Habitable Zones and UV Habitable Zones around Host Stars

Jianpo Guo\textsuperscript{1,2,3}, Fenghui Zhang\textsuperscript{1,2}, Xianfei Zhang\textsuperscript{1,2,3}, and Zhanwen Han\textsuperscript{1,2}

\textsuperscript{1} National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming, 650011, P.R. China
e-mail: guojianpo1982@hotmail.com
\textsuperscript{2} Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming, 650011, P.R. China
\textsuperscript{3} Graduate School of the Chinese Academy of Sciences, Beijing, 100049, P.R. China

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Abstract. Ultraviolet radiation is a double-edged sword to life. If it is too strong, the terrestrial biological systems will be damaged. And if it is too weak, the synthesis of many biochemical compounds can not go along. We try to obtain the continuous ultraviolet habitable zones, and compare the ultraviolet habitable zones with the habitable zones of host stars. Using the boundary ultraviolet radiation of ultraviolet habitable zone, we calculate the ultraviolet habitable zones of host stars with masses from 0.08 to 4.00 $M_\odot$. For the host stars with effective temperatures lower than 4,600 K, the ultraviolet habitable zones are closer than the habitable zones. For the host stars with effective temperatures higher than 7,137 K, the ultraviolet habitable zones are farther than the habitable zones. For hot subdwarfs as a host star, the distance of the ultraviolet habitable zone is about ten times more than that of the habitable zone, which is not suitable for life existence.

Key words. Ultraviolet: stars — Stars: subdwarfs — 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 liquid phase, which has been widely researched (eg., Hart, 1978; Kasting et al., 1993; Franck et al., 2000; Noble et al., 2002). The boundary flux of HZ not only depends on luminosity, but also depends on effective temperature ($T_{\text{eff}}$) (eg., Forget & Pierrehumbert, 1997; Williams & Kasting, 1997; Mischna et al., 2000; Jones, 2004; Jones et al., 2006). As the higher $T_{\text{eff}}$, the less the infrared fraction in luminosity, and the less this fraction, the less the greenhouse effect for a given stellar flux (Jones et al., 2006). Thus, the distances at both the inner and the outer HZ boundaries are closer to host star, with higher $T_{\text{eff}}$, than they would have been if the $T_{\text{eff}}$ effect is not taken into consideration.

However, others pointed out that life existence not only needs clement temperature, but also appropriate ultraviolet radiation (eg., Setlow & Doyle, 1954; Lindberg & Horneck, 1991; Cockell, 1998; Hoyle & Wickrasinghe, 2003; Segura et al., 2003). UV radiation can induce DNA destruction and make life inactivate (Buccino et al., 2006; Tepfer & Leach, 2006). And UV radiation is also one of the most important energy source for the synthesis of many biochemical compounds on the primitive Earth (Buccino et al., 2006).

The “Principle of Mediocrity” is in the “hard core” of all the research programs that search for life in the universe (Lakatos, 1974). In the points of this hypothesis, life and intelligence will develop with the same rules of natural selection wherever the proper conditions and the needed time are given (von Hoerner, 1961, 1973). In other words, the conditions that give place to the origin and evolution of life on Earth are average, in comparison to other worlds in the universe (Buccino et al., 2006). Using the “Principle of Mediocrity”, Buccino et al. (2006) gave the boundary UV radiation of ultraviolet habitable zone (UV-HZ), but not the continuous UV-ZHs.

Previously, it was pay attention to the HZs of host stars at main sequence (MS) phase, as the evolution from biochemical compounds to primary life needs very long time. However, life-seeds may migrate from one planet to another (Buccino et al., 2007). One hundred Myr may be too short for the pre-biological evolution, but the features of biology can change greatly in the same period, based on the “Principle of Mediocrity”. Hence, it is meaningful to study the HZs and the UV-HZs of host stars at post-MS phase (eg., Franck et al., 2000; Noble et al., 2002).
Hot subdwarfs are known as Extreme Horizontal Branch stars and believed to be core He-burning objects with extremely thin hydrogen envelopes (less than 0.02 $M_\odot$). They are an important source of far-UV light in the galaxy and successfully used to explain the UV-upturn in elliptical galaxies (Kilkenny et al., 1997; Han et al. 2007). The typical core mass of a hot subdwarf is 0.475 $M_\odot$, which can stably burn more than 160 Myr.

Using the boundary UV radiation of UV-HZ (Buccino et al., 2006), we achieve the the distances at both the inner and the outer UV-HZ boundaries, as a function of stellar parameter, $\delta_{\text{UV}} = 0.12$ (Pols et al., 1997; Schröder et al., 1997). In our calculation, the value of metallicity is 0.02 and stellar mass is from 0.10 to 4.00 $M_\odot$ (Paper I).

We adopt the metal mixture by Grevesse & Sauval (1998). We use OPAL high temperatures opacity tables (Iglesias & Rogers, 1996; Eldridge & 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 & Tout, 2007; Guo et al., 2008).

### 2.2. Stellar luminosity, Radius and $T_{\text{eff}}$

In the subsection 3.1 of Paper I, we gave the fitting formulae of luminosities and radiuses of stars with masses from 0.08 to 4.00 $M_\odot$, at ZAMS and at TMS. And stellar $T_{\text{eff}}$ can be obtained from $L = 4\pi R^2 \sigma T_{\text{eff}}^4$. Thus, we can obtain luminosities, radiuses and $T_{\text{eff}}$ of host stars, which can be used to calculate the HZs and the UV-HZs of the host stars.

### 2.3. Boundary flux of HZ

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 CO$_2$ crystals out of the atmosphere (von Bloh et al., 2007). Jones et al. (2006) gave the flux at both the inner and the outer HZ boundaries, as a function of $T_{\text{eff}}$:

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

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

where $S_\odot$ is solar constant and $T_{\text{eff}}$ is in Kelvin.

### 2.4. Boundary UV radiation of UV-HZ

UV radiation is a double-edged sword to life. If it is too strong, the terrestrial biological systems will be damaged. And if it is too weak, the synthesis of many biochemical compounds can not go along. Therefore, UV radiation should fitly not damage DNA at the inner UV-HZ boundary, and nicely supply enough energy for the synthesis of biochemical compounds at the outer UV-HZ boundary. Buccino et al. (2006) gave the expression of UV photons at both the inner and the outer UV-HZ boundaries:

$$N_{\text{in}} = \int_{200 \text{nm}}^{315 \text{nm}} B(\lambda) \frac{L_\lambda}{hc} \frac{1}{4\pi d^2} d\lambda,$$  \quad (3)

$$N_{\text{out}} = \int_{200 \text{nm}}^{315 \text{nm}} B(\lambda) \frac{L_\lambda}{hc} \frac{1}{4\pi d^2} d\lambda.$$  \quad (4)

Where $L_\lambda$ is stellar luminosity at wave length $\lambda$, and $B(\lambda)$ is the probability of a UV photon of energy $(hc)/\lambda$ to dissociate free DNA, whose expression is

$$\log B(\lambda) \sim \frac{6.113}{1 + \exp((\lambda[\text{nm}] - 310.9)/8.8)} - 4.6. \quad (5)$$

Primary life had come forth on the Archean Earth about 3.8 Gyr ago (Rosing, 1999). Based on the “Principle of Mediocrity”, a terrestrial planet needs to receive form half to two times of the UV radiation received by
the Archean Earth, to be suited to biological evolution (Buccino et al., 2006). The expressions are just as

\[ N_{\text{in}} = 2N_{\text{in(Arc)}} \]  \hspace{1cm} (6)

\[ N_{\text{out}} = 0.5N_{\text{out(Arc)}} \]  \hspace{1cm} (7)

3. Results

3.1. Boundary distances of UV-HZs

We simply take that star is a black body, the expression of \( L_{\lambda} \) is

\[ L_{\lambda} = \frac{4\pi R^2 \lambda^2}{h \lambda c} \left( \frac{1}{e^{h \lambda / k T_{\text{eff}}} - 1} \right) \]  \hspace{1cm} (8)

Combining Eqs. (3), (6) and (8), it obtains the expression of the distance at the inner UV-HZ boundary:

\[ d_{\text{in}} = \frac{2}{\sqrt{2}} \frac{R}{R_{\text{Arc}}} \sqrt{\frac{F_1(T_{\text{eff}})}{F_1(T_{\text{Arc}})}} \]  \hspace{1cm} (9)

Where \( R \) is in solar units, \( T_{\text{eff}} \) is in Kelvin and \( d_{\text{in}} \) is in units of AU. The values of \( R_{\text{Arc}} \) and \( T_{\text{Arc}} \) are 0.9113 \( R_{\odot} \) and 5,603 K, just as the radius and the \( T_{\text{eff}} \) of Solar about 3.8 Gyr ago, respectively. The expression of \( F_1 \) is

\[ F_1(T) = \int_{200 \text{nm}}^{315 \text{nm}} \frac{B(\lambda)}{\lambda^2} \frac{1}{e^{h \lambda / k T} - 1} d\lambda \]  \hspace{1cm} (10)

Combining Eqs. (4), (7) and (8), it achieves the expression of the distance at the outer UV-HZ boundary:

\[ d_{\text{out}} = \frac{2}{\sqrt{2}} \frac{R}{R_{\text{Arc}}} \sqrt{\frac{F_2(T_{\text{eff}})}{F_2(T_{\text{Arc}})}} \]  \hspace{1cm} (11)

And the expression of \( F_2 \) is

\[ F_2(T) = \int_{200 \text{nm}}^{315 \text{nm}} \frac{1}{\lambda^2} e^{h \lambda / k T} - 1 d\lambda \]  \hspace{1cm} (12)

3.2. HZs and UV-HZs around host stars

According to Eqs (9)-(12) and the correlative fitting formulae in the subsection 3.1 of Paper I, we calculate the UV-HZs around host stars with masses from 0.08 to 4.00 \( M_{\odot} \) at ZAMS. As the MS lifetimes of M type stars are from 131 Gyr to several trillion years, which are many times longer than the universe age. Hence, M type stars with masses from 0.08 to 0.50 \( M_{\odot} \) almost stay at ZAMS, within the universe age. Therefore, we only calculate the UV-HZs around host stars with masses from 0.50 to 4.00 \( M_{\odot} \) at TMS.

As we have given the HZs around host stars with masses from 0.08 to 4.00 \( M_{\odot} \) (Paper I). In order to comparing the UV-HZs with the HZs of host stars more intuitively, we put them on the same graphs, seen in Figs. 1 and 2. It is seen that the UV-HZs are near to the HZs for solar-like stars, the UV-HZs are closer than the HZs for M and K type stars, and the UV-HZs are farther than the HZs for upper MS stars.

This is because both the boundary flux of HZ and the boundary UV radiation of UV-HZ depend on \( T_{\text{eff}} \) for a given stellar flux, but with the contrary effects. For HZ, the higher \( T_{\text{eff}} \), the less the infrared fraction in luminosity, and the less this fraction, the less the greenhouse effect for a given stellar flux. Therefore, a terrestrial planet around a host star with higher \( T_{\text{eff}} \) needs greater flux to remain the water in liquid phase. Thus, the distances at both the inner and the outer HZ boundaries are closer to the host stars with higher \( T_{\text{eff}} \), and farther to the host stars with lower \( T_{\text{eff}} \), for a given stellar flux.

On the contrary, the higher \( T_{\text{eff}} \), the higher the UV fraction in luminosity. Therefore, a terrestrial planet around a host star with higher \( T_{\text{eff}} \) need lower flux to be suitable for life existence. Thus, the distances at both
the inner and the outer UV-HZ boundaries are farther to the host stars with higher $T_{\text{eff}}$, and closer to the host stars with lower $T_{\text{eff}}$, for a given stellar flux. Hence, the UV-HZs are farther than the HZs for the host stars with higher $T_{\text{eff}}$, and closer than the HZs for the host stars with lower $T_{\text{eff}}$.

For the host stars with masses less than $0.777 M_\odot$ at ZAMS and the host stars with masses less than $0.590 M_\odot$ at TMS, the UV-HZs at the outer boundary are closer than the HZs at the inner boundary. And the host star with mass $0.777 M_\odot$ at ZAMS (see the left dotted line of Fig. 1) and the host star with mass $0.590 M_\odot$ at TMS (see the left dotted line of Fig. 2) have the same $T_{\text{eff}}$, just as $4,600$ K. Hence, the UV-HZs are closer than the HZs and there is no intersection between them, for the host stars with $T_{\text{eff}}$ lower than $4,600$ K. And the lower are the $T_{\text{eff}}$ of host stars, the more are the differences between the UV-HZs and the HZs of the host stars.

For the host stars with masses more than $1.752 M_\odot$ at ZAMS and the host stars with masses more than $1.910 M_\odot$ at TMS, the UV-HZs at the inner boundary are farther than the HZs at the outer boundary. And the host star with mass $1.752 M_\odot$ at ZAMS (see the right dotted line of Fig. 1) and the host star with mass $1.910 M_\odot$ at TMS (see the right dotted line of Fig. 2) have the same $T_{\text{eff}}$, just as $7,137$ K. Hence, the UV-HZs are farther than the HZs and there is no intersection between them, for the host stars with $T_{\text{eff}}$ higher than $7,137$ K. And the higher are the $T_{\text{eff}}$ of host stars, the more are the differences between the UV-HZs and the HZs of the host stars.

Therefore, the UV-HZs and the HZs are near to each other and there are intersections between them, for the host stars with $T_{\text{eff}}$ from $4,600$ to $7,137$ K. For the host star with mass $1.037 M_\odot$ at ZAMS (see the middle dotted line of Fig. 1) and the host star with mass $0.955 M_\odot$ at TMS (see the middle dotted line of Fig. 2), the UV-HZs and the HZs entirely coincide with each other, at both the inner and the outer boundaries. And the host star with mass $1.037 M_\odot$ at ZAMS and the host star with mass $0.955 M_\odot$ at TMS have the same $T_{\text{eff}}$, just as $5,636$ K. Hence, the UV-HZs and the HZs are in the same regions, for the host stars with $T_{\text{eff}}$ $5,636$ K.

### 3.3. Impacts of the differences between HZs and UV-HZs on biological evolution

For the host stars with $T_{\text{eff}}$ from $4,600$ to $7,137$ K, most of which are solar-like stars, the UV-HZs are near to the HZs. This means that there is appropriate UV radiation in the HZs for solar-like stars, which is suited to biological evolution.

However, the UV-HZs are closer than the HZs for the host stars with $T_{\text{eff}}$ lower than $4,600$ K, most of which are M and K type stars. This means that there are inadequate UV radiation in the HZs for M and K type stars, especially for M type stars. And UV radiation is used to drive the synthesis of many essential biomolecules. Fortunately, stellar flares of M type stars can generate adequate UV radiation (Heath et al., 1999), which supply the energy source for the synthesis of many biochemical compound. But the stellar flares had better not be too strong, which may damage biological systems. Hence, M type stars with moderate flares are the best candidates to host habitable planets (Buccino et al., 2007).

On the contrary, the UV-HZs are farther than the HZs for the host stars with $T_{\text{eff}}$ higher than $7,137$ K, most of which are upper MS stars. This means that there are too strong UV radiation in the HZs for upper MS stars, which can induce DNA destruction and cause damage to a wide variety of proteins and lipids. Therefore, the probability of life existence around these stars will decrease dramatically.

For example, the $T_{\text{eff}}$ is $10,473$ K at ZAMS, for the host star with mass $3.00 M_\odot$. The distance at the inner UV-HZ boundary is $20.008$ AU, where the UV radiation nicely does not destroy DNA. And the distances at both the inner and the outer HZ boundaries are $4.254$ and $9.236$ AU, respectively. Therefore, the UV radiation in the HZ is from $4.693$ to $22.117$ times of the UV radiation damaging DNA, which is not suited to life existence.

### 3.4. HZ and UV-HZ of hot subdwarf

Hot subdwarfs are known as Extreme Horizontal Branch stars and believed to be core He-burning objects with extremely thin hydrogen envelopes. In this paper, the core mass of hot subdwarf is a typical value $0.475 M_\odot$ and envelope mass is $0.001 M_\odot$, which is calculated by Zhang et al. (2009). And we obtain both the HZ and the UV-HZ of the hot subdwarf at the whole evolutionary phase, seen in Fig. 3.

For example, the $T_{\text{eff}}$ of the hot subdwarf is $33.029$ K, with age $50$ Myr. The distance at the inner UV-HZ boundary is $7.838$ AU. And the distances at both the inner and the outer HZ boundaries are $4.254$ and $9.236$ AU, respectively. Therefore, the UV radiation in the HZ is from $4.693$ to $22.117$ times of the UV radiation destructing DNA, which is not suited to life existence.
DNA, and this strong UV radiation can easily kill the lives living in the HZ.

4. Discussion

In this paper, we use the boundary UV radiation of Buccino et al. (2007). In the UV-HZ of a host star, the number of UV photons $N$ meets $0.5N_{\text{Arc}} \leq N \leq 2N_{\text{Arc}}$. This confine may be too strict, how about $0.5N_{\text{Arc}} \leq N \leq 4N_{\text{Arc}}$? That may induce broader UV-HZ, and the intersection between UV-HZ and HZ will enlarge. However, the UV-HZs are also closer than the HZs for the host stars with lower $T_{\text{eff}}$, and farther than the HZs for the host stars with higher $T_{\text{eff}}$.

X-ray and extreme ultraviolet (EUV) could also play a key role in the origin and development of life on Earth and possibly on Mars (Luhmann & Bauer, 1992). Using the “Principle of Mediocrity”, we can also calculate X-ray habitable zones and EUV habitable zones of host stars. It is speculated about that these two habitable zones are also closer than the HZs for the host stars with lower $T_{\text{eff}}$ and farther than the HZs for the host stars with higher $T_{\text{eff}}$. And the intersection between these two habitable zones and HZ for the same host star will decrease.

5. Conclusion

Firstly, we give the boundary distances of UV-HZ, as a function of stellar radius and $T_{\text{eff}}$, we obtain the UV-HZs around host stars with masses from 0.08 to 4.00 $M_\odot$, and compare the UV-HZs with the HZs. The UV-HZs are closer than the HZs for the host stars with $T_{\text{eff}}$ lower than 4,600 K, and farther than the HZs for the host stars with $T_{\text{eff}}$ higher than 7,137 K. Secondly, we make out the impacts of the differences between HZs and UV-HZs on biological evolution. The UV radiation is very strong in the HZs for upper MS stars, which is negative to live existence. Thirdly, we give the HZ and the UV-HZ of a hot subdwarf, with core mass 0.475 $M_\odot$ and envelope mass 0.001 $M_\odot$. The UV radiation in the HZ is from 22.257 to 135.696 times of the UV radiation dissociating DNA, and this strong UV radiation can easily kill the lives living in the HZ. Finally, we present discussions about the boundary UV radiation and X-ray and EUV radiation.

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