the equator (40). This situation would result in enormous seasonal temperature swings that could render a planet uninhabitable. In the case of synchronous rotators, the obliquity should be close to zero degrees and therefore well below Dole's limit. Even in the worst case situation where the obliquities of all the other potentially habitable planets are randomly distributed, more than half would still be within the limit. If potentially habitable planets are evenly distributed among stars of all spectral types, only about 10 percent of them would be stricken with excessive obliquities.

But this situation was permanently complicated five years ago with the discovery that the obliquities of fast-rotating terrestrial planets vary chaotically over time due to the perturbing influences of other planets. Jacques Laskar and Philippe Robutel of Astronomie et Systèmes Dynamiques, Bureau des Longitudes in Paris, developed computer models which showed that the precession and nutation rates of a planet's rotational axis can enter secular resonances with the perturbing forces of other planets (43). When this happens, the tilt of a terrestrial planet starts changing chaotically. Under such conditions, obliquity can reach values as high as 85°. Not only are such high obliquity values a problem for life on the affected world, but the relative suddenness of these changes presents challenges to their adaptability.

Earth has escaped this fate so far because of the presence of the Moon. The additional torques the Moon produces on the Earth's equatorial bulge keep its rotational axis precessing quickly enough to avoid entering the secular resonances that lead to chaos (43). Since the Moon is generally believed to have originated by chance in a glancing collision between the proto-Earth and a Mars-sized planetesimal (44), the likelihood that other potentially habitable planets have a moon large enough to stabilize their obliquities is very small. As a result, habitable planets like the Earth could be rare. But even the protection afforded by a large moon is not permanent. The Earth's rotation rate is slowing and the Moon is receding as a result of tidal interactions transferring angular momentum from Earth to the Moon. Because of these changes, Earth's obliquity is expected to begin to vary chaotically in 1.5 to 4.5 billion years (45).

Darren Williams and James Kasting have used the two-dimensional energy-balance climate model they developed to study the effects of excessive planetary obliquity on seasonal surface temperatures (17). As had been found in their earlier simulations, increasing the Earth's tilt to 90° has a drastic effect on regional climates. The poles would experience significantly enhanced temperatures. While they would endure the same six-month period of darkness that they do now, the Sun would be within 40° of zenith for 80 days of the year, resulting in greatly increased heating. Summer temperatures in the Arctic could reach as high as 47 degrees C and skyrocket to as much as 80 degrees C in the heart of the landlocked Antarctic. In the tropics, where the sun would spend little time near zenith, temperatures would be cold enough to maintain permanent snow cover (17). While such a situation would hardly sterilize the Earth's surface, it does seriously compromise this planet's global habitability.

Williams and Kasting also investigated the effects of various distributions of continental masses on temperatures. They found that the situation with a polar supercontinent to be the most extreme regardless of obliquity. Even with Earth's present-day 23.5° obliquity, the heart of a polar supercontinent would range from a high of 53 degrees C during the summer to a low of only –56 degrees C (17). Only in a narrow band along the coast near the moderating influence of the global ocean would the temperature extremes be small enough to allow reasonably habitable conditions to exist. Increasing the tilt to only 35° results in seasonal temperature extremes of –77 to +91 degrees C in the heart of the supercontinent. The effects of a 90° tilt could not be investigated with this model due to the extremes of the resulting conditions.

When the supercontinent is located at the equator, the situation is radically different. At an Earth-like obliquity, this world has a lower mean surface temperature and lessened seasonal extremes than the Earth (17). At high obliquity, decreases in the weathering rate push the carbon dioxide levels up to 1670 parts per million and the average surface temperature is 12 degrees C higher. Surprisingly the seasonal temperature extremes are only slightly greater on this world than on the Earth with its present obliquity. A similar situation would exist if the supercontinent were replaced with a group of smaller equatorial continents. While somewhat disquieting, this exercise demonstrates that geography can have as profound an influence on planetary habitability as obliquity.

Further investigations by Williams and Kasting have shown that a dense carbon dioxide atmosphere will help to moderate these temperature extremes since it heats up more slowly and retains heat more effectively. For the next round of simulations, the situation at a distance of 1.4 AU was explored in detail. Except for the case with a polar supercontinent on a planet with a high obliquity, average surface temperatures were comparable to present-day Earth's regardless of geography or obliquity. With a predicted 2 bars of carbon dioxide, these atmospheres would experience seasonal temperature variations smaller than we do today. Obviously planets with denser atmospheres would be even less affected by planetary geography or obliquity.

The conclusion drawn from this work is that somewhere between about 1.0 and 1.4 AU lies a geography-dependent boundary where extreme obliquity is no longer a factor in determining planetary habitability (17). If the edge of the habitable zone lies as far as 2.4 AU from the Sun (24), there would be ample room for habitable planets not affected by chaotic changes in obliquity.

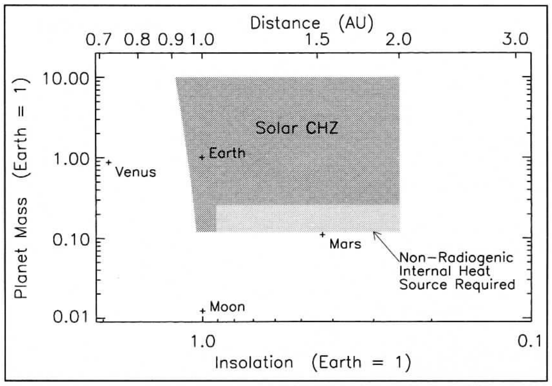

Figure 10: *The shaded area shows the approximate extent of our Sun's current continuously habitable zone (CHZ) in insolation-planetary mass space. The inner boundary is defined by the water-loss limit while the outer one is defined by the maximum greenhouse limit with carbon dioxide clouds at the beginning of the Sun's life on the main sequence 4.6 billion years ago. Also indicated are the positions of Earth, the Moon, Venus, and Mars. The shaded region shows where a body can no longer maintain the carbonate-silicate cycle due to inadequate geologic activity. Such a body can only remain habitable by using nonradiogenic internal heat sources such as tidal heating. Any planet or moon that lies significantly beyond the bounds of this shaded region will not be habitable.*

Even though the earliest work in the field predicted rather limited opportunities for habitability, the size of a star's habitable zone has turned out to be quite large despite the assaults of newly recognized concerns (Figure 10). The addition of the carbonate-silicate cycle to models of planetary habitability can produce robustly habitable planets under a wide range of conditions.

As long as suitably sized planets and moons are common around the stars, there should be billions of habitable worlds in our galaxy where life thrives today.

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