Habitable Zones of Host Stars During the Post-MS Phase

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Received 16 Nov. 2009; accepted 9 Feb. 2010

Abstract. A star will become brighter and brighter with stellar evolution, and the distance of its habitable zone will become farther and farther. Some planets outside the habitable zone of a host star during the main sequence phase may enter the habitable zone of the host star during other evolutionary phases. A terrestrial planet within the habitable zone of its host star is generally thought to be suited to life existence. Furthermore, a rocky moon around a giant planet may be also suited to life survive, provided that the planet-moon system is within the habitable zone of its host star. Using Eggleton’s code and the boundary flux of habitable zone, we calculate the habitable zone of our Solar after the main sequence phase. It is found that Mars’ orbit and Jupiter’s orbit will enter the habitable zone of Solar during the subgiant branch phase and the red giant branch phase, respectively. And the orbit of Saturn will enter the habitable zone of Solar during the He-burning phase for about 137 million years. Life is unlikely at any time on Saturn, as it is a giant gaseous planet. However, Titan, the rocky moon of Saturn, may be suitable for biological evolution and become another Earth during that time. For low-mass stars, there are similar habitable zones during the He-burning phase as our Solar, because there are similar core masses and luminosities for these stars during that phase.

Key words. Stars: horizontal branch — Planets: moons — Astrobiology

1. Introduction

Typically, stellar habitable zone (HZ) is defined as a region near the host star where water at the surface of a terrestrial planet is in the liquid phase (e.g., Kasting et al. 1993; Franck et al. 2000; Noble et al. 2002; Jones et al. 2006). The inner HZ boundary is determined by the loss of water via photolysis and hydrogen escape. And the outer HZ boundary is determined by the condensation of carbon dioxide crystals out of the atmosphere (von Bloh et al. 2007).

Previously, it was generally paid attention to the HZs of host stars during the main sequence (MS) phase, because the evolution from biochemical compounds to primary life needs long enough time. And a terrestrial planet around a host star covers a presumed heavy bombardment phase as on Earth (Jones 2004; Lal 2008), during the initial evolutionary stage of the host star. And the heavy bombardments make the temperature on the surface of a terrestrial planet become very high, which is not suitable for biological evolution. Only when the temperature on the surface of a terrestrial planet goes down, the evolution from biochemical compounds to primary life may start. These mean that the evolutionary age of a host star when life comes into being on a terrestrial planet around the host star is longer than the evolutionary timescale from biochemical compounds to primary life on the terrestrial planet.

The evolutionary timescale of a host star during the MS phase is generally much longer than the timescale of heavy bombardments on a planet around the host star. Therefore, all the planets around a host star had become stable, when the MS phase of the host star is terminated. Without heavy bombardments, the temperature on the surface of a planet is mainly decided by the luminosity of its host star and the distance from the planet to the host star. Generally speaking, a host star becomes brighter and brighter during the post main sequence (post-MS) phase, mainly including subgiant branch phase, red giant
branch (RGB) phase, horizontal branch (HB) phase and asymptotic giant branch (AGB) phase. And some terrestrial planets outside the HZ of a host star during the MS phase will enter the HZ of the host star during the post-MS phase. Once these terrestrial planets enter the HZ of the host star, the evolution from biochemical compounds to primary life may start immediately. The timescale of the evolution from biochemical compounds to prokaryote life in habitable environment may be as short as about 100 million years (Watson 2008). And all the evolutionary timescales of low-mass stars (defined in subsection 3.2) during the subgiant branch phase, the RGB phase and the HB phase are longer than 100 million years. Furthermore, positional changes of the HZ with stellar age are considered in future studies of long-term changes of the planetary biospheric conditions (Franck et al. 2000; Noble et al. 2002). Hence, it is meaningful to study the HZs of host stars during the post-MS phase. Life-seeds may also migrate from one terrestrial planet to another (Buccino et al. 2007). A 1.9 kg meteorite (ALH84001) discovered in 1984 in Allan Hills, Antarctica, is believed to have been blasted off the Martian surface due to an asteroid or comet impact about 15 million years ago (McKay et al. 1996; Hoyle and Wickramasinghe 1999a). There are also some meteorites found on Earth, whose source is the Moon (Warren 1994). These proves that a major meteorite impact on a planet or a moon would eject fragments into space and the fragments may finally fall down another planet. If there are life-seeds (such as spore, fungi, bacterial and plant seed) in the fragments, they can be ejected into space. Some microbes may also survive after a long journey through space from one planet to another planet (Joseph 2009; Wickramasinghe et al. 2009). And some plant seeds resist deleterious conditions found in space, e.g., ultra low vacuum, extreme temperatures and intense ultraviolet light. In a receptive environment, life-seeds could liberate a viable embryo, viable higher cells or a viable free-living organism (Tepfer and Leach 2006). Therefore, life can transfer from one planet to another through ejected fragment. In addition, life seeds may also be saved on comets and can be sent to remote places by the comets, and the life seeds may take root, provided that the conditions they visit on become habitable (Hoyle and Wickramasinghe 1999a, 1999b, 1999c; Wickramasinghe et al. 2009).

Generally speaking, a terrestrial planet in the HZ of a host star is suited to life existence. Moreover, a rocky moon orbiting a giant planet or a brown dwarf could also be habitable, provided that the planet-moon system or the brown dwarf-moon system is within the HZ of the host star (Williams et al. 1997; Lal 2010). There are several rocky moons in solar system, such as Europa, Ganymede and Titan. These rocky moons will be habitable when Solar becomes brighter enough during the RGB phase or the HB phase. And there may be lives, which can generate from biochemical evolution or be transferred from other planets or moons, living on the rocky moons during that time. Furthermore, it is even thought that there may be life existence on these moons now, considering the potential of extremophiles to survive in highly inhospitable environments on Earth (Lal 2008).

Using the boundary distances of HZ (Jones et al. 2006), we calculate the HZs of host stars during the post-MS phase. It is found that Mars’ orbit, Jupiter’s orbit and Saturn’s orbit will enter the HZ of Solar during the subgiant branch phase for about 1.48 Gyr, the RGB phase for about 175 million years and the HB phase for about 137 million years, respectively. For low-mass stars, there are similar HZs as Solar during the HB phase. This means that a plant may also enter the HZ of a low-mass star during the HB phase, provided that the distance from the planet to the host star is just equal to the distance from Saturn to Solar. For intermediate-mass stars (defined in subsection 3.3), the HZs of host stars during the He-burning phase become farther and farther, with the stellar masses increasing.

The outline of the paper is as follows: we describe our methods in Section 2, show our results in Section 3, present some discussions in Section 4, and then finally in Section 5 we give our conclusions.

2. Methods

2.1. Input physics about stellar evolution

We use the stellar evolution code of Eggleton (1971, 1972, 1973), which has been updated with the latest input physics over the last three decades (Han et al. 1994; Pols et al. 1995, 1998). We set the convective overshooting parameter, $\delta_{ov} = 0.12$ (Pols et al. 1997; Schröder et al. 1997). We also take Reimers’ type mass-loss (Reimers 1975) into account, with Reimer’s parameter $\eta = 1/4$. In our calculation, the value of metallicity is 0.02 and stellar mass is from 0.80 to 4.00 $M_{\odot}$ (Guo et al. 2009).

We adopt the metal mixture by Grevesse and Sauval (1998). We use OPAL high temperatures opacity tables (Iglesias and Rogers 1996; Eldridge and Tout 2004) in the range of $4.00 < \log(T/\text{K}) \leq 8.70$, and the new Wichita state low temperature molecular opacity tables (Ferguson et al. 2005) in the range of $3.00 \leq \log(T/\text{K}) \leq 4.00$. And we have made the opacity tables match well with Eggleton’s code (Chen and Tout 2007; Guo et al. 2008).

2.2. Boundary distances of HZ

Jones et al. (2006) gave the flux at both the inner and the outer HZ boundaries, as a function of effective temperature ($T_{\text{eff}}$).

\[
\frac{S_{\text{in}}}{S_{\odot}} = 4.190 \times 10^{-8}T_{\text{eff}}^2 - 2.139 \times 10^{-4}T_{\text{eff}} + 1.296, \quad (1)
\]

\[
\frac{S_{\text{out}}}{S_{\odot}} = 6.190 \times 10^{-9}T_{\text{eff}}^2 - 1.319 \times 10^{-5}T_{\text{eff}} + 0.2341, \quad (2)
\]

where $S_{\odot}$ is solar constant and $T_{\text{eff}}$ is in Kelvin.
As \( L = 4\pi d^2S \), and the three parameters are just as \( L_\odot \), AU and \( S_\odot \), for our Earth. Hence, the distances at both the inner and the outer HZ boundaries are given by

\[
d_{\text{in}} \text{AU} = \left[ \frac{L}{L_\odot} \frac{S_{\text{in}}}{S_\odot} \right]^{1/2},
\]

\[
d_{\text{out}} \text{AU} = \left[ \frac{L}{L_\odot} \frac{S_{\text{out}}}{S_\odot} \right]^{1/2}.
\]

3. Results

3.1. HZ of Solar during the post-MS phase

Let us firstly define the termination of the main sequence (TMS) for a star, when hydrogen is exhausted in the center of the star. This is noted as an asterisk on the Hertzsprung-Russell (H-R) diagram of our Solar in Fig. 1. We then calculate the HZ for our Solar from TMS to the tip of the RGB phase, as seen in Fig. 2. At the start of TMS, the orbit of Mars is just within the HZ of our Solar and remains so for the first about 1.48 Gyr. The temperature on the surface of Mars is moderate and water can remain to be in the liquid phase.

Jupiter’s orbit is within the HZ of our Solar during the RGB phase for about 175 million years. Life is unlikely at any time on Jupiter, as it is a giant gaseous planet. However, the rocky moons of Jupiter, such as Europa and Ganymede, may be suitable for biological evolution and life may come forth on the rocky moons during that time. Furthermore, life seeds may also migrate from other planets with lives to Europa or Ganymede, the two rocky moons of Jupiter may become another two Earths during that time.

The He-burning phase for a star generally contains two phases, just as HB phase and AGB phase. During the HB phase, there is a He-burning core for a star and the change of the luminosity is not evident. And the luminosity during the whole HB phase is near to the luminosity at the zero age horizontal branch (ZAHB), for low-mass stars. By contrast, Helium is exhausted in the center of a star during the AGB phase, there is a He-burning envelope for the star and the change of the luminosity is great and rapid. Generally speaking, the evolutionary timescale of a star during the AGB phase is much shorter than that of the star during the RGB phase. We give the age-luminosity diagram of our Solar during the He-burning phase, the ZAHB is noted as a point and the start of the AGB phase (just as the termination of the HB phase) is noted as a square, as seen in Fig. 3. It is found that the luminosity changes tinily and the evolutionary timescale is 136.89 million years for our Solar during the HB phase. On the contrary, the luminosity changes evidently and the evolutionary timescale is only 9.81 million years for our Solar during the AGB phase.

As we have get the \( T_{\text{eff}} \), the luminosity and the evolutionary timescale of our Solar during the He-burning phase, we calculate the HZ of Solar during the He-burning phase, as seen in Fig. 4. It is found that the HZ of Solar during the whole HB phase is near to the HZ of Solar at...
the ZAHB, as the luminosity of Solar changes tinily during the HB phase. By contrast, the HZ of Solar during the AGB phase changes greatly and rapidly, as the luminosity of Solar changes greatly and rapidly during the AGB phase. Saturn’s orbit is within the HZ of Solar during the whole HB phase, and also within the HZ of Solar at the start of the AGB phase for 0.31 million years. Therefore, Saturn’s orbit is within the HZ of Solar during the He-burning phase for 137.20 million years. Life is unlikely at any time on Saturn, as it is also a giant gaseous planet. However, Titan, the rocky moon of Saturn, may be suitable for biological evolution and become another Earth during that time. And Uranus’ orbit is within the HZ of Solar during the AGB phase for only 5.48 million years, which is so short that the evolution from biochemical compounds to primary life can not be accomplished.

3.2. HZs of low-mass stars during the He-burning phase

The low-mass stars in this paper are defined as the stars which develop degenerate helium cores on the RGB phase and ignite helium in a degenerate flash at the tip of the RGB phase (Hurley et al. 2000). The maximum masses of low-mass stars with different metallicities are different. In our calculation, the value of metallicity is 0.02. Hence, the maximum mass of low-mass stars is about 2.00 $M_\odot$, which is also the minimum mass of intermediate-mass stars. And the core masses for all low-mass stars during the He-burning phase have similar values, just as about 0.47 $M_\odot$ in our calculation. Therefore, low-mass stars during the He-burning phase, also including HB phase and AGB phase, have similar $T_{\text{eff}}$ and luminosities, as seen in Fig. 5.

We calculated the HZs of low-mass stars during the He-burning phase, with masses 0.80, 1.20 and 1.50 $M_\odot$, as seen in Fig. 6. There are also similar HZs for the three low-mass stars during the He-burning phase. As the three host stars have similar core masses, $T_{\text{eff}}$ and luminosities during the He-burning phase. It is found that Saturn’s orbit is also within the HZs for all the three host stars during the HB phase for more than 130 million years. It means that a planet is also in the HZs for all the low-mass stars during the HB phase, provided that the distance from the planet to its host star is just equal to the distance from Saturn to Solar.
Fig. 7. HZs of intermediate-mass stars during the He-burning phase, with masses 2.50 (bottom) and 3.00 $M_{\odot}$ (upper). The two dotted lines and the two solid lines are the inner and the outer boundaries of the HZs around the host stars with masses 2.50 and 3.00 $M_{\odot}$, respectively. And the three horizontal lines have the same meanings as in Fig. 4.

3.3. HZs of intermediate-mass stars during the He-burning phase

The intermediate-mass stars in this paper are defined as the stars which evolve to the RGB phase without developing degenerate helium cores, also igniting helium at the tip of the RGB phase (Hurley et al. 2000). The core masses of intermediate-mass stars during the He-burning phase become bigger and bigger, with the stellar masses increasing. Therefore, the luminosities of intermediate-mass stars during the He-burning phase become higher and higher, and the evolutionary timescale become shorter and shorter, with the stellar masses increasing.

We calculated the HZs of intermediate-mass stars during the He-burning phase, with masses 2.50 and 3.00 $M_{\odot}$, as seen in Fig. 7. The evolutionary timescales for the stars with masses 2.50 and 3.00 $M_{\odot}$ during the HB phase are about 169 and 91 million years, respectively. And Saturn’s orbit is within the HZ of the host star with mass 2.50 $M_{\odot}$ during the HB phase. However, the distance from Solar to Saturn is shorter than the distance from the host star with mass 3.00 $M_{\odot}$ to the HZ of the host star during the HB phase. It means that the boundary distances of the HZs for intermediate-mass stars during the HB phase become farther and farther, with the stellar masses increasing.

4. Discussion

During the RGB phase, low-mass stars will remarkably lose masses (Catelan 2009). And stellar mass loss will also cause the planet’s orbit spirally outward by conservation of angular momentum (Tarter et al. 2007) and the law of universal gravitation. Therefore, it meets $M_{ZAMS}R_{ZAMS} = M_{ZAHB}R_{ZAHB}$; where $M_{ZAMS}$ and $R_{ZAMS}$ are stellar mass and the semimajor axis of a planet’s orbit for the host star at the ZAMS, $M_{ZAHB}$ and $R_{ZAHB}$ are stellar mass and the semimajor axis of the planet’s orbit for the same host star at the ZAHB. For our solar system, $M_{ZAMS} = 1.00 M_{\odot}$, $R_{ZAMS} = 9.576 AU$ (semimajor axis of Saturn’s orbit) and $M_{ZAHB} = 0.8778 M_{\odot}$, so that $R_{ZAHB} = 10.909 AU$. And the distance of HZ for Solar at the ZAHB is from 6.966 to 13.825 AU. Hence, Saturn’s orbit is also within the HZ of Solar at the ZAHB, taking the outward movement of planet’s orbit into consideration.

The strong ultraviolet radiation can induce DNA destruction and cause damage to most of the biological systems (Buccino et al. 2006). And the $T_{\text{eff}}$ of low-mass stars during the post-MS phase is not high. Therefore, the UV radiation is not strong in the HZs of low-mass stars during the post-MS phase (Guo et al. 2010), which is suitable for biological evolution on terrestrial planets or rocky moons in the HZs.

There is no terrestrial planet in the HZ for our Solar during the HB phase. However, the situation may be different for other low-mass stars. Using the data of Ida and Lin (2005) and the correlative method of Guo et al. (2009), we calculate the probability of terrestrial planets within the HZs around different mass stars at the ZAHB. For the host star with mass 1.00 $M_{\odot}$, the probability is 0.203; for the host star with mass 1.50 $M_{\odot}$, the probability is 0.346. These mean that there may be lives living on terrestrial planets around some low-mass stars during the HB phase.

5. Conclusion

Firstly, we calculate the HZ of Solar during the post-MS phase. It is found that Mars’ orbit, Jupiter’s orbit and Saturn’s orbit will enter the HZ of Solar during the subgiant branch phase, the RGB phase and the HB phase, respectively. These mean that Titan will be suited to biological evolution, when Solar evolves to the HB phase. Secondly, we calculate the HZs of low-mass stars during the He-burning phase. As there are similar core masses, $T_{\text{eff}}$ and luminosities for low-mass stars during the HB phase, there are also similar HZs for them. Therefore, Saturn’s orbit is also within the HZs for all low-mass stars during the HB phase. Thirdly, we calculate the HZs of intermediate-mass stars during the He-burning phase. It is found that the HZs of host stars become farther and farther with the stellar masses increasing. Finally, we present discussions about the outward movement of planet’s orbit, the UV radiation and the terrestrial planets within the HZs of low-mass stars during the HB phase. One may also send any special request to guojianpo1982@hotmail.com or guojianpo16@163.com.

Acknowledgments. This work is supported by the National Natural Science Foundation of China (Grant Nos. 10773026, 10821061 and 2007CB815406), the Chinese Academy of Sciences (Grant No. KJ CX2-YW-T24) and Yunnan Natural Science Foundation (Grant No. 06GJ061001).
References

Buccino, A.P., Lemarchand, G.A., Mauas, P.J.D.: Icarus 183, 491 (2006)
Buccino, A.P., Lemarchand, G.A., Mauas, P.J.D.: Icarus 192, 582 (2007)
Catelan, M.: Astrophys. Space Sci. 320, 261 (2009)
Chen, X.F., Tout, C.A.: Chin. J. Astron. Astrophys. 7(2), 245 (2007)
Eggleton, P.P.: Mon. Not. R. Astron. Soc. 151, 351 (1971)
Eggleton, P.P.: Mon. Not. R. Astron. Soc. 156, 361 (1972)
Eggleton, P.P.: Mon. Not. R. Astron. Soc. 163, 279 (1973)
Eldridge, J.J., Tout C.A.: Mon. Not. R. Astron. Soc. 348, 201 (2004)
Ferguson, J.W., Alexander, D.R., Allard, F., et al.: Astrophys. J. 623, 585 (2005)
Franck, S., von Bloh, W., Bounama, C., et al.: J. Geophys. Res. 105 (E1), 1651 (2000)
Grevesse, N., Sauval, A.J.: Space Sci. Rev. 85, 161 (1998)
Guo, J.P., Zhang, F.H., Chen, X.F., Han, Z.W.: Chin. J. Astron. Astrophys. 8(3), 262 (2008)
Guo, J.P., Zhang, F.H., Chen, X.F., Han, Z.W.: Astrophys. Space Sci. 323(4), 367 (2009)
Guo, J.P., Zhang, F.H., Zhang, X.F., Han, Z.W.: Astrophys. Space Sci. 325(1), 25 (2010)
Han, Z.W., Podsiadlowski, Ph., Eggleton, P.P.: Mon. Not. R. Astron. Soc. 270, 121 (1994)
Hoyle, F., Wickramasinghe, N.C.: Astrophys. Space Sci. 268, 1 (1999a)
Hoyle, F., Wickramasinghe, N.C.: Astrophys. Space Sci. 268, 333(1999b)
Hoyle, F., Wickramasinghe, N.C.: Astrophys. Space Sci. 268, 333(1999c)
Hurley, J.R., Pols, O.R., Tout, C. A.: Mon. Not. R. Astron. Soc. 315, 543 (2000)
Ida, S., Lin, D.N.C.: Astrophys. J. 626, 1045 (2005)
Iglesias, C.A., Rogers, F.J.: Astrophys. J. 464, 943 (1996)
Jones, B.W.: Life in the Solar System and Beyond. Springer, London (2004)
Jones, B.W., Sleep, P.N., Underwood, D.R.: Astrophys. J. 649, 1010 (2006)
Joseph, R.: J. Cosmology 1, 1 (2009)
Kasting, J.F., Whitmire, D.P., Reynolds, R.T.: Icarus 101, 108 (1993)
Lal, A.K.: Astrophys. Space Sci. 317, 267 (2008)
Lal, A.K.: J. Cosmology 5, 801 (2010)
McKay, D.S., Gibson, E.K., Thomas-Keprta, K.L., et al.: Science 273, 924 (1996)
Noble, M., Musielak, Z.E., Cuntz, M.: Astrophys. J. 572, 1024 (2002)
Pols, O.R., Tout, C.A., Eggleton, P.P., et al.: Mon. Not. R. Astron. Soc. 274, 964 (1995)
Pols, O.R., Tout, C.A., Schröder, K.-P., et al.: Mon. Not. R. Astron. Soc. 289, 860 (1997)
Pols, O.R., Schröder, K.-P., Hurley, J.R., et al.: Mon. Not. R. Astron. Soc. 298, 525 (1998)
Reimers, D.: MSRSL. 8, 369 (1975)
Schröder, K.-P., Pols, O.R., Eggleton, P.P.: Mon. Not. R. Astron. Soc. 285, 696 (1997)
Tarter, J.C., Backus, P.R., Mancinelli, R.L., et al.: Astrobiology 7(1), 30 (2007)
Tepfer, D., Leach, S.: Astrophys. Space Sci. 306, 69 (2006)
von Bloh, W., Bounama, C., Cuntz, M., Franck, S.: Astron. Astrophys. 476, 1365 (2007)
Warren, P.H.: Icarus 111, 338 (1994)
Watson, A.J.: Astrobiology 8(1), 175 (2008)
Williams, D.M., Kasting, J.F., Wade, R.A.: Nature 385, 234 (1997)
Wickramasinghe, J.T., Wickramasinghe, N.C., Napier, W.M.: Comets and the Origin of Life. World Scientific Publishing, Singapore (2009)