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A SIMPLE EVOLUTIONAL MODEL OF THE UV HABITABLE ZONE AND THE POSSIBILITY OF PERSISTENT LIFE EXISTENCE: THE EFFECTS OF MASS AND METALLICITY

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ABSTRACT

In addition to the habitable zone (HZ), the UV habitable zone (UV-HZ) is important when considering the existence of persistent life in the universe. The UV-HZ is defined as the area where the UV radiation field from a host star is moderate for persistent life existence. This is because UV is necessary for the synthesis of biochemical compounds. The UV-HZ must overlap the HZ when life appears and evolves. In this paper, following our previous study of the HZ, we examine the UV-HZ in cases with a stellar mass range from 0.08 to 4.00 $M_\odot$ with various metallicities during the main sequence phase. This mass range was chosen because we are interested in an environment similar to that of Earth. The effect of metallicity is reflected in the spectrum of the host stars, and we reexamine it in the context of the UV-HZ. The present work shows the effect of metallicity when that in the UV-HZ is less than that in the HZ. Furthermore, we find that the chance of persistent life existence declines as the metallicity decreases, as long as the UV radiation is not protected and/or boosted by any mechanisms. This is because the overlapped region of a persistent HZ and UV-HZ decreases. We find that the most appropriate stellar mass for the persistence of life existence is from 1.0 to 1.5 $M_\odot$ with metallicity $Z = 0.02$, and only about 1.2 $M_\odot$ with $Z = 0.002$. When $Z = 0.0002$, the chance of persistent life existence is very low, assuming that the ocean does not protect the life from UV radiation.

Key words: astrobiology – extraterrestrial intelligence – planets and satellites: terrestrial planets – stars: evolution – ultraviolet: stars

1. INTRODUCTION

From the era of Strughold (1953) and Huang (1959), there are many studies on the habitable zone (HZ; e.g., Dole 1964; Budyko 1969; Sellers 1969; North 1975; Rasool & De Bergh 1970; Hart 1979; Fogg 1992; Kasting et al. 1993; Spiegel et al. 2010; Abe et al. 2011; Danchi & Lopez 2013; Kopparapu 2013; Shchekinov et al. 2013; Vladilo et al. 2013; Zsom et al. 2013; Ramirez & Kaltenegger 2014; Safonova et al. 2016). However, detailed study of the the UV habitable zone (UV-HZ) remains to be done.

The inner and outer boundaries of the UV-HZ are defined as a region where the UV radiation field from a host star is moderate for persistent life existence (e.g., Buccino et al. 2007; Grenfell et al. 2014), whereas the inner and outer HZ boundaries are determined by the existence of liquid water on the surface of a terrestrial planet (Shapley 1953). UV radiation has both good and bad influences on the existence of life. If UV radiation is too weak, the synthesis of many biochemical compounds cannot occur. However, if it is too strong, the terrestrial biological systems are damaged (e.g., Rea 2000).

It should be noted that the supply of UV radiation does not come only from steady radiation from host stars but also from exceptional phenomena such as gamma-ray bursts and flares of magnetic active stars. Furthermore, there are factors other than UV radiation that affect the emergence of life. For example, the sources of organic molecules, primitive life, and water molecules include comets, and life can emerge in abnormal environments such as hydrothermal vents (e.g., Sreedhara et al. 2004; Furukawa et al. 2009; Callahan et al. 2011). Furthermore, there is a theory that lightning causes amino acids, which are made from methane, hydrogen, ammonia, and water in the atmosphere (see Schoph 1991). There is a probability that life emerges because of these sources in the absence of UV radiation. However, because stellar UV radiation is important, we discuss the effects of stellar UV radiation in this paper.

In their characteristic work, Buccino et al. (2006), Jones et al. (2006) and Guo et al. (2010) propose simple UV-HZ models. They construct UV-HZ models around host stars, the masses of which range from 0.08 to 4.00 $M_\odot$, and consider stellar evolution along the main sequence at Zero-Age Main Sequence (ZAMS) and Terminal-Age Main Sequence (TMS). Similar to the HZ, they determine the inner and outer UV-HZ boundaries by fitting formulas between stellar luminosity, L, and radius, R, calculating the boundary flux, S. Using these values, they determine the inner and outer UV-HZ boundaries by using the stellar luminosity at wavelengths from 200 to 315 nm, the range of UV-B and UV-C in the electromagnetic spectrum. UV photon flux is estimated as UV radiation does not damage DNA at the inner UV-HZ boundary and supplies enough energy for the synthesis of biochemical compounds at the outer UV-HZ boundary. According to their estimate, the UV-HZ is closer than the HZ in cases with an effective temperature $T_{\rm eff}$ lower than 4600 K and is farther than the HZ in cases with $T_{\rm eff}$ higher than 7137 K.

It is notable that they study only the case in which the metallicity is $Z = 0.02$, like the Sun. The effect of metallicity depends on $T_{\rm eff}$ more than luminosity L and mass M (Tout et al. 1996). Hence, following our previous study (Oishi & Kamaya 2016), we consider the UV-HZ with low metallicity to study more broadly the possibility of the existence of life. The importance of metallicity is also suggested by many observations (e.g., Orosz et al. 2012; Barclay et al. 2013; Campante et al. 2015; Crossfield et al. 2015). Considering the long lifespan of low-mass stars, it is important to examine metallicity, because these stars have formed at the early period of the universe and have little metallicity. Furthermore, if metallicity is less than that of the Sun, the stellar spectrum changes because of its low opacity. So, in this work, we consider $1/10$ and $1/100$ metallicity of the Sun as extreme cases.

The current model is an extension of our previous work (Oishi & Kamaya 2016). A simple model of HZ is useful. Indeed, Guo et al. (2009) developed a model including the effect of stellar evolution. Consequently, they can discuss HZ according to the mass spectrum of host stars. In another context, a simple UV-HZ is modeled by Buccino et al. (2006). Coupling Guo et al. (2009) and Buccino et al. (2006), Guo et al. (2010) constructed a simple UV-HZ model with stellar evolution. After that, Oishi & Kamaya (2016) discussed the effect of metallicities of host stars with various masses and their evolution, and they found that the possibility of persistent life existence decreases if the metallicity becomes lower. However, the UV-HZ problem remains to be discussed. Thus, this paper proposes a model coupling Guo et al. (2010) and Oishi & Kamaya (2016). It is notable that the stellar evolution effect is ineffective if stellar mass is smaller than about $0.8\,M_{\odot}$ (e.g., Oishi & Kamaya 2016). So we focus our attention on the mass range larger than about $0.8\,M_{\odot}$.

On this basis, in this paper, we construct simple models of the inner and outer UV-HZ boundaries, considering the effect of metallicity in addition to the formulas of Guo et al. (2010). The outline of the paper is as follows: we introduce the HZ model with the metallicity effect and present our formula of UV-HZ in Section 2 and present our numerical results in Section 3. A discussion is provided in Section 4, followed by a summary of our paper.

2. MODEL DESCRIPTION

This section describes our formulation for studying the UV-HZ affected by stellar evolution and metallicity, following Buccino et al. (2007). That is, our formula is an extension of Guo et al. (2010). Using the formulas and values in Oishi & Kamaya (2016), we determine the distance of the inner and outer UV-HZ boundaries at each evolutionary phase at ZAMS and TMS. In this work, we do not consider masses, $M_{\rm planet}$, and sizes, $R_{\rm planet}$, of planets. This is because the effect of size is nearly canceled, as found from the most simple case (heating by stellar radiation is ∼blackbody radiation cooling): $\pi R_{\rm planet}^2 S \sim 4\pi R_{\rm planet}^2 \sigma T^4$. Then, in this work and previous works (e.g., Guo et al. 2009, 2010 and Oishi & Kamaya 2016), we mainly discuss the greenhouse effect. In the following, we adopt typical models of $Z = 0.0002$, 0.002, and 0.02 for clear discussions. For the reader's convenience, we present our previous formulation of HZ in the Appendix. In this paper, the inner and outer boundaries of HZ at each evolutionary phase are denoted as $d_{\rm out,HZZAMS}$, $d_{\rm in,HZZAMS}$, $d_{\rm out,HZTMS}$, and $d_{\rm in,HZTMS}$, respectively.

In addition to HZ models, we determine the inner and outer UV-HZ boundaries. The inner UV-HZ boundaries are defined by UV radiation that should not damage DNA, and the outer UV-HZ boundaries are defined by UV radiation that nicely supplies enough energy for the synthesis of biochemical compounds. We calculate stellar luminosity, L_λ, at wavelength, λ, and UV photons, N, at both the inner and outer UV-HZ boundaries using stellar radius, R, and effective temperature, $T_{\rm eff}$. The expression of L_λ is

$$L_\lambda = 4\pi R^2 \pi \frac{2{\rm hc}}{\lambda^3} \frac{1}{e^{\frac{\rm hc}{kT_{\rm eff}\lambda}} - 1}, \tag{1}$$

and those of UV photons at both inner and outer UV-HZ boundaries are

$$N_{\rm in} = \int_{200\ {\rm nm}}^{315\ {\rm nm}} B(\lambda) \frac{\lambda}{\rm hc} \frac{L_\lambda}{4\pi d^2} d\lambda, \tag{2}$$

$$N_{\rm out} = \int_{200\ {\rm nm}}^{315\ {\rm nm}} \frac{\lambda}{\rm hc} \frac{L_\lambda}{4\pi d^2} d\lambda, \tag{3}$$

where $B(\lambda)$ is the probability of a UV photon of energy ${\rm hc}/\lambda$ to dissociate free DNA and its expression is

$$\log B(\lambda) \simeq \frac{6.113}{1 + \exp\frac{\lambda - 310.9}{8.8}} - 4.6. \tag{4}$$

And according to Buccino et al. (2006), a terrestrial planet needs to receive from half to twice of the UV radiation received by the Archean Earth for biological evolution. So, the expressions are simply estimated as

$$N_{\rm in} \sim 2 N_{\rm in}({\rm Arc}), \tag{5}$$

$$N_{\rm out} \sim 0.5 N_{\rm out}({\rm Arc}). \tag{6}$$

Combining Equations (1)–(6), we can obtain the distance of the inner and the outer UV-HZ boundaries from a host star

$$d_{\rm uvin} = \frac{\sqrt{2}}{2} \frac{R}{R_{\rm Arc}} \sqrt{\frac{F_1(T_{\rm eff})}{F_1(T_{\rm Arc})}}, \tag{7}$$

$$d_{\rm uvout} = \sqrt{2} \frac{R}{R_{\rm Arc}} \sqrt{\frac{F_2(T_{\rm eff})}{F_2(T_{\rm Arc})}}. \tag{8}$$

And the expressions of F_1 and F_2 are

$$F_1(T) = \int_{200\ {\rm nm}}^{315\ {\rm nm}} \frac{\frac{B(\lambda)}{\lambda^2} d\lambda}{e^{\frac{\rm hc}{kT\lambda}} - 1}, \tag{9}$$

$$F_2(T) = \int_{200\ {\rm nm}}^{315\ {\rm nm}} \frac{\frac{1}{\lambda^2} d\lambda}{e^{\frac{\rm hc}{kT\lambda}} - 1}. \tag{10}$$

In these equations, R is in solar units, $T_{\rm eff}$ is in Kelvin, and d is in units of au. $R_{\rm Arc}$ is $0.9113\ R_{\odot}$ and $T_{\rm Arc}$ is 5603 K, which are quantities at the Archean Earth (about 3.8 Gyr ago). In the following, the inner and outer boundaries of the UV-HZ at each evolutionary phase are denoted as $d_{\rm out,UVZAMS}$, $d_{\rm in,UVZAMS}$, $d_{\rm out,UVTMS}$, and $d_{\rm in,UVTMS}$, respectively.

3. NUMERICAL RESULTS

In this section, we present our numerical results for the UV-HZ. Because we are interested in main-sequence stars with low and intermediate mass, the mass range is selected from 0.08 to 4.00 $M_{\odot}$ since we are interested in planets like Earth. Furthermore, we adopt various metallicities, since long-lived stars can be detected in future observational surveys. Then, we select $1/10$ and $1/100$ metallicity of the Sun as extreme cases (Guo et al. 2010 and Oishi & Kamaya 2016). Thus, we determine the inner and outer UV-HZ boundaries at ZAMS and TMS by means of Equations (7) and (8). Results are presented in the following figures.

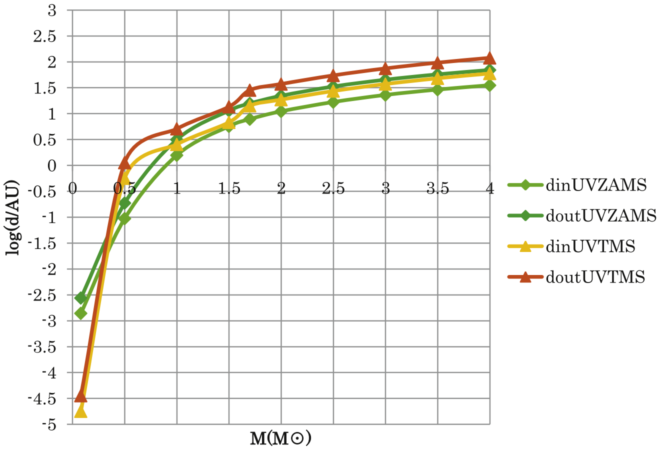


Figure 1. Relationship between the masses and the distances from host stars at both UV-HZ boundaries at each ZAMS and TMS with the metallicity $Z = 0.0002$. There is overlapped region of UV-HZ ($d_{\mathrm{out,UVZAMS}} > d_{\mathrm{in,UVTMS}}$) at $M \geqslant 1.0\,M_{\odot}$.

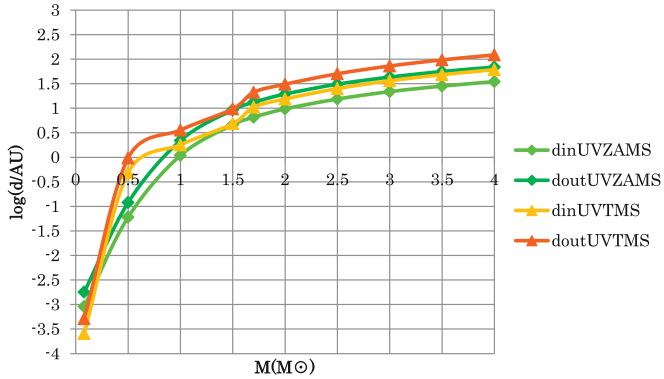


Figure 2. Relationship between the masses and the distances from host stars at both UV-HZ boundaries at each ZAMS and TMS with the metallicity $Z = 0.002$. The overall properties of the graph are almost the same as in Figure 1.

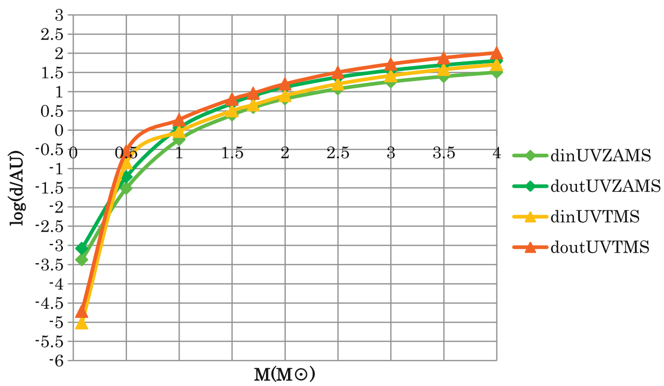


Figure 3. Relationship between the masses and the distances from host stars at both UV-HZ boundaries at each ZAMS and TMS with the metallicity $Z = 0.02$. We find strong undulation at $M \leqslant 1.0\,M_{\odot}$, resembling like the low metallicity cases.

In Figure 1, the case of metallicity $Z = 0.0002$, diamonds represent ZAMS cases and triangles are TMS ones. All units are the same as in Figures 1–3 of Oishi & Kamaya (2016). Here, we find bumps at about $M = 0.6\,M_{\odot}$ and $1.6\,M_{\odot}$ for both the inner and outer UV-HZ boundaries at TMS. And we also find that the overlapped region of UV-HZ ($M \geqslant 1.0\,M_{\odot}$), at which the outer UV-HZ boundary of ZAMS overtakes the inner UV-HZ boundary of TMS ($d_{\mathrm{out,UVZAMS}} > d_{\mathrm{in,UVTMS}}$), is wider than that of the HZ whose overlapped region ($d_{\mathrm{out,HZZAMS}} > d_{\mathrm{in,HZTMS}}$) is limited to more than about $M \geqslant 1.8\,M_{\odot}$. It is notable that although the bump at about $M = 1.6\,M_{\odot}$ in the case of the TMS of Figure 1 is not as clear as that in the case of the HZ, we find strong undulation at $M \leqslant 1.0\,M_{\odot}$ of Figure 1. In other words, the effect of metallicity for UV-HZ at TMS is weaker than HZ at $M \geqslant 1.0\,M_{\odot}$, whereas it is stronger than HZ at $M \leqslant 1.0\,M_{\odot}$.

In Figure 2, we present the $Z = 0.002$ case, which is larger than the Z of Figure 1. All units are the same as in Figure 1. The shapes of graphs, the overlapped region, and the positions of bumps are almost the same as those depicted in Figure 1. In this case, the effect of metallicity is also weaker than HZ at $M \geqslant 1.0\,M_{\odot}$ and stronger than HZ at $M \leqslant 1.0\,M_{\odot}$. Even in Figure 3, in which we present the case of $Z = 0.02$, the overlapped region is almost the same as that in cases of $Z = 0.0002$ and $Z = 0.002$. Although there is no bump at $M = 1.6\,M_{\odot}$, we can find undulation at around $M = 0.6\,M_{\odot}$, resembling the cases of low metallicity.

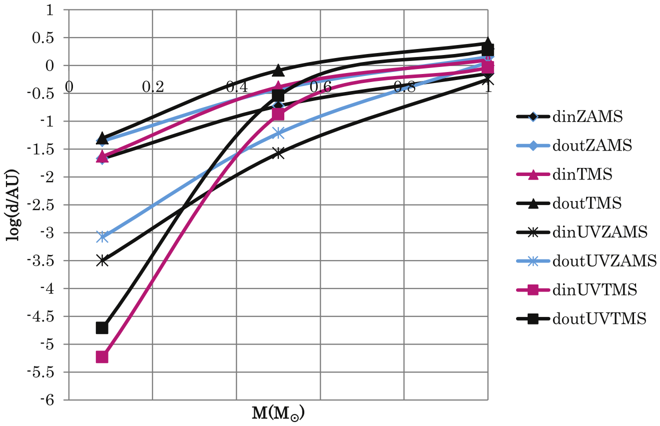
4. DISCUSSION

4.1. The Effect of Metallicity

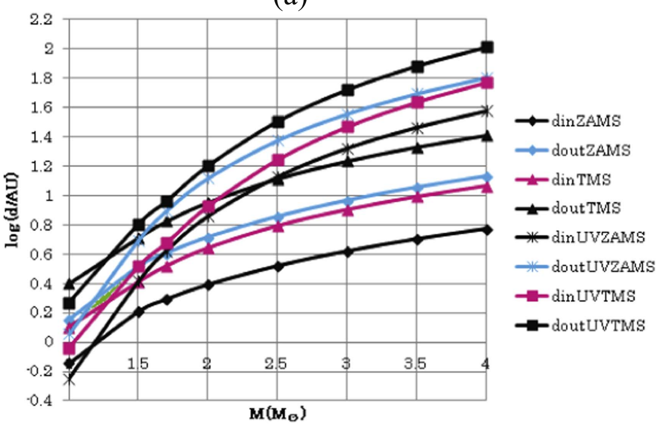
In the case of the HZ, we find that the effect of metallicity is important for the mass range from 1.5 to $2.0\,M_{\odot}$ (Oishi & Kamaya 2016). If the metallicity is comparable to that of the Sun, it is not an issue because the overlapped region—that at which the outer HZ boundary at ZAMS ($d_{\mathrm{out,HZZAMS}}$) overtakes the inner HZ boundary at TMS ($d_{\mathrm{in,HZTMS}}$)—exists widely along the mass range from 0.08 to $4.0\,M_{\odot}$. However, if the metallicity is small, the chance of life existence decreases because the region ($d_{\mathrm{out,HZZAMS}} > d_{\mathrm{in,HZTMS}}$) is limited to about $M \geqslant 1.8\,M_{\odot}$.

It is notable that in the UV-HZ case, the overlapped region ($d_{\mathrm{out,UVZAMS}} > d_{\mathrm{in,UVTMS}}$) is limited to about $M > 1.0\,M_{\odot}$ for any metallicity of host stars. Metallicity does not affect the overlapped region of UV-HZ very much because the escape probability of UV photons from host stars does not change much. In other words, the opacity of UV photons is determined mainly by ionization of hydrogen and free–free scattering. These physical processes are little affected by metallicity because Z is at most about 0.02. Then, for the variety of models of metallicity, we find a unique trend. By the way, we find that the effect of metallicity is depicted in very small bumps at $M \sim 1.6\,M_{\odot}$ in the figures. This trend emerges in the results of low metallicity models because the total opacity is affected by the ionization of metals.

Furthermore, when metallicity of host stars is small, we find another trend in which the inner and outer boundaries at $1.0\,M_{\odot} < M < 2.0\,M_{\odot}$ of both ZAMS and TMS shift further as the metallicity decreases. Here, we present a physical reason to explain this trend. If metallicity is small, the number of photoelectrons from metals by UV radiation decreases. That is why the total opacity of the atmosphere of host stars, especially those later than F-type, decreases as metallicity becomes low. In addition, the more luminous host stars are, the more the total escape number of UV photons from the stellar atmosphere simply increases. Then, when the opacity

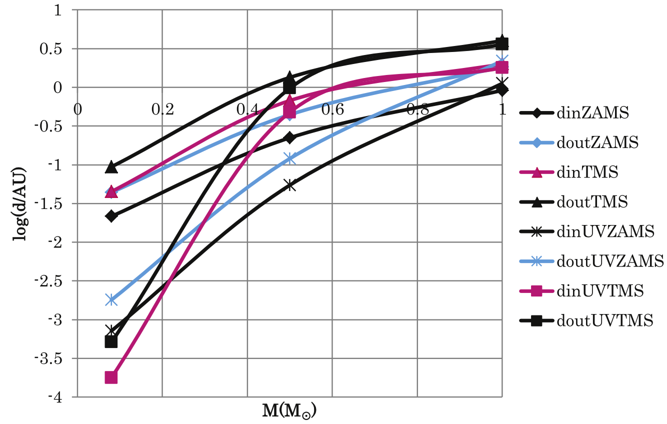


(a)

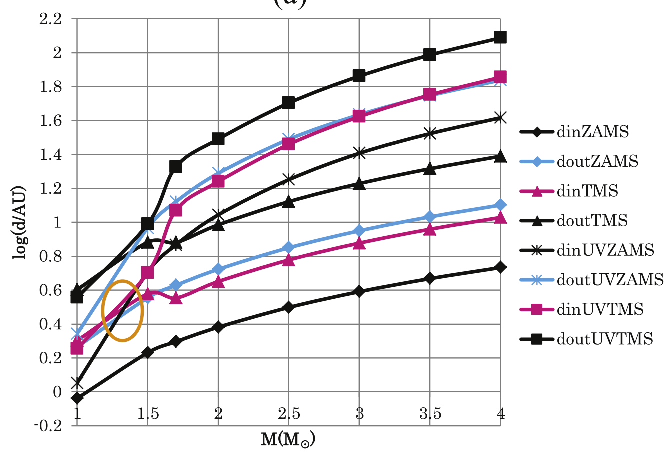


(b)

Figure 4. (a) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.02$ and a mass range from 0.08 to 1.0 $M_\odot$. (b) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.02$ and a mass range from 1.0 to 4.0 $M_\odot$. We find that the coexisting region is the mass range from 1.0 to 1.5 $M_\odot$.



(a)



(b)

Figure 5. (a) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.002$ and a mass range from 0.08 to 1.0 $M_\odot$. (b) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.002$. The coexisting region is limited at only around 1.2 $M_\odot$.

diminished by the metallicity decrement, UV radiation flux increases and the distances of the UV-HZ from host stars increase during their main-sequence evolutions, since the luminosity of TMS is brighter than that of ZAMS. When $M < 1.0\,M_\odot$, the fraction of UV photons is essentially very small, so this trend does not appear.

4.2. Possibility of Life Existence

In our study, we calculate the distances of HZ boundaries ($d_{\rm out,HZZAMS}$, $d_{\rm in,HZZAMS}$, $d_{\rm out,HZTMS}$, and $d_{\rm in,HZTMS}$) and UV-HZ boundaries ($d_{\rm out,UVZAMS}$, $d_{\rm in,UVZAMS}$, $d_{\rm out,UVTMS}$, and $d_{\rm in,UVTMS}$) by using simple and obvious models. Here, we compare the overlapped regions of HZ and UV-HZ. To have persistent life existence, the region where the area defined as the outer boundary of HZ at ZAMS overtakes the outer boundary of HZ at TMS ($d_{\rm out,HZZAMS} > d_{\rm in,HZTMS}$) must overlap with the area defined as the outer boundary of UV-HZ at ZAMS overtakes the outer boundary of UV-HZ at TMS ($d_{\rm out,UVZAMS} > d_{\rm in,UVTMS}$). In other words, we need any one of the following conditions of $d_{\rm out,UVZAMS} > d_{\rm out,HZZAMS} > d_{\rm in,UVTMS} > d_{\rm in,HZTMS}$, $d_{\rm out,HZZAMS} > d_{\rm out,UVZAMS} > d_{\rm in,HZTMS} > d_{\rm in,UVTMS}$, $d_{\rm out,UVZAMS} > d_{\rm out,HZZAMS} > d_{\rm in,HZTMS} > d_{\rm in,UVTMS}$, and $d_{\rm out,HZZAMS} > d_{\rm out,UVZAMS} > d_{\rm in,UVTMS} > d_{\rm in,HZTMS}$. Here, we call it the coexisting region.

As described in Figure 4(b), we find that the overlapped region of HZ and UV-HZ coexists at the mass range from 1.0 to 1.5 $M_\odot$ when $Z = 0.02$. Hypothesizing for the solar system, UV-HZ exists from about 0.6–1.1 au at ZAMS and from about 0.9 to 1.9 au at TMS. According to these estimates, the coexisting region of UV-HZ is from about 0.9 to 1.1 au. The distance from the Sun to Venus is about 0.7 au, and that from Mars is about 1.5 au. Namely, these planets exist outside of the coexisting region at the moment. Once, Venus existed in UV-HZ, but was excluded from this area owing to the evolution of the Sun. In the case of Mars, the reverse will occur.

When $Z = 0.002$, the coexisting region is limited at only around 1.2 $M_\odot$ (Figure 5(b)). Of interest, when $Z = 0.0002$, there are no coexisting regions (Figures 6(a) and (b)). Considering this trend, the possibility of life existence extremely decreases as the metallicity decreases. This is because the lack of UV radiation lets the coexisting region disappear when metallicity is low. If we expect life emergence at low metallicity stars, we need increments of bolometric luminosity and UV radiation. For example, exceptional phenomena like the Coronal Mass Ejection (CME) may make the coexisting region wider. If the CME occurs in magnetically

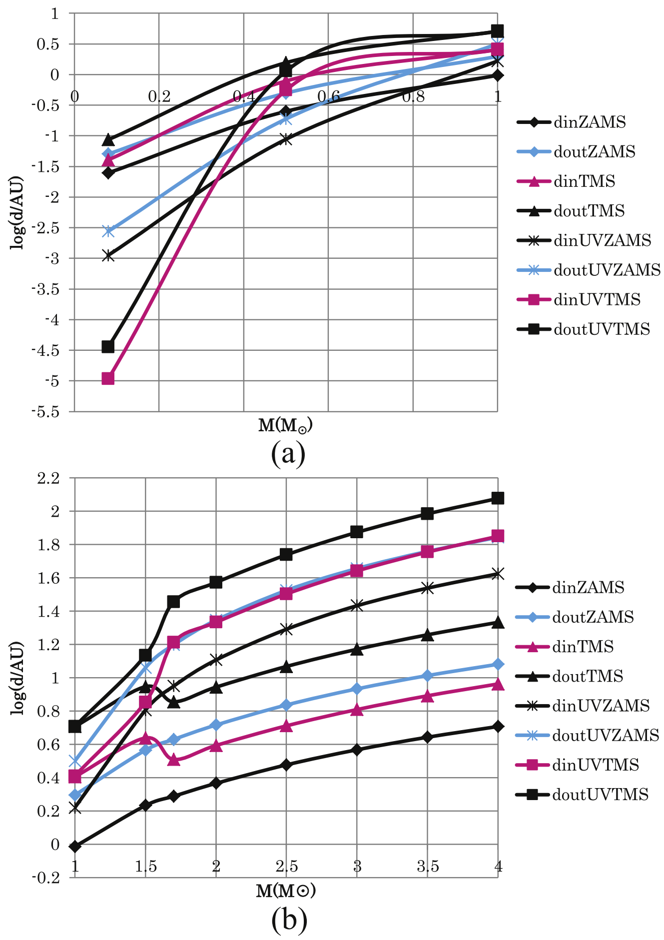


Figure 6. (a) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.0002$ and a mass range from 0.08 to 1.0 $M_\odot$. (b) The relationship between the masses and the distances from host stars at both the HZ and UV-HZ boundaries at each ZAMS and TMS, with the metallicity $Z = 0.0002$. There is no coexisting region.

active low mass stars, the luminosity and UV radiation momentarily increase when it collides with planets, so we expect the coexisting region to become wider and life emergence to be possible even around low-mass and low-metallicity stars.

In the future, the observational technique for surveying stars with low mass and low metallicity in the infrared band will be possible. For example, the *Transiting Exoplanet Survey Satellite* (Ricker et al. 2014) project will be useful, and will attempt to discover thousands of exoplanets, monitoring more than 200,000 stars for temporary drops in brightness. It is important to note that red dwarfs and K-type main-sequence stars are also the targets. When this project is launched in the future, we will be able to study low-mass and low-metallicity stars as targets for life emergence.

4.3. The Importance of the Ocean

The above discussions are questionable if there is not a large amount of water like a sea, for example. Our conclusion suggests the necessity of a source of protection against UV radiation. DNA damage occurs directly when DNA absorbs a UV-B photon, which causes thymine base pairs next to each other in genetic sequences to bond together into pyrimidine dimers. However, if planets of sea, these processes do not work well, and life can emerge and evolve there.

Furthermore, UV radiation has distinct mutagenic properties. A hallmark of UV-C and UV-B mutagenesis is the high frequency of transition mutations at dipyrimidine sequences containing cytosine. This means that if there were no energetic sources like hydrothermal vents in the deep sea, life would not evolve. With the current conclusion of our paper, then, the sea may be essential for the emergence and evolution of life on low-metallicity habitable planets.

4.4. Life Emergence on Exo-moons

For moons, the existence of life might be unexpected because they have no atmosphere and suffer the bad effects of UV radiation and cosmic rays. However, the situation has dramatically changed. It could be possible on Europa, which seems to have liquid water under the surface because of tidal heating by Jupiter (e.g., McCollom 1999, Schulze-Makuch & Irwin 2001, Marion et al. 2003). As another example, on Ceres, water under the surface is also expected because water vapor ejects from there (Küppers et al. 2014). If similar condition are possible on exo-moons in extrasolar systems, life may exist under their surfaces. However, in case of lack of atmosphere, life is not protected from harmful radiation. And then, primitive life is not able to prosper and do not evolve to evolved life.

5. CONCLUSION

Confirming the previous results for HZs, this paper examines the effect of metallicity on the inner and outer UV-HZ boundaries in which the main sequence stellar mass range is from 0.08 to 4.00 $M_\odot$. To obtain clear results, we proposed runaway greenhouse and maximum greenhouse models. Then, we found that the overlapped regions of the UV-HZ at ZAMS and TMS are little affected by the effect of metallicity. The possibility of minimally persistent life existence at the relatively wide mass range is discussed, comparing the HZ and UV-HZ. That is, considering the coexisting area of the HZ and UV-HZ, we find the possibility decreases significantly. The possibility is limited to the mass range of host stars only from 1.0 to 1.5 $M_\odot$ with at most $Z = 0.02$, whereas when $Z = 0.0002$, we cannot find the possibility at any masses. If we expect life in cases of low-mass and low-metallicity host stars, we must consider the effect of a sea and/or increments of UV radiation.

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APPENDIX

Herein we present the formulation of the HZ in the previous paper (Oishi & Kamaya 2016). This is the extension of Guo et al. (2009) according to the detailed studies of Tout et al. (1996) and Hurley et al. (2000). All of the coefficients can be found in Oishi and Kamaya. In the case of ZAMS,

$$L_{\rm ZAMS} = \frac{(a_1 M^{5.5} + a_2 M^{11})}{(a_3 + M^3 + a_4 M^5 + a_5 M^7 + a_6 M^8 + a_7 M^{9.5})}, \tag{11}$$

$$R_{\mathrm{ZAMS}} = \frac{a_8 M^{2.5} + a_9 M^{6.5} + a_{10} M^{11} + a_{11} M^{19} + a_{12} M^{19.5}}{a_{13} + a_{14} M^2 + a_{15} M^{8.5} + M^{18.5} + a_{16} M^{19.5}}, \quad (12)$$

and in the case of TMS,

$$L_{\mathrm{TMS}} = \frac{a_{17} M^3 + a_{18} M^4 + a_{19} M^{a_{22}+1.8}}{a_{20} + a_{21} M^5 + M^{a_{22}}}, \quad (13)$$

$$R_{\mathrm{TMS}} = \frac{a_{23} + a_{24} M^{a_{26}}}{a_{25} + M^{a_{27}}} (M \leqslant 1.5), \quad (14)$$

$$R_{\mathrm{TMS}} = \frac{a_{28} M^3 + a_{29} M^{a_{32}} + a_{30} M^{a_{32}+1.5}}{a_{31} + M^5} (M > 1.5), \quad (15)$$

are adopted by us. Coefficients and indexes in the above equations are denoted by means of metallicity, Z, as

$$a_n = \alpha + \beta \log_{10} \frac{Z}{Z_\odot} + \gamma \left[\log_{10} \frac{Z}{Z_\odot}\right]^2 + \delta \left[\log_{10} \frac{Z}{Z_\odot}\right]^3 + \varepsilon \left[\log_{10} \frac{Z}{Z_\odot}\right]^4 (1 \leqslant n \leqslant 32), \quad (16)$$

in which the five Greek characters are summarized in Table 1 of Oishi & Kamaya (2016). The inner HZ boundary is determined by the runaway greenhouse in the broad sense and the withdrawal of water in the narrow sense. We calculate flux, S, of the inner and outer HZ boundaries by using Equations (11)–(15) and $L = 4\pi R^2 \sigma T_{\mathrm{eff}}{}^4$. Our effective stellar fluxes are

$$\frac{S_{\mathrm{in}}}{S_\odot} = 4.190 \times 10^{-8}\, T_{\mathrm{eff}}{}^2 - 2.139 \times 10^{-4}\, T_{\mathrm{eff}} + 1.296, \quad (17)$$

$$\frac{S_{\mathrm{out}}}{S_\odot} = 6.190 \times 10^{-9}\, T_{\mathrm{eff}}{}^2 - 1.319 \times 10^{-5}\, T_{\mathrm{eff}} + 0.2341, \quad (18)$$

where $S_\odot$ is the solar constant and T_{eff} is in units of Kelvin. Equations (17) and (18) are determined on the basis of the greenhouse effect, following Underwood et al. (2003) and Jones et al. (2006). Using these equations and $L = 4\pi d^2 S$, we determine distances at both the inner and outer HZ boundaries, d, as follows,

$$\frac{d_{\mathrm{in}}}{\mathrm{au}} = \left[\frac{L}{L_\odot} \frac{S_\odot}{S_{\mathrm{in}}}\right]^{0.5}, \quad (19)$$

$$\frac{d_{\mathrm{out}}}{\mathrm{au}} = \left[\frac{L}{L_\odot} \frac{S_\odot}{S_{\mathrm{out}}}\right]^{0.5}. \quad (20)$$

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