Chapter from the "European Research Course on Atmosphere", vol. 3
From Urban Pollution to Extra-Solar Planets
Edited by C. Boutron,
EDP science, Les Ulis, France, 1998.

CHAPTER 20

Climate and Habitability of Terrestrial Planets around other Stars

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Abstract. The recent discovery of extra-solar giant planets, the quest for extraterrestrial radio-signals with the SETI programs, and recent improvements in climate modelling have recently triggered theoretical studies on the climatic conditions on possible terrestrial planets orbiting other stars. Not surprisingly, the key question that has to be addressed is about the location of planets with climate suitable for life. The region around a star in which life-supporting planets can exist has been termed the "habitable zone". Determining the extent of the habitable zone requires to address many interesting issues, which are briefly described here.

1. INTRODUCTION

1.1. Worlds Around Other Stars

Are there other Earths ? Are we alone ? this commonplace questioning has generated countless fiction stories, but is also motivating more and more hard-science studies within the growing fields of "exobiology" or "bioastronomy". These disciplines involve chemistry, biology, astrophysic as well as planetary sciences and climatology.

Are there other Earths ? a few years ago we did not even know if there were some planets around other stars. Planets are difficult to detect directly, because they are at least one hundred thousand times fainter than their parent stars. Nevertheless, in 1995, Mayor and Quelloz (1995) announced that they had discovered a planet orbiting the solar-type star 51 Pegasi, about 50 light-years from the Earth. Over the subsequent three years, ten other planetary systems have been discovered, and more are expected (see the web page http://wwwusr.obspm.fr/planets/catalog.html). All of these planets have been detected by precision Doppler spectroscopy: a planet impels its host star to move in a small counter-orbit, and the wobbles can be detected as a subtle periodic blue and red shift in the spectrum of the stars (Fig. 1). Currently, such measurements of the stars radial velocities can only detect Jupiter-size or larger giant planets, but the sensitivity of the instruments is improving. Several other technologies may also find planets in the near future. First, precision astrometry (measurement of the position of the star relative to distant background objects) could also detect the wobble of the star, and space-based observatory using interferometry may be able to detect Earth-mass terrestrial planets around nearby stars within twenty years. Photometry measurements may also be able to detect terrestrial planets through the detection of stellar brightness variations which are indicative of the presence of a planetary system (microlensing events, where the planet crosses in front of a distant star, and transit events, where the planet crosses in front of its own central star). In addition, next-generation interferometers able to perform spectroscopy of extrasolar-planets in the infrared are planned for the second decade of the next millenium. Such missions could detect atmospheric ozone, which is thought to be a good signature for the presence of molecular oxygen and probably life. On a longer time scale, it has been proposed to build an enormous, kilometer-sized space telescope that would be capable of imaging the mountains and oceans on Earth-like planets around other stars. Finally, some scientists are trying to detect extraterrestrial intelligent life directly by looking for radio signals. The "Search for Extra-Terrestrial Intelligence" (SETI) programs involve several major radio-telescopes around the world. The main SETI project used to be a NASA program, but it is now mainly supported by private institutions. No signal have been detected, yet.

1.2. The Habitable Zone

Within this context, the concept of "habitable zone" deals with the following questions: where can be found planets where life can originate and evolve ? at which distance from a given star ? around which stars ? Behind these questions lies an even more fundamental one: what does it take for a world to support life ? Obviously, the answer depends on the kind of life that we want to consider or can imagine. One can speculate on forms of life based on liquid NH_3 or even plasma ions interactions. However, most studies so far have intentionally focussed on "life as we know it", and our experience on Earth has told us that the requirement for life is liquid water directly, regardless of mean temperature and pressure (Brack 1993). This may be chauvinistic, but if optimistic conclusions can be reached with such a narrow focus, then whatever we have ignored could only serve to broaden the biological arena (Sagan 1996). Within this context, the "habitable zone" is usually defined as

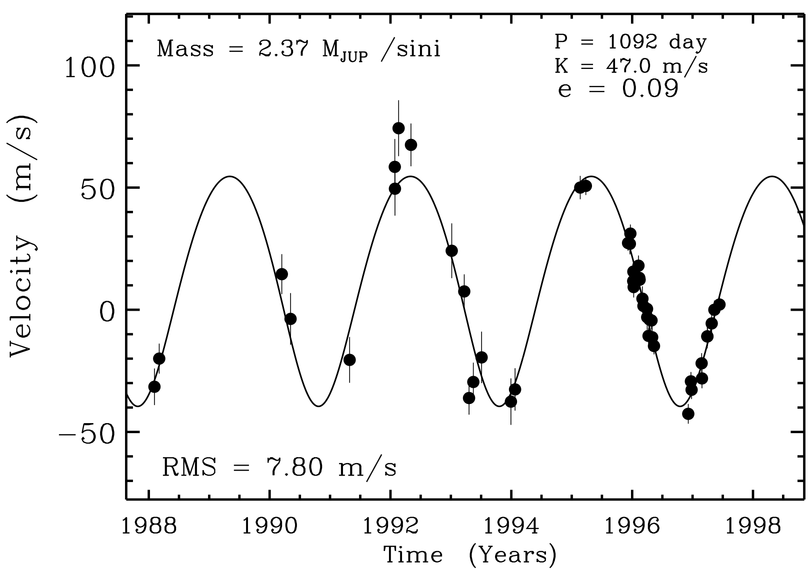

Figure 1. Radial velocity of star 47 Ursae Majoris about 43 light-years away. The sinuous shape betrays the presence of an unseen planet tugging at its parent stars. The planet orbit is almost circular, at 2.1 AU from the star (1 AU is the mean distance of Earth from the Sun). The planet has about 2.5 times the mass of Jupiter. Although it may be within the "habitable zone", such a giant planet probably lack a solid or liquid surface suitable for life. However, it could have an habitable moon (Williams et al. 1997). Figure from Butler and Marcy (1996).

the range of orbital distance within which worlds can maintain liquid water on their surface. Following numerous papers published over the past thirty years, the key reference on the subject remains the masterly work published by Kasting, Whitmire and Reynolds (1993) (see reference therein for previous studies). Since then, several papers have contributed in a significant way to the subject (See Doyle 1996, Joshi et al. 1997, Williams et al. 1997, Williams and Kasting 1997, Forget and Pierrehumbert 1997). And of course, extrasolar systems have been at last discovered. Here, we provide a short review of this wide subject.

2. HABITABLE ZONE AROUND A SUN-LIKE STAR

2.1. Inner Edge

The habitable zone around a solar-type star (G2) is defined by its boundaries. Obviously, a planet will not be habitable if it is too close to its star so that nowhere on this planet temperature below the boiling point of water can be found.

2.1.1. The Runaway greenhouse limit

As defined, the inner edge may not be very far inside the current Earth orbit because of a destabilizing mechanism called the "runaway" greenhouse effect: if a planet with liquid water on its surface is "moved" toward the sun, its surface warms, increasing the amount of water vapor in the atmosphere. This water vapor strongly enhances the greenhouse effect, which tends to further warm the surface. This positive feedback is thought to have destabilized Venus climate early in its history. In practice, even for a well-known planet like ours, the runaway greenhouse limit is not easy to determine because other physical processes may help stabilize the climate and limit the runaway effect (Gerard and Francois 1988). For instance, adding water vapor in the atmosphere tends to reduce the atmospheric lapse rate (locally toward a "moist adiabatic lapse rate") and thus reduces the mean greenhouse effect. Also, more clouds may form in a wetter and warmer atmosphere. By their effect on the planetary albedo, they would tend to protect the planet from the sun and reduce the surface temperature. Taking into account the lapse rate effect in a 1D radiative-convective model of an Earth-like planet, but ignoring the clouds, Kasting (1988) found a well defined runaway greenhouse limit at 0.84 Astronomical Units (AU) from the sun (Fig 2b).

2.1.2. The Water-loss Limit

Kasting (1988) also showed that in his model -and probably in reality-, there were a critical limit located even farther from the sun (at 0.95 AU in his simulation) where the stratosphere was suddenly becoming completely wet (Fig 2a). In a wet stratosphere, water vapor can be rapidly dissociated by ultraviolet radiation, and hydrogen lost to space through an efficient process called hydrodynamic escape. In such conditions, an Earth-like planet would lose its entire oceans in a few million years (the Earth currently keeps its water thanks to a cold-trapping of water at the tropopause). Clearly, this water-loss limit is the one of primary physical concern on the inner edge of the habitable zone. There again, a lot of uncertainties exist, and the 0.95 AU limit can be considered to be conservative, mostly because clouds feedbacks are ignored (Kasting et al. 1993). Assuming that clouds may protect a planet by raising its albedo up to 80% (this approximately corresponds to a continuous and thick water clouds cover), an habitable planet at about 0.5 AU from the sun is conceivable. This

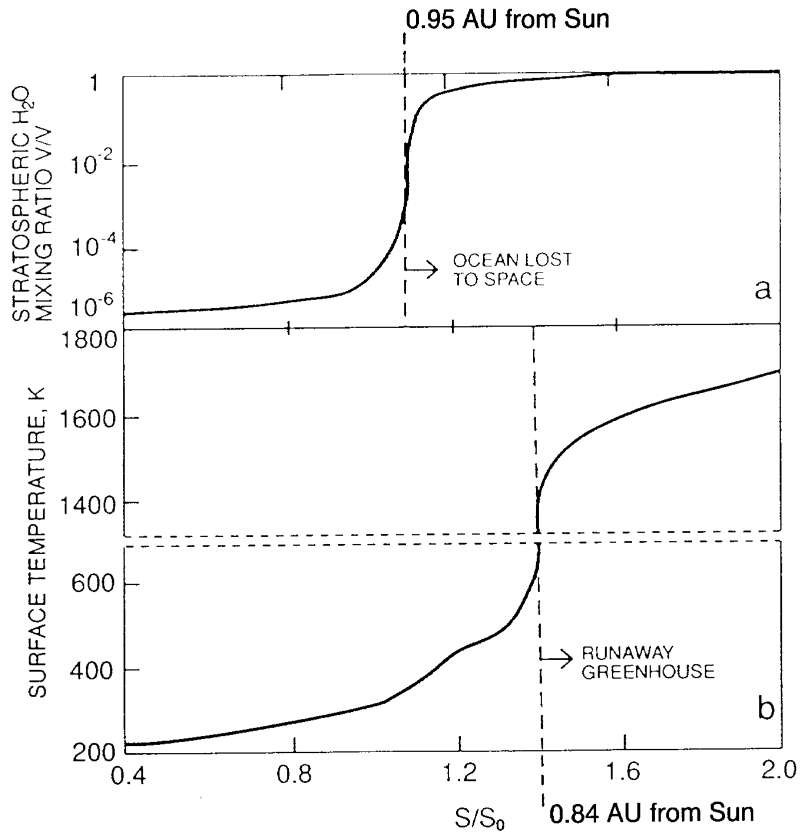

Figure 2. Response of an Earth-like planet's atmosphere to change in solar flux S, according to the 1D radiative-convective model of Kasting (1988). The corresponding orbital distance is $d = \sqrt{S_0/S}$. S_0 is the present solar flux at the Earth's orbit. a) Mean stratospheric water mixing ratio. b) Mean surface temperature. The effect of clouds are neglected. Figure from Kasting and Grinspoon (1991).

is an extreme value: physical processes able to maintain liquid water at say, 0.4 AU, are hard to imagine.

2.2. Outer Edge

2.2.1. The Earth's case

The outer edge of the habitable zone is the limit outside which water is completely frozen on the planet surface, i.e. where nowhere on a planet surface temperature higher than 273 K can be found. Estimating this limit with a classical model of Earth climate, even sophisticated, gives pessimistic conclusions because of strong positive feedbacks on the temperature related to the process of "runaway glaciation": a lower solar flux decreases the surface temperatures, and thus increases the snow and ice cover, leading to higher surface albedos which tend to further decrease the surface temperature. Simple energy-balance models predict that the Earth would become globally glaciated if it was 1 to 2% farther from the Sun (see e.g. Sellers, 1969 or more recently Gérard et al. 1992). More realistic 3D models accounting for various continental configurations and for the seasonal cycle simulate a more progressive evolution toward the completely frozen solution, with possibly liquid water as far as 1.15 AU (Longdoz and François 1997).

However, in the Earth case, there are evidences that additional, long term processes have insured climate stability so that liquid water has almost always been present on our planet in spite of variations of the solar luminosity larger than 25% (Kasting 1997). The most likely of these processes is the carbonate-silicate cycle (Walker et al. 1981), which may provide a long-term control of the CO_2 concentration in Earth's atmosphere in order to ensure a CO_2 greenhouse effect compatible with the presence of liquid water. On Earth, CO_2 is removed from the atmosphere by the weathering of calcium and magnesium silicates in rocks and soil, releasing various ions, including carbon ions (HCO_3^-, CO_3^{2-}). These ions are transported into the world ocean through river or ground water runoff. There, they form carbonate and precipitate to the seafloor to make carbonate sediments. Ultimately, the seafloor is subducted into the mantle, where silicate are reformed and CO_2 is released and vented back to the atmosphere by volcanos. Assuming that weathering is an increasing function of the mean surface temperatures (through a presumed enhanced role of the water cycle, precipitation, runoff, with higher temperatures) one can see that this cycle should strongly stabilize the climate. Although this assumption and the degree of control of the climate by the CO_2 cycle remain speculative (François et al. 1993), it is clear that a planet like Earth would remain habitable even far from the sun: on a completely frozen Earth with no liquid water (no precipitation, no runoff, no river, no weathering and no ocean) , CO_2 would begin to accumulate in the atmosphere. Ultimately, a dense CO_2 atmosphere would be formed in a few millions years, and the CO_2 greenhouse effect would tend to melt the ice (see a recent speculation for the Earth 700 millions years ago in Hoffman et al. 1998).

2.2.2. Other Planets

Can this process be generalized to other terrestrial planets ? In principle, this would mean that we assume a relatively large CO_2 inventory on exo-terrestrial planets. Based on our solar system experience where this is generally the case, we can only say that this is the most likely configuration. Other chemical inventories are of course possible, but then similar processes could play a similar role.

Within this context, one can define the outer edge of the habitable zone as the limit where a realistic atmosphere -in terms of composition and thermal structure- can keep its surface warm enough for liquid water. Atmospheres warm the surface by their greenhouse effect which, to first order, depends on 1) the amount and the efficiency of the greenhouse gases present in the atmosphere, 2) the mean temperature difference between the emitting upper atmosphere and the surface 3) possibly clouds. The most likely greenhouse gases on an habitable planet are CO_2 and of course H_2O. Other gases like NH_3 or CH_4 are possible in a reducing atmosphere, but they are rapidly photodissociated so that they must be shielded from solar UV (Sagan and Chyba 1997) or produced by a continuous source or a recycling process (Kasting 1997). It turns out that a thick CO_2 atmosphere may be among the most efficient solution for keeping a planet warm. This is not due to the properties of the CO_2 gas itself. In fact, the greenhouse effect of a purely gaseous atmosphere is limited, and in particular adding more and more greenhouse gas to keep a planet warm does not work indefinitely. For instance, once the atmosphere becomes opaque at all infrared wavelengths, adding more gases usually increase the albedo by Rayleigh scattering (and thus reduce the absorbed solar energy) without increasing the greenhouse effect. This is particularly true for CO_2 which molecules are efficient Rayleigh scatterers. In addition, in a CO_2 atmosphere above a surface at liquid water temperature, CO_2 should condense at every latitude for surface pressure larger than a few tens of millibars. As first shown by Kasting (1991), the condensation of CO_2 decreases the mean temperature difference between the emitting upper atmosphere and the surface, and thus limits the greenhouse effect. In such conditions, Kasting et al. (1993) estimated that the maximum gaseous CO_2 greenhouse effect was reached with about 8 bars of CO_2. According to their 1D radiative-convective model, the corresponding maximum distance from the sun compatible with a mean surface temperature above the freezing point of water was 1.67 AU. In this calculation, the radiative effects of the CO_2 ice clouds resulting from the CO_2 condensation were ignored. Because they are perfect scatterers at solar radiation wavelengths, the CO_2 ice particles should raise the planetary albedo. Kasting et al. worried that these clouds could thus cool the planet by reflecting the solar light. However, unlike water ice, CO_2 ice is quite transparent in the thermal infrared, and CO_2 ice clouds particle should be able to scatter the infrared radiation as well. On this basis, Forget and Pierrehumbert (1997) showed that CO_2 ice clouds may in fact be able to warm the planet by reflecting upwelling thermal IR radiation more effectively than incoming solar radiation. Overall, this process was found to be extremely efficient to warm a planet surface, and was suggested to explain how Mars could have supported flowing water early in its history as shown by geomorphic evidence. Taking into account this process, the outer edge of the habitable zone was extended as far as 2.5 AU (Fig. 3). This value is an extreme, to be kept in mind along with the more conservative 1.67 AU value obtained with no other greenhouse gas than CO_2 and H_2O, and ignoring clouds effects.

2.2.3. Beyond the "surface-liquid-water" limit

Outside the outer edge of the habitable zone defined above, there are still possibilities for liquid water very far from a star if the heat necessary to keep

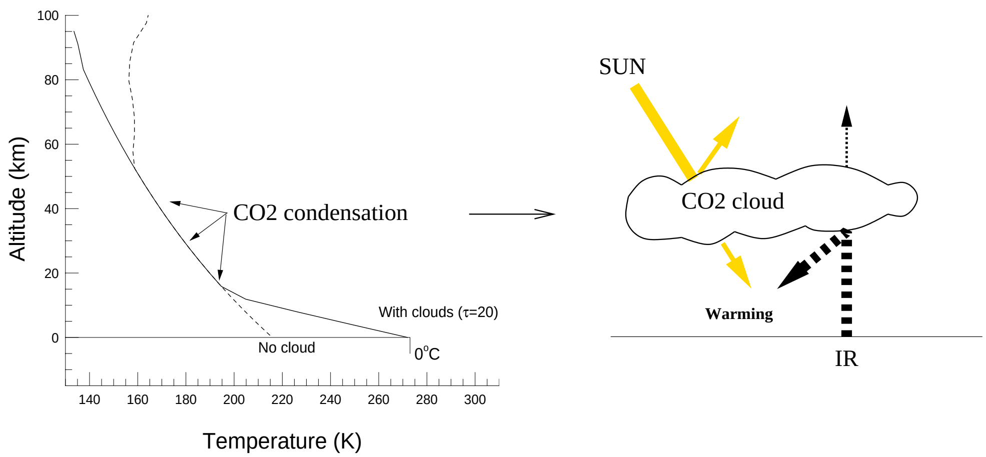

Figure 3. Mean temperature profiles on a terrestrial planet located 2.5 AU from a sun-like star, with an atmosphere composed of 5 bars of pure CO_2. Assuming a global coverage of pure CO_2 ice clouds of visible optical depth $\tau = 20$, the mean surface temperature is raised up to the melting point of water because of trapping of the thermal radiation by the IR reflecting CO_2 ice clouds. Results obtained with Forget and Pierrehumbert (1997)'s model.

the temperature above the freezing point of water is not coming from sunlight. Heat can also come from the interior of the planet. This is the case if the planet is large enough, with radiogenic activities, as in the Earth's case. What would have happened to the Earth as we know it had it form at several AU from the sun ? It is conceivable that a form of tectonic would have occurred, and that locally, nearby volcanos and vents below the frozen oceans, liquid water habitats could have supported life. The heat can also results from tidal forces as in the case of satellite Europa around Jupiter. Europa has received a great deal of attention because of the possible existence of global water ocean between its icy surface and the rocky interior (Carr et al. 1998). Did life emerge on Europa ? In any case, it is striking that Europa, one of two prime candidates with Mars for a second habitable world in our own Solar System lies well beyond the surface-liquid-water zone, has only about a hundredth of Earth's mass, and has almost no atmosphere (Chyba 1997).

2.3. Habitability through time

Time is required for life to begin and evolve. For instance, the formation of Earth occurred about 4.5 Gyr ago. Evidence from stromatolites and micro-fossils provides strong evidence that life was present on Earth by 3.5 Gyr ago (Schopf 1993) and probably 3.8 Gyr ago (Mojzsis et al. 1996). However, the

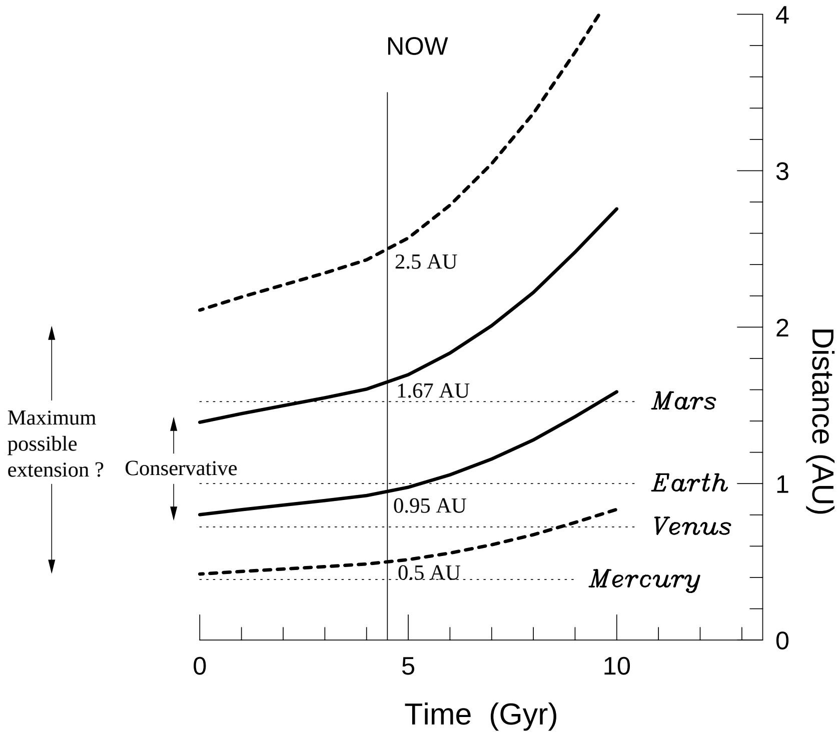

Figure 4. Evolution of the habitable zone during the main sequence of a solar-mass star. Solid lines show "conservative" limits for Earth-like planets and the dashed lines illustrate what is thought to be the maximum possible extension of the surface-liquid-water habitable zone (no internal heat), as defined in the text. Dotted lines show the location of the terrestrial planets orbits in the solar system. The solar luminosity evolution function is taken from Kasting et al. (1993).

first multicellular animals only appeared about 0.6 Gyr ago and technological civilization a few years ago... It is not known if this evolution time is typical for other planets as well, but the question of habitability through time must be addressed.

2.3.1. Star Evolution.

The habitable zone described previously tends to migrate outward with time because stars become brighter as they age (Gough 1981). According to models, the Sun was approximately 30% dimmer when the solar system formed 4.6 Gyr ago and will increase to about 2.2 times its present luminosity by the time it leaves the main sequence at the end of core hydrogen burning in about 6.5 Gyr (Whitmire and Reynolds 1996). The evolution of the habitable zone limits previously determined is shown in Fig. 4. It appears that the "continuously habitable zone" (CHZ), i.e. the orbital range where a planet can remain habitable long enough for life to begin and evolve is quite narrower than the habitable zone at a given time.

2.3.2. Examples in the Solar System

The mean orbital radius of the terrestrial planets of the solar system are also shown on Fig. 4. The Earth is the only planet which has stayed within the "conservative" definition of the habitable zone throughout its lifetime. Venus started slighly too close to the sun to be within the conservative habitable zone, whereas the presence of large amount of water billions years ago is expected by planet formation models. The discovery of a 100-fold enrichment in deuterium in the Venus atmosphere has traditionally been considered as an evidence of this presence, such an enrichment being interpreted as the consequence of water escape to space (escaping can be less efficient for deuterium than hydrogen) (Donahue et al. 1982). Although alternative explanations for this enrichment are now more and more considered (Grinspoon 1993), early Venus may have been covered by oceans of liquid water when the sun was weaker than today. Then Venus probably lost its oceans by photodissociation of stratospheric water followed by hydrogen escape as described above (see Kasting 1988). From then on, any carbon dioxide exhaled by volcanoes or delivered by impacts on Venus could no longer be removed from the atmosphere by chemical weathering because of the lack of liquid water. As carbon dioxide accumulated in the atmosphere, the greenhouse effect grew ever more intense, leading to the dry and hot planet with a thick CO_2 atmosphere that we know now. Similarly, there is sound geomorphic evidence that Mars was habitable 3.8 billion years ago as suggested by the observation of ubiquitous dry river valleys in the oldest terrains. Mars was then outside the conservative outer edge limit: such a warm and wet climate cannot be explain by the conventional greenhouse warming of a thick atmosphere composed of only CO_2 and H_2O. CO_2 ice clouds, or possibly other greenhouse gas and geothermalism probably played a role. Later, Mars lost most its atmosphere, probably because of a high rate of escape to space and the lack of tectonic activity able to recycle CO_2 after incorporation in carbonate rocks (Jakosky and Jones 1997).

2.3.3. Keeping an atmosphere

The Martian example reminds us that to remain habitable a planet must keep its atmosphere. In particular, a recycling mechanism of the surface back to the atmosphere (plate tectonic on Earth) is probably needed. This may require a relatively large planet because larger planet cool in more time than smaller planet. A possible exception is the case of habitable moons orbiting giant planets which might be tidally heated in a manner similar to Jupiter's moons Io and Europa (Williams et al. 1997). In any cases, to hold onto its atmospher over time, a planet must be large enough to prevent its molecules to escape to space through thermal escape or erosion due to meteorit impacts.

Volatiles can also be lost to space due to sputtering by charged particles from the solar wind. This process may have played a key role in the loss of Mars's atmosphere (Jakosky and Jones 1997). Sputtering would particularly affect the atmospheres of extra-solar giant planets' moons because of the charged particles trapped within the planet's magnetosphere (Williams et al. 1997). To avoid this problem, Mars's size extrasolar planet and moons around giant planets may need a strong magnetic field to deflect the solar wind and the charged particles, as on Earth currently.

2.3.4. Orbital evolution and climate stability

Laskar et al. (1993) recently calculated that the obliquities of the terrestrial planets in the solar system (except the Earth) undergo large-amplitude, chaotic fluctuations on time scales of about 10 myr. Earth is an exception, but only because it has a large moon that accelerates its rate of spin axis precession. Were it not for the fortuitous presence of the Moon, Earth's obliquity would vary chaotically from 0^o to 85^o. Such variations would strongly affect the climate. Given the fact that the moderate $\pm 1.3^o$ variations of present Earth obliquity are thought to trigger the glacial-interglacial oscillations of Earth climate, one can wonder about the effect of much larger variations on an extra-solar planet. Would such a planet remain habitable ?

During periods with very low obliquities, the climate should be very stable with a small seasonal cycle. However, the average annual insolation near the poles would be near zero and locally polar temperature may get very low. One threat would thus be the irreversible condensation of water and CO_2 into massive water and carbon dioxide polar ice caps (atmospheric collapse). However, this process has not been studied in details.

At large obliquities, Williams and Kasting (1997) used an energy balance model to show that the Earth's climate would become regionally severe, with temperature extreme on continents which might be damaging to many forms of life, depending on the land-sea distribution. Nevertheless, they concluded that a significant fraction of extrasolar Earth-like planet may still be habitable.

3. AROUND OTHER STARS

3.1. Massive Stars

The main sequence lifetime of a star decreases rapidly with its mass M (it is proportional to $M^{-3.75}$; Whitmire and Reynolds 1994). Thus, habitable planets may exist around stars much more massive than the sun, but it is doubtful that life will be able to really evolves. If one assume that, say, 2 Gyr are necessary for complex organisms to exist (and build radiotelescope to say hello), only stars with mass less than 1.5 solar mass can be considered. The stellar mass also affects the radiation output from the star. An higher mass corresponds to an higher effective radiating temperature. Thus, not only

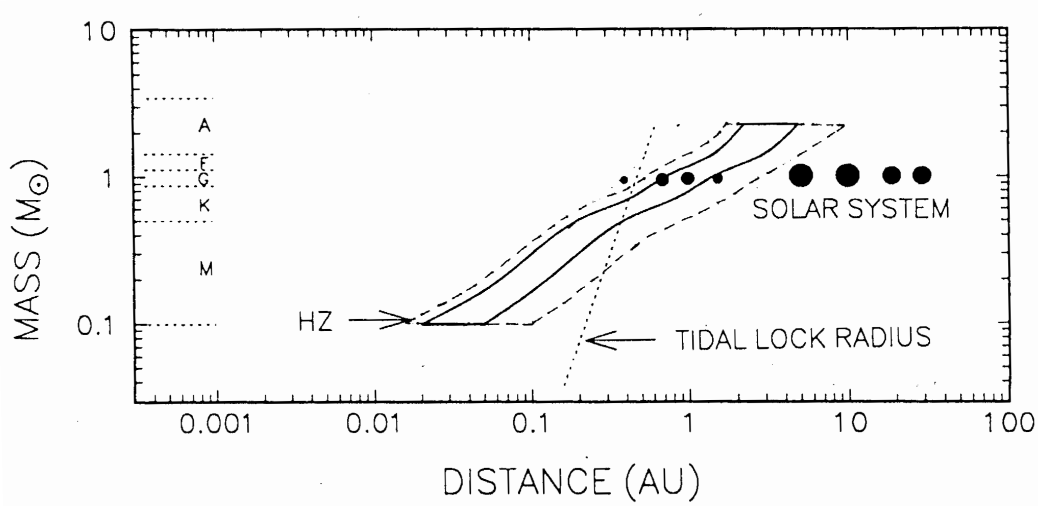

Figure 5. Diagram showing the habitable zone as a function of stellar mass at the beginning of the main sequence of the stars (i.e. 4.5 Gyr ago for our Sun). The solid and dashed lines correspond respectively to the boundaries of the "conservative" and "maximum possible extension" of the surface liquid water habitable zone, as in Fig. 4 (note that the dashed lines were extrapolated from the solid lines originally drawn, and that they are shown here for illustration only). The dotted line represents the distance at which an Earth-like planet in a circular orbit would be locked into synchronous rotation within 4.5 Gyr as a results of tidal damping, like for the Moon around the Earth. All Earth-like planets within the habitable zone of a small M star would be within this radius. Figure adapted from Kasting et al. (1993)

the total energy flux from the star will be stronger (and the habitable zone moved outward on an absolute scale) but the radiation will be emitted a shorter wavelengths. This increases the planetary albedo (because of less atmospheric absorption in the near-infrared and more Rayleigh scattering), and thus tends to move the boundaries of the habitable zone toward regions with higher energy flux compared to the solar system case. Figure 5 shows how the habitable zone varies with stellar mass. A possible problem could be the high ultraviolet flux emanating from such stars, which would require a superefficient ozone screen to allow the drylands to be habitable (Kasting et al. 1993).

3.2. Small Stars

Stars less massive than the sun have a longer lifetime and are the most numerous in the Galaxy. In fact, the M stars with masses 0.1-0.5 times the mass of the sun constitute approximately 75 % of the stellar population, and have lifetimes longer than the age of the universe. Their evolution in 10 Gyr is negligible, so their continuously habitable zone is identical to their initial habitable zone. Because they are much less luminous than the sun, the habitable zones around such stars are very close (Fig. 5). A planet lying this close to its star will tend to become locked as a results of tidal damping like for the moon around the Earth (see dotted line on Fig. 5). Therefore, one side of the planet will be permanently illuminated while the other side is in perpetual darkness. Can such planets be habitable ? This could result in the permanent freezing of all water and other volatiles on the dark hemisphere, and in very high temperature on the other side. However, the night and day temperature gradient can be reduced by atmospheric and possibly oceanic transport. For instance, using an simplified general circulation model, Joshi et al. (1997) found that a modest surface pressure higher than 30 mb only is required to prevent a CO_2 atmosphere from freezing out and generate an atmospheric collapse, and that a surface pressure of 1000-1500 mb of CO_2 would allow the planet to support stable liquid water on the darkside at the inner edge of the habitable zone. In fact, the planet's slow rotation, as well as the synchronous heating induce an atmospheric circulation regime which is very efficient to transport heat. As for Venus and Titan (Hourdin et al. 1995) the atmosphere rotates much faster than the solid planet at most levels. This "superrotation" is combined with a thermally direct longitudinal cell transporting heat from the dayside to the nightside. The circulation is three-dimensional, with low level winds returning mass to the dayside across the polar regions. Joshi et al. (1997) also noted that since M stars are relatively cool, they radiate very little energy at short wavelengths, which strongly decreases the rate of photodissociation of H_2O. In such conditions, the water-loss limit found around Solar-mass stars may not be an issue. However, they also mentioned that the small M stars experience flares that are relatively large in magnitude when compared to solar-type stars, and that this stellar activity could hinder habitability. Nevertheless, Joshi et al. (1997) concluded that the planets orbiting M stars can support atmosphere over a large range of conditions and are likely to be habitable.

3.3. Binary and Multiple Star System

Double and multiple stars systems are established to be more abundant than single stars (such as the sun), at least in the solar neighborhood (Duquennoy and Mayor 1991). The effects of nearby stellar companions on the habitability of terrestrial planets must thus be considered in estimating the number of potential life-bearing planets within the Galaxy. A first issue concerns the actual existence of such systems, since it has been suggested that the perturbation by the secondary star may preclude the planet formation. However, recent results suggest that in most case this should not be a major problem (Whitmire et al. 1997). A second issue concerns the stability of planetary orbits in multiple systems. There again, although preliminary studies were rather pessimistic, modern computations have shown that many such stable orbits do exist, either around the multiple system as a whole, or around one component of the system.

4. CONCLUSION

Most recent studies on the habitability of extra-solar planets have yield relatively optimistic conclusions, with a relatively wide habitable zone and modelling results which suggest that large obliquity variations, synchronous rotation or other apparently dangerous configurations should not preclude the habitability of the planets. A recent study performed using a sophisticated model of the formation of the terrestrial planets and asteroids around different kinds of stars have yield the conclusion that solar-mass star should almost always have at least one planet of mass $> 1/3$ Earth mass in their habitable zone, and that the presence of an habitable planet is quite possible around stars as small as 0.5 solar mass or as large as 1.5 solar mass (Wetherill 1996). However, one must keep in mind that all the results presented in this chapter are based on our solar system experience only, and that its is difficult to know if the physical processes which are thought to control the formation, the evolution and the current status of the Earth and the other planets in the solar system are representative of other stellar systems. By definition, our experience is biased by the fact that we live on a very habitable planet, at least from our point of view.

References

Brack, A. (1993). *Orig. of Life*, 3-10:23.

Butler, P. and Marcy, G. (1996). A planet orbiting 47 Uma. *Ap.J. Letters*, 464:L153–L156.

Carr, M. H. and 21 co-authors (1998). Evidence for aubsurface ocean on Europa. *Nature*, 391:363–365.

Chyba, C. F. (1997). Life on other moons. *Nature*, 385:201.

Donahue, T. M., Hoffman, J. H., Hodges, R. R., and Watson, A. J. (1982). Venus was wet: a measurement of the ratio of deuterium to hydrogen. *Science*, 216:630–633.

Doyle, L. R., editor (1996). *Circumstellar Habitable Zone.* Travis House Pulications, Menlo Park, California.

Duquennoy, A. and Mayor, M. (1991). Multiplicity among solar-type stars in the solar neighborhood. II. Distribution of the orbital elements in an unbiased sample. *Astron. Astrophys.*, 248:485–524.

Forget, F. and Pierrehumbert, R. T. (1997). Warming early Mars with carbon dioxide clouds that scatter infrared radiation. *Science*, 278:1273–1276.

Francois, L. M., Walker, J. C. G., and Opdyke, B. N. (1993). The history of global weathering and the chemical evolution of the ocean-atmosphere system. In Takahashi, E., Jeanloz, R., and Dubie, D., editors, *Evolution of the Earth and Planets*, volume 14, pages 143–159. IUGG.

Gerard, J. C. and Francois, L. M. (1988). A sensitivity study of the effects of solar luminosity changes on the earth's global temperature. *Annales Geophysicae*, 6:101–112.

Gerard, J.-C., Hauglustaine, D. A., and Francois, L. M. (1992). The faint young sun climatic paradox: a simulation with an interactive seasonal climate-sea ice model. *Paleogeogr., Paleoclimatol., Paleoecol.*, 97:133–150.

Gough, D. O. (1981). Solar interior structure and luminosity variations. *Solar Phys.*, 74:21–34.

Grinspoon, D. H. (1993). Implications of the high D/H ratio for the sources of water in venus' atmosphere. *Nature*, 363:428–431.

Hoffman, P. F., Kaufman, A. J., Halverson, G. P., and Schrag, D. P. (1998). A neoproterozoic snowball Earth. *Science*, 281:1342–1346.

Hourdin, F., Talagrand, O., Sadourny, R., Régis, C., Gautier, D., and McKay, C. P. (1995). General circulation of the atmosphere of Titan. *Icarus*, 117:358–374.

Jakosky, B. M. and Jones, J. H. (1997). The history of Martian volatiles. *Review of Geophysics*, 35:1 –16.

Joshi, M. M., Haberle, R. M., and Reynolds, R. T. (1997). Simulations of the atmospheres of synchronously rotating terrestrial planets orbiting M dwarfs: conditions for atmospheric collapse and the implications for habitability. *Icarus*, 129:450–465.

Kasting, J., Whitmire, D. P., and Reynolds, R. T. (1993). Habitable zones around main sequence stars. *Icarus*, 101:108–128.

Kasting, J. F. (1988). Runaway and moist greenhouse atmosphere and the evolution of Earth and Venus. *Icarus*, 74:472–494.

Kasting, J. F. (1991). CO_2 condensation and the early climate of Mars. *Icarus*, 94:1–13.

Kasting, J. F. (1997). Warming early earth and mars. *Science*, 276:1213–1215.

Kasting, J. F. and Grinspoon, M. S. (1991). The faint young sun problem. In Sonett, C., Grinspoon, M., and Matthews, M., editors, *The sun in time*, pages 447–462.

Laskar, J. and Robutel, P. (1993). The chaotic obliquity of the planets. *Nature*, 361:608–612.

Longdoz, B. and Francois, L. M. (1997). The faint young sun paradox: influence of the continental configuration and of the seasonal cycle on the climatic stability. *Global and Planetary change*, 14:97–112.

Mayor, M. and Queloz, D. (1995). A Jupiter-mass companion to a solar-type star. *Nature*, 378:355–359.

Mojzsis, S. J., Arrhenius, G., McKeegan, K, D., Harrison, T. M., Nutman, A. P., and Friend, C. R. L. (1996). Evidence for life on earth before 3,800 million years ago. *Nature*, 384:55–59.

Sagan, C. (1996). Circumstellar habitable zones: an introduction. In Doyle, L. R., editor, *Circumstellar Habitable Zones*, pages 3–14.

Sagan, C. and Chyba, C. (1997). The early faint young sun paradox: organic shielding of ultraviolet-labile greenhouse gases. *Science*, 276:1217–1221.

Schopf, J. W. (1993). Microfossils of the early archean apex chert: new evidence of the antiquity of life. *Science*, 260:640–646.

Sellers, W. (1969). A climate model based on the energy balance of the Earth-atmosphere system. *J. Appl. Met.*, 8:392–400.

Walker, J. C. G., Hays, P. B., and Kasting, J. F. (1981). A negative feedback mechanism for the long term stabilization of the earth's surface temperature. *J. Geophys. Res.*, 86:9776–9782.

Wetherill, G. W. (1996). The formation and habitability of extra-solar planets. *Icarus*, 119:219–238.

Whitmire, D., Matese, J., Criswell, L., and Mikkola, S. (1997). Habitable planet formation in binary star systems. *Icarus*, 132:196.

Whitmire, D. P. and Reynolds, R. T. (1996). Circumstellar habitable zones: Astronomical considerations. In Doyle, L. R., editor, *Circumstellar Habitable Zones*, pages 117–142.

Williams, D. M. and Kasting, J. F. (1997). Habitable planets with high obliquities. *Icarus*, 129:254–267.

Williams, D. M., Kasting, J. F., and Wade, R. A. (1997). Habitable moons around extrasolar planets. *Nature*, 385:234–236.