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An Upper Limit on the Ratio Between the Extreme Ultraviolet and the Bolometric Luminosities of Stars Hosting Habitable Planets

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Abstract. A large number of terrestrial planets in the classical habitable zone of stars of different spectral types have already been discovered and many are expected to be discovered in the near future. However, owing to the lack of knowledge on the atmospheric properties, the ambient environment of such planets are unknown. It is known that sufficient amount of Extreme Ultraviolet (EUV) radiation from the star can drive hydrodynamic outflow of hydrogen that may drag heavier species from the atmosphere of the planet. If the rate of mass loss is sufficiently high, then substantial amount of volatiles would escape causing the planet to become uninhabitable. Considering energy-limited hydrodynamical mass loss with an escape rate that causes oxygen to escape alongwith hydrogen, an upper limit for the ratio between the EUV and the bolometric luminosities of stars which constrains the habitability of planets around them is presented here. Application of the limit to planet-hosting stars with known EUV luminosities implies that many M-type of stars should not have habitable planets around them.

Key words. Hydrodynamics—planetary systems—stars—Earth: atmosphere.

1. Introduction

Two decades after the first confirmed discovery of planets outside the solar system (Wolszczan 1994; Mayor & Queloz 1995), we know more than 1500 confirmed planets of different mass, size and surface temperature that are orbiting around stars of different spectral types. Many of the gas giant planets discovered are orbiting so close to their parent stars that tidal effects of the star and atmospheric erosion due to strong stellar irradiation play dominant role in determining their physical properties and evolution (Lammer *et al.* 2003; Baraffe *et al.* 2004; Hubbard *et al.* 2007; Erkaev *et al.* 2007; Penz *et al.* 2008; Sanz-Forcada *et al.* 2011). On the other hand, many small and possibly rocky planets are recently discovered that may have surface temperatures similar to that of the Earth. Therefore, the focus has rapidly changed into detecting planets that may have favorable environment to harbor life.

Classically, a habitable zone is defined as the one that has favorable ambient temperature to keep water in liquid state (Huang 1959; Hart 1978; Kasting *et al.* 1993; Selsis *et al.* 2007). In the recent years a good number of planets are detected within the habitable zone around stars of various spectral types (Udry *et al.* 2007; Vogt *et al.* 2010; Pepe *et al.* 2011; Borucki *et al.* 2011, 2012; Bonfils *et al.* 2013).

It is known that about 75% of the stars in the extended solar neighborhood are M dwarfs (Reid *et al.* 2002). Analysis of data obtained by using the transit method indicates the occurence rate of small and potentially rocky planets with radius ranging from 0.5 to $2.0R_{\oplus}$ ($R_{\oplus}$ is the radius of the Earth) around M dwarf stars which is about 0.51 per star (Dressing & Charbonneau 2013; Kopparapu 2013) while that using the radial velocity method is 0.41 per star (Bonfils *et al.* 2013). It is believed that a good fraction of these rocky planets are situated within the habitable zone of their star. Therefore, there may exist a large number of habitable planets in the solar neighborhood and in our galaxy.

However, a habitable planet should have appropriate amount of hydrogen, nitrogen, oxygen gas and water molecules that support a habitable environment. Various thermal and non-thermal mechanisms cause hydrogen to escape the atmosphere of a terrestrial planet. Thermal mechanisms include hydrodynamic escape and Jeans escape. The loss of hydrogen from a planetary atmosphere is limited either at the homopause by diffusion or at the exobase by energy. Diffusion causes substantial hydrogen loss during the early evolutionary period of a terrestrial planet. In today's Earth, the atmosphere is collisionless above the tropopause and hence the barometric laws break down. Therefore, Jeans law is not applicable. Jean's law is also not applicable if the atmosphere is not under hydrostatic equilibrium. This may occur by the absorption of stellar Extreme Ultraviolet (EUV) radiation with wavelengths ranging from 100 to 920 Å. Strong EUV irradiation heats up the hydrogen-rich thermosphere so significantly that the internal energy of the gas becomes greater than the gravitational potential energy. This leads to the expansion of the atmosphere and powers hydrodynamic escape of hydrogen which can drag off heavier elements if the escape flux is high enough. The Earth does not receive sufficiently strong EUV irradiation from the Sun at present. Also the total hydrogen mixing ratio in the present stratosphere is as small as 10^{-5}. Therefore, in today's Earth, hydrogen escape is limited by diffusion through the homopause.

The bolometric luminosity is one of the important observable stellar properties that determines the distance of the Habitable Zone (HZ) or the circumstellar region in which a planet can have appropriate temperature to sustain water in liquid state. On the other hand, the EUV luminosity determines the rate at which hydrogen escapes from the atmosphere of a planet in the HZ. If the bolometric luminosity of the star is low, the HZ is closer to the star and hence a planet in the HZ is exposed to stronger EUV irradiation. If the EUV luminosity of such faint stars is sufficiently high then a habitable planet would lose substantial amount of hydrogen and heavier gases. It would lead to oxidation of the surface and accumulation of oxygen in the atmosphere, scarcity of hydrocarbon and significant reduction in surface water. All these would make the planet uninhabitable. If a habitable planet undergoes runway greenhouse, water vapor would reach the stratosphere where it would get photolyzed and subsequently should escape the atmosphere.

In this paper, an analytical expression for the upper limit of the ratio between the EUV and the bolometric luminosities of a planet-hosting star of any spectral type which serves as an essential condition to ensure the presence of sufficient amount of hydrogen, nitrogen, oxygen, water etc. that supports the habitability of a rocky planet in the HZ of the star is presented. Since both $L_{\rm EUV}$ and $L_{\rm B}$ are observable quantities, it will help to determine if a planet in the habitable zone of a star is really habitable or not. Thus the limit should serve as a ready reckoner for eliminating candidate habitable planets.

2. Criteria for planetary habitability

The distance of a habitable planet from its parent star is given by (Kasting *et al.* 1993; Kopparapu *et al.* 2013)

$$d = \left(\frac{L_{\rm B}}{L_{\odot} S_{\rm eff}}\right)^{1/2} d_{\rm E}, \tag{1}$$

where $L_{\rm B}$ and $L_{\odot}$ are the bolometric luminosity of the star and the Sun respectively, $d_{\rm E}$ is the distance between the Earth and the Sun (1 AU) and $S_{\rm eff}$ is the normalized effective stellar flux incident on the planet.

Let $L_{\rm EUV}$ be the EUV luminosity at the surface of a star. If ϵ is the efficiency at which the EUV is absorbed by the planetary atmosphere then the sphere-averaged and efficiency corrected heating rate in the planetary thermosphere due to stellar EUV irradiation is

$$S = \frac{L_{\rm EUV}}{L_{\rm B}} \left(\frac{\epsilon S_{\rm eff} L_{\odot}}{4\pi d_{\rm E}^2}\right). \tag{2}$$

The heating efficiency is less than one because part of the total incident EUV energy drives ionization, dissociation and other reactions without striping out the atoms or molecules from the atmosphere.

In order to remain habitable, S must be low enough so that the rate of hydrogen escape from the planetary surface due to EUV irradiation does not exceed a critical value that may cause the heavier constituents including oxygen to be entrained with the outflow of hydrogen. If the mixing ratio of hydrogen is low in the lower atmosphere, hydrogen escape should be limited by diffusion. Therefore the critical rate of energy limited loss should be comparable to that of diffusion limited escape under such circumstances.

Let $S_{\rm c}$ be the value of S corresponding to the critical rate of hydrogen-loss. Therefore, the necessary condition to prevent hydrogen loss at critical rate by EUV irradiation can be written as

$$\frac{L_{\rm EUV}}{L_{\rm B}} < \frac{4\pi d_{\rm E}^2}{\epsilon S_{\rm eff} L_{\odot}} S_{\rm c}. \tag{3}$$

Now we need to derive $S_{\rm c}$, the sphere-averaged, efficiency-corrected and energy-limited critical EUV flux that causes hydrogen to escape at the critical rate.

3. Energy-limited EUV flux

In order to derive the energy-limited critical EUV flux S_c, the formalism given by Watson *et al.* (1981) is adopted. Watson *et al.* (1981) applied this formalism to estimate the mass loss of Earth's hydrogen exosphere due to solar EUV irradiation. It was also used by Lammer *et al.* (2003) for explaining the observed extended atmosphere for the close-in hot and giant transiting planet HD 209458b (Vidal-Madjar *et al.* 2003). The formalism is derived from the usual steady state equations of mass momentum and energy conservation of a dynamically expanding, non-viscous gas of constant molecular weight in which the pressure is isotropic. Unlike the Jean's treatment, this formalism can be applied to a dense thermosphere of hydrogen with a fixed temperature at the lower boundary located sufficiently above the homopause such that the mixing ratios of heavier gases are negligible as compared to that of hydrogen. All the EUV energy is absorbed in a narrow region with visible optical depth less than unity and no EUV energy is available below this region due to complete absorption. The rate of mass loss estimated by using this method is within a factor of few of the same (Hubbard *et al.* 2007) provided by other models including those that involve detailed numerical solutions (Baraffe *et al.* 2004; Tian *et al.* 2005; Yelle 2004). However, Murray-Clay *et al.* (2009) argued that for the irradiated EUV flux greater than 10^4 erg cm $^{-2}$ s^{-1}, mass loss ceases to be energy limited and becomes radiation/recombination limited. As a consequence the formalism prescribed by Watson *et al.* (1981) is not applicable in that case.

The two equations that provide the maximum rate of hydrogen escape and the expansion of the atmosphere due to EUV heating are given as (Watson *et al.* 1981):

$$\xi = \frac{2}{q+1}\left[\frac{(\lambda_1/2)^{(1+q)/2}+1}{\lambda_0-\lambda_1}\right]^2 \tag{4}$$

and

$$\beta = \xi\lambda_1^2\left[\lambda_0 - \left\{\frac{2}{(1+q)\xi}\right\}^{1/2}\right]. \tag{5}$$

In the above equations, the dimensionless parameters ξ, β, λ_0 and λ_1 are related with the physical parameters by

$$\xi = F_m\left(\frac{k^2T_0}{\kappa_0 G M_P m_H}\right), \tag{6}$$

$$\beta = S\left(\frac{G M_P m_H}{\kappa_0 k T_0^2}\right), \tag{7}$$

$$\lambda_{0,1} = \frac{G M_P m_H}{k T_0 r_{0,1}}, \tag{8}$$

where $r_0 = R_P$ is the radius of the planet where the visible optical depth is one and the temperature is T_0, r_1 is the radius of the region where all the EUV energy is absorbed. The optical depth of the atmosphere to EUV energy at the lower boundary r_0 is much greater than unity. F_m is the sphere averaged flux of escaping particles (escape flux of particles per steradian per second), k is the Boltzmann constant, M_{P} is the total mass of the planet, m_{H} is the mass of hydrogen atom and κ is the thermal conductivity of the gas which is parametrized by $\kappa = \kappa_0 \tau^q$, where τ is the visible optical depth of the thermosphere such that $\tau(\lambda_0) = 1$.

4. Analytical and numerical solutions

Equations (4) and (5) need to be solved numerically for an arbitrary value of q. However, for $q = 1$ we obtain analytical solutions for λ_1 and β and hence S. Thus for $q = 1$, equation (4) gives

$$\lambda_1 = \frac{2(\xi^{1/2}\lambda_0 - 1)}{1 + 2\xi^{1/2}}. \tag{9}$$

Substituting equation (9) in equation (5), equation (7) gives

$$S(q = 1) = 4\xi \left(\frac{\xi^{1/2}\lambda_0 - 1}{1 + 2\xi^{1/2}} \right)^2 \left(\lambda_0 - \frac{1}{\xi^{1/2}} \right) \left(\frac{\kappa_0 k T_0^2}{G M_{\mathrm{P}} m_{\mathrm{H}}} \right). \tag{10}$$

Now, $S = S_{\mathrm{c}}$ when $F_m = F_{\mathrm{c}}$ in the expression for ξ given in equation (6) where F_{c} is the critical rate of hydrogen escape. Hydrogen diffuses before it reaches the thermobase if the background gas of heavier species is static. This happens if the heavier species are not absorbed or cannot escape at the surface. The diffusion limit for hydrogen is achieved when the heavier gases attain the maximum upward velocity such that the background becomes non-static (Hunten 1973). Therefore if F_{c} is greater than or equal to the diffusion limit, heavier species would escape. The rate of hydrogen loss limited by diffusion is given by (Hunten 1973; Zahnle *et al.* 1990)

$$F_{\mathrm{H}}(\text{diffusion}) = \frac{bg(m_s - m_{\mathrm{H}})}{kT_0(1 + X_s/X_{\mathrm{H}})}, \tag{11}$$

where $b = 4.8 \times 10^{17} (T/K)^{0.75}$ cm^{-1} s^{-1} is the binary diffusion coefficient for the two species (Zahnle & Kasting 1986), X_{H} and X_s are the molar mixing ratio at the exobase for hydrogen and the heavier atom with mass m_s respectively and g is the surface gravity of the planet. Therefore we set

$$F_m = F_{\mathrm{c}} = R_{\mathrm{P}}^2 \frac{bg(m_s - m_{\mathrm{H}})}{kT_0(1 + X_s/X_{\mathrm{H}})} \text{ particles sr}^{-1}\text{s}^{-1} \tag{12}$$

which gives the cross over mass $m_s = m_{\mathrm{H}} + (kT_0 F_{\mathrm{c}}/R_{\mathrm{P}}^2)/(bgX_{\mathrm{H}})$ such that any species with mass less than or equal to m_s would be efficiently dragged by the escaping hydrogen (Hunten *et al.* 1987). In the present derivation, $m_s = m_{\mathrm{O}} = 16m_{\mathrm{H}}$ is considered such that the critical rate of hydrogen loss would enable oxygen and other atoms lighter than oxygen to be dragged with the escaping gas. We assume that both hydrogen and oxygen are atomic near the exobase due to fast dissociation of the molecules by photolysis (Murray-Clay *et al.* 2009).

Therefore, from equation (3) we obtain, for $q = 1$,

$$\frac{L_{\rm EUV}}{L_{\rm B}} < \frac{16\pi d_{\rm E}^2 \kappa_0 k T_0^2}{\epsilon G M_{\rm P} m_{\rm H} (1-e^2)^{1/2} S_{\rm eff} L_\odot} \frac{\xi^{1/2}(\lambda_0 \xi^{1/2} - 1)^3}{(2\xi^{1/2}+1)^2}, \tag{13}$$

where λ_0, the parameter for the planetary radius is given by equation (8) and

$$\xi = R_{\rm P}^2 \frac{bg(m_{\rm O} - m_{\rm H})}{1 + X_{\rm O}/X_{\rm H}} \frac{k}{\kappa_0 G M_{\rm P} m_{\rm H}}. \tag{14}$$

The term $(1-e^2)^{1/2}$ in the denominator is introduced in order to include elliptical orbit with eccentricity e.

The above analytical expression is derived by taking $q = 1$. However, for a neutral gas, $q \simeq 0.7$ (Banks & Kockarts 1973). Therefore, equation (4) and equation (5) are solved numerically for different values of $q \leq 1.0$ keeping all other parameters fixed. Figure 1 presents the values of $S_{\rm c}$ for different values of q and shows that $S_{\rm c}(q = 1) < S_{\rm c}(q < 1)$. Therefore, equation (3) implies that the inequality given by equation (13) is valid for any value of $q \leq 1$. It is worth mentioning that the bolometric luminosity of a main sequence star increases with time. For a solar-type star, the bolometric luminosity increases by about 10% in every 1 Gyr. The Sun was about 30% fainter in the visible light during the first billion years after its birth. On

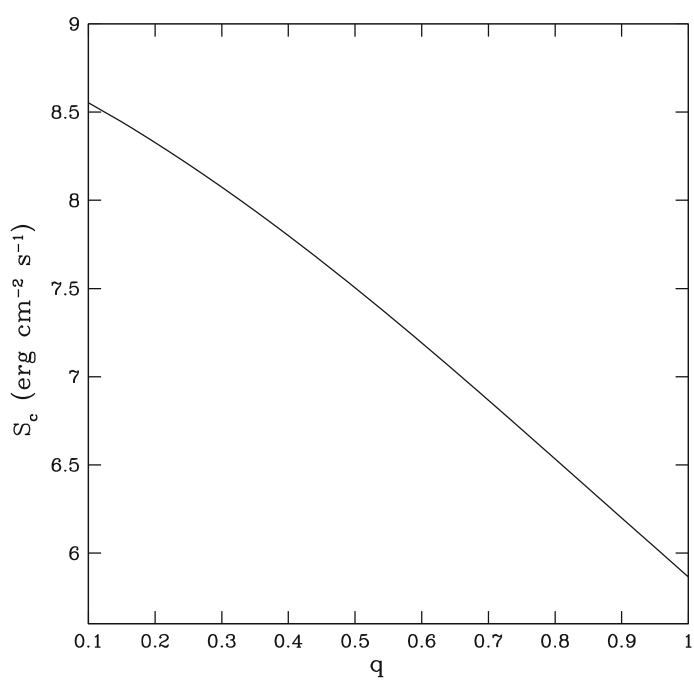

Figure 1. The sphere-averaged, efficiency-corrected and energy-limited critical EUV flux $S_{\rm c}$ as a function of the conductivity index q. Terrestrial parameters are used to calculate $S_{\rm c}$. For neutral gas, $q \simeq 0.7$.

the other hand, the EUV luminosity is governed by the coronal activities of a star. Since a star rotates faster during younger age resulting into greater coronal activities, the EUV emission rate or the EUV luminosity was higher in the past and it decreases with time. Consequently, the rate of mass loss from the planetary surface was higher in the past. Since, the value of $L_{\rm EUV}/L_{\rm B}$ in the past was greater than its present value, the condition derived here is valid for a constant rate of mass loss corresponding to the present value of $L_{\rm EUV}/L_{\rm B}$. A time-dependent solution would have provided more stringent condition.

5. Application to habitable exoplanets

The thermal conductivity of hydrogen is $\kappa_0 = 4.45 \times 10^4$ ergs cm^{-1}s^{-1}K^{-1} (Hanley *et al.* 1970). The size and the mass of the planets are usually determined from the observed parameters of the planet. Transit method provides the size and the orbital inclination angle of the planet and radial velocity method provides the projected mass of the planet for known stellar mass. Therefore, the two unknown parameters in equation (13) are T_0 and $S_{\rm eff}$.

The lower boundary r_0 is located some distance above the homopause and the temperature T_0 at the lower boundary may be fixed at the equlibrium temperature of the planet (Watson *et al.* 1981). However, as shown in Fig. 2, the above limit is weakly dependent on T_0 because the parameter λ_0 is inversely proportional to T_0. Therefore, without loss of generality, T_0 can be fixed at 254 K, the equilibrium

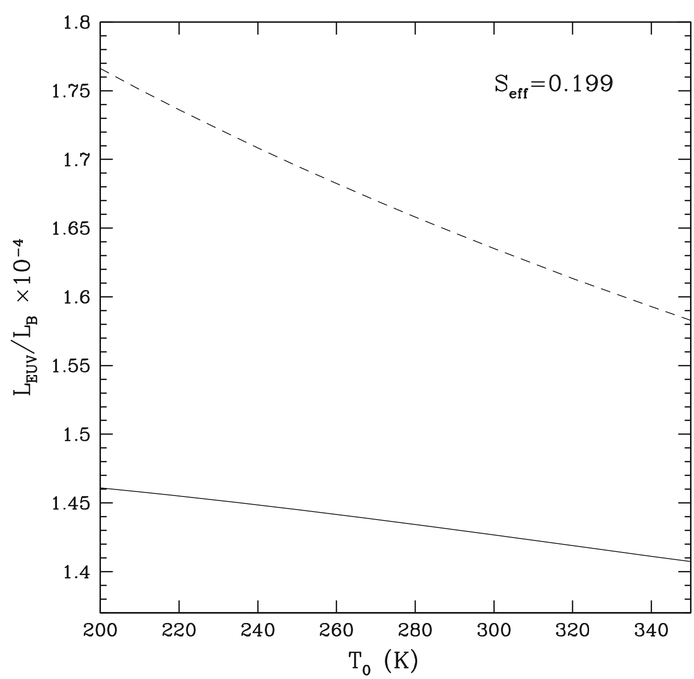

Figure 2. $L_{\rm EUV}/L_{\rm B}$ for different values of T_0. Solid line represents $L_{\rm EUV}/L_{\rm B}$ for $q = 1.0$ and dashed line represents that for $q = 0.7$.

temperature of the Earth. This makes the above expression independent of planetary albedo because derivation of equilibrium temperature requires the value of planetary albedo. With $T_0 = 254$ K and taking $X_{\rm O} = 1/3$ and $X_{\rm H} = 2/3$, we obtain $F_{\rm c} = 1.43 \times 10^{13}$ cm^{-2} s^{-1} which is two orders of magnitude higher than that calculated by Watson *et al.* (1981) for the Earth irradiated by solar EUV radiation. This ensures that the cross over mass m_s is equal to $m_{\rm O}$. The total mass of hydrogen ($M_{\rm H}$) in the atmosphere, ocean and in the crust of the Earth is about 1.9×10^{23} gm (Anders & Owen 1977; Sharp *et al.* 2009). Therefore at this critical rate, an Earth-like planet would lose all of its surface hydrogen in about 50 Myr. Water molecules would be photo-dissociated into hydrogen and oxygen atoms that would subsequently escape the planet. Even if the amount of water is not reduced sufficiently, such a significant loss of hydrogen and other heavier gases such as nitrogen and oxygen would make the environment drastically different than that of the present Earth.

Kopparapu *et al.* (2013) have presented relationships between the stellar effective temperature $T_{\rm eff}$ and the normalized stellar flux $S_{\rm eff}$ impinging on the top of the atmosphere of an Earth-like planet at the habitable zone. These relationships are applicable in the range 2600 K$\leq T_{\rm eff} \leq 7200$ K. According to these relationships, $S_{\rm eff}$ is minimum at $T_{\rm eff} = 2600$ K and increases with the increase in $T_{\rm eff}$. $S_{\rm eff}$ also varies for different atmospheric conditions that determines the inner and the outer boundaries of the habitable zone. While condition like 'Recent Venus', 'Runway Greenhouse' or 'Moist Greenhouse' determines the inner boundary, condition such as 'Maximum Greenhouse' or 'Early Mars' determines the outer boundary of the habitable zone. Since, $L_{\rm EUV}/L_{\rm B}$ in equation (13) is inversely proportional to $S_{\rm eff}$, I use the minimum value of $S_{\rm eff}$ corresponding to $T_{\rm eff} = 2600$ K. This makes the upper limit on $L_{\rm EUV}/L_{\rm B}$ independent of the effective temperature of the star. As $S_{\rm eff}$ increases with the increase in $T_{\rm eff}$, the value of $S_{\rm eff}$ corresponding to the actual $T_{\rm eff}$ of the star would only tighten the limit. It is worth mentioning here that according to the relationships provided by Kopparapu *et al.* (2013), $S_{\rm eff}$ increases only by 2–3 times with the increase in $T_{\rm eff}$ from 2600 K to 7200 K.

Taking the equilibrium temperature of the Earth, $T_0 = 254$ K, the radius of the Earth, $R_{\rm P} = 6.378 \times 10^8$ cm, the mass of the Earth, $M_{\rm P} = 5.9726 \times 10^{27}$ gm and $\epsilon = 0.15$ (Watson *et al.* 1981), we derive, from equation (13), the upper limit on $L_{\rm EUV}/L_{\rm B}$ for planets within the outer boundary of the habitable zone. The values are presented in Table 1. For the same set of parameters, the numerical solution of equations (4) and (5) for $q = 0.7$ is also presented in Table 1.

The critical EUV flux $S_{\rm c}$ is less than 10 erg cm^{-2} s^{-1} which ensures energy-limited escape. Also, equation (9) gives the expanded radius $r_1 = 1.57 R_{\rm P}$ for $T_0 = 254$ K.

Table 1. Upper limit on $L_{\rm EUV}/L_{\rm B}$ for $S_{\rm eff}$ corresponding to $T_{\rm eff} = 2600$ K under atmospheric conditions that determines the outer boundary of the habitable zone. For $q = 0.7$, the results are obtained numerically.

Conditions	$S_{\rm eff}$	$L_{\rm EUV}/L_{\rm B}$	
		$q = 1.0$	$q = 0.7$
Maximum Greenhouse	0.215	1.33×10^{-4}	1.56×10^{-4}
Early Mars	0.199	1.44×10^{-4}	1.69×10^{-4}

6. Discussions and conclusions

Estimating the stellar EUV luminosities is difficult not only because the energy gets completely absorbed at the uppermost layer of the Earth's atmosphere but also due to photoelectric absorption by the interstellar medium along the line-of-sight. Using the ROSAT space telescope, Hodgkin & Pye (1994) estimated the EUV luminosities of a large number of nearby stars with spectral type ranging from F to M . Here, I use the bolometric and EUV luminosities of planet-hosting stars of spectral type ranging from A to M, given by Sanz-Forcada *et al.* (2011) who derived the EUV and bolometric luminosities by using the data from ROSAT, XMM-Newton and Chandra space telescopes. I have considered only those stars that are older than 1 Gyr. It is found that out of all such stars, only two of the planet-hosting M stars satisfy the criteria presented in this work. The value of $L_{\rm EUV}/L_{\rm B}$ for 2MASS 1207 (spectral type M8) is 1.23×10^{-3}. For GJ 317 (M3.5), GJ 674 (M2.5) and GJ 176 (M2.5V), the values of $L_{\rm EUV}/L_{\rm B}$ are 1.78×10^{-3}, 2.95×10^{-4} and 4.26×10^{-4} respectively. Therefore, none of these M stars can have a planet with habitable environment. GJ 832 (M1.5V) has $L_{\rm EUV}/L_{\rm B} = 10^{-4}$ and so it marginally satisfies the habitability criteria. However, since the effective temperature of this M1.5V spectral type star is higher than 2600 K, this planet should also be considered uninhabitable. On the other hand, the values of $L_{\rm EUV}/L_{\rm B}$ for GJ 436 (M2.5) and GJ 876 (M4V) are 1.58×10^{-5} and 1.9×10^{-5} respectively. Therefore, these two M stars satisfy the EUV habitability criteria provided in table 1. This is expected because M stars are the faintest among stars of all spectral types. As a consequence the HZ of M stars is located very near to the stars and hence a planet in the habitable zone is exposed to strong EUV radiation. It is worth mentioning here that a rocky planet in the habitable zone of M stars may lose much of its volatiles during the formation because the pre-main sequence phase of such stars are comparatively longer. However, if the planet accretes sufficiently large amount of water during formation or if it were formed far away from the star and then migrated to the HZ, it may remain habitable (Lissauer 2007). But strong EUV irradiation should make it uninhabitable.

However, planet hosting stars of all other spectral types listed by Sanz-Forcada *et al.* (2011) have $L_{\rm EUV}/L_{\rm B}$ much lower than the upper limits provided here. The values of $L_{\rm EUV}/L_{\rm B}$ for GJ 86 (K1V) is 9.77×10^{-5}. Therefore, according to the present upper limit, this star marginally satisfies the habitability criteria of having sufficient amount of water. On the other hand, the values of $L_{\rm EUV}/L_{\rm B}$ for HD 87883 (K0V), ϵ Eridani (K2V), HD 46375 (K1V), HD 93083 (K3V), HD 130322 (K0V), HD 189733 (K1-K2) and HD 218566 (K3V) are 2.75×10^{-5}, 2.19×10^{-5}, 1.02×10^{-5}, 1.479×10^{-5}, 1.95×10^{-5}, 2.4×10^{-5} and 1.66×10^{-5} respectively. So, all of them satisfy the upper limit for $L_{\rm EUV}/L_{\rm B}$.

Hence, the upper limit presented here is important in deciding the habitability of planets around M stars. Note that the numerical values of the parameters involved in the present habitability condition do not differ much from that of the Earth. The density of a rocky planet should be about 4.0–5.5 gm cm^{-3}. Therefore, the radius of a rocky planet does not exceed 1.6 times the Earth's radius and the mass must be less than 5 times the Earth's mass (Rogers 2015). More massive planets are Neptune and Jupiter types of gaseous planets (Marcy *et al.* 2014). Therefore, a large value of $L_{\rm EUV}/L_{\rm B}$ for M stars may rule out the presence of habitable planets around them.

Owing to our poor knowledge on the actual environment of exoplanets, the habitability of rocky planets around the habitable zone remains ambiguous and incomplete. However, we must impose as many conditions as can be determined directly and easily in order to narrow down our search for planets that may possibly harbor life. The present result provides such an important condition as it depends on two observable quantities of the planet hosting star – the bolometric and EUV luminosities. Spectra of habitable planets around M-type stars that do not satisfy the EUV criteria presented here should show lack of hydrogen, nitrogen and oxygen in their atmosphere and hence can confirm the limit presented here.

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