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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 has already been discovered and many are expected to be discovered in 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 along with hydrogen, I present an upper limit for the ratio between the EUV and the bolometric luminosities of stars which constrains the habitability of planets around them. 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.

Subject headings: 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 effect 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, Micela & Lammer 2008; Sanz-Forcada et al. 2011). On the other hand, many small and possibly rocky planets are recently discovered that may have surface temperature 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 planet is defined as the one that has favorable ambient temperature to keep water in liquid state and a rocky surface to retain liquid water (Huang 1959; Hart 1978; Kasting, Whitmire & Raynolds 1993; Selsis et al. 2007). In the recent years a good number of such planets are detected 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, Gizis & Hawley 2002). Analysis of data obtained by using the transit method indicates the occurrence rate of habitable planets with radius ranging from 0.5 to 2.0 $R_\oplus$ ($R_\oplus$ is the radius of the Earth) around M dwarf stars is about 0.51 per star (Dressing & Charbonneau 2013; Kopparapu 2013) while that by using the radial velocity method is 0.41 per star (Bonfils et al. 2013). Therefore, it is usually believed that there exists a large number of habitable planets in the solar neighborhood and in our galaxy.

However, the definition of habitable planets presumes that the planet has sufficient 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 of a star 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 runaway greenhouse, water vapor would reach the stratosphere where it would get photolyzed and subsequently should escape the atmosphere.

In this letter, I present 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. The limit should serve as a ready reckoner for eliminating candidate habitable planets.

2. CRITERIA FOR PLANETARY HABITABILITY

The outer and the inner edges of the HZ correspond to the freezing and the boiling point of water respectively. The distance of a habitable planet from its parent star is given by (Scharf 2009)

\[
d = \left[ \frac{L_B}{16\pi\sigma T_g^4} (1 - A_B)(1 + 0.75\tau_g) \right]^{1/2},
\]

where \( L_B \) is the bolometric luminosity of the star, \( A_B \) is the bond albedo of the planetary surface, \( \tau_g \) is the mean infra-red optical depth of the atmosphere which determines the amount of infra-red radiation trapped and gives rise to the Greenhouse effect, \( T_g \) is the mean ambient temperature of the planetary atmosphere after the Greenhouse effect is included and \( \sigma \) is the Stefan-Boltzmann constant. The values of \( A_B \) and \( \tau_g \) depend on the chemical composition and the physical properties of the planetary atmosphere.

Let \( L_{EUV} \) be the EUV luminosity at the surface of a star. If \( \epsilon \) 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
\[ S = \frac{L_{EUV}}{L_B} \left[ \frac{4\epsilon\sigma T_g^4}{(1 - A_B)(1 + 0.75\tau_g)} \right]. \] (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 circumstance.

Let \( S_c \) 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:
\[ \frac{L_{EUV}}{L_B} < \frac{(1 - A_B)(1 + 0.75\tau_g)}{4\epsilon\sigma T_g^4} S_c. \] (3)

Now we need to derive \( S_c \), 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, Donahue & Walker (1981) is adopted. Watson, Donahue & Walker (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...
bellow this region due to complete absorption. The rate of mass loss estimated by using this method is within a factor of few (Hubbard et al. 2007) of the same provided by other models including those that involve detail numerical solutions (Baraffe et al. 2004; Tian et al. 2005; Yelle 2004). However, Murray-Clay, Chiang & Murray (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, Donahue & Walker (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, Donahue & Walker 1981):

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

(4)

and

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

(5)

In the above equations the parameters $\xi$, $\beta$, $\lambda_0$ and $\lambda_1$ are defined as

$$\xi = F_m \frac{k^2 T_g}{\kappa_0 G M_P m_H (1 + 0.75 \tau_g)^{1/4}},$$

(6)

$$\beta = S \frac{G M_P m_H (1 + 0.75 \tau_g)^{1/2}}{k T_g^2 \kappa_0},$$

(7)

$$\lambda_{0,1} = \frac{G M_P m_H (1 + 0.75 \tau_g)^{1/4}}{(k T_g r_{0,1})},$$

(8)

$r_0 = R_P$ being the radius of the planet where the visible optical depth is one and the temperature is $T_{eq} = T_g (1 + 0.75 \tau_g)^{-1/4}$ (Scharf 2009) and $r_1$ is the radius of the region where all the EUV energy is absorbed. $T_{eq} = [L_B (1 - A_B) / (16 \pi \sigma d^2)]^{1/4}$ is the equilibrium temperature of the planet (Scharf 2009; Saumon et al. 1996) i.e. the temperature without the Greenhouse effect. The lower boundary is located some distance above the homopause and the temperature at the lower boundary is fixed at $T_{eq}$. The optical depth of the atmosphere to EUV energy at the lower boundary 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 $\kappa$ is the thermal conductivity of the gas which is parameterized by $\kappa = \kappa_0 \tau_g$ where $\tau$ is the visible optical depth of the thermosphere such that $\tau(\lambda_0) = 1$. 
4. ANALYTICAL AND NUMERICAL SOLUTIONS

Equation (4) and equation (5) need to be solved numerically for an arbitrary value of \( q \). However, for \( q = 1 \) we obtain analytical solutions for \( \lambda_1 \) and \( \beta \) 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) and rearranging, we obtain

\[
S(q = 1) = 4\xi \left(\frac{\xi^{1/2}\lambda_0 - 1}{1 + 2\xi^{1/2}}\right)^2 \left(\lambda_0 - \frac{1}{\xi^{1/2}}\right) \left[\frac{kT_g^2\kappa_0}{GM_Pm_H(1 + 0.75\tau_g)^{1/2}}\right]. \tag{10}
\]

Now, \( S = S_c \) when \( F_m = F_c \) in the expression for \( \xi \) 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 \[\text{[Hunten 1973]}\]. 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 \[\text{[Hunten 1973]; Zahnle, Pollack & Kasting 1990]}\]

\[
F_H(\text{diffusion}) = \frac{bg(m_s - m_H)}{kT_eq(1 + X_s/X_H)} \tag{11}
\]

where \( b = 4.8 \times 10^{17}(T/K)^{0.75} \text{ cm}^{-1}\text{s}^{-1} \) is the binary diffusion coefficient for the two species \[\text{[Zahnle & Kasting 1986]}\], \( X_H \) 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

\[
F_m = F_c = \frac{bg(m_s - m_H)}{kT_eq(1 + X_s/X_H)} \text{ particles s}^{-1} \text{s}^{-1} \tag{12}
\]

which gives the cross over mass \( m_s = m_H + (kT_eqF_c/R_P^2)/(bgX_H) \) such that any species with mass less than or equal to \( m_s \) would be efficiently dragged by the escaping hydrogen \[\text{[Hunten et al. 1987]}\]. In the present derivation I consider \( m_s = m_O = 16m_H \) such that the critical rate of hydrogen loss would enable oxygen and other atoms lighter than oxygen to be dragged with the escaping gas. I assume that both hydrogen and oxygen are atomic near the exobase due to fast dissociation of the molecules by photolysis \[\text{[Murray-Clay, Chiang & Murray 2009]}\].
Therefore, from equation (3) we obtain, for $q = 1$

$$\frac{L_{EUV}}{L_B} < \frac{k \kappa_0 (1 - A_B) (1 + 0.75 \tau_g)^{1/2}}{\epsilon \sigma T_g^2 GM_p m_H (1 - e^2)^{1/2}} \frac{\xi^{1/2} (\lambda_0 \xi^{1/2} - 1)^3}{(2 \xi^{1/2} + 1)^2},$$

(13)

where $\lambda_0$, the parameter for the planetary radius is given by equation (8) and

$$\xi = \frac{\lambda_0^2 b g (m_O - m_H)}{k T_{eq} (1 + X_O / X_H)} \left[ \frac{k^2 T_g}{\kappa_0 G M_p m_H (1 + 0.75 \tau_g)^{1/4}} \right].$$

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

However, for a neutral gas, $q \simeq 0.7$ (Banks & Kockarts 1973). Therefore, I solve equation (4) and equation (5) numerically for different values of $q \leq 1.0$ keeping all other parameters fixed. Fig. 1 presents the values of $S_c$ for different values of $q$ and shows that $S_c(q = 1) < S_c(q < 1)$. 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 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 $L_{EUV} / L_B$ 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 $L_{EUV} / L_B$. A time-dependent solution would have provided more stringent condition.

5. APPLICATION TO HABITABLE EXOPLANETS

The thermal conductivity of hydrogen $\kappa_0 = 4.45 \times 10^4$ ergs cm$^{-1}$s$^{-1}$K$^{-1}$ (Hanley, McCarty & Interman 1970). The ambient temperature $T_g$ after the correction for the Greenhouse effect determines if water can be sustained in liquid state at the surface of the planet. However, estimating $T_g$ for an exoplanet and hence determining if the ambient temperature of the atmosphere indeed is suitable for water to exist in liquid state requires detail knowledge on the physical properties of the planetary atmosphere. In the absence of detail knowledge on the atmospheric properties of any habitable exoplanets discovered till date, I use the terrestrial parameters to estimate the numerical value of the right hand side of the habitability criteria as given
in equation (13). Under such situation, one can estimate the upper limit of \( \frac{L_{\text{EUV}}}{L_B} \) that constrains the presence of an Earth-like or terrestrial planet around a star instead of just a habitable planet. It is worth mentioning that at present we know only the Earth to harbor life and it is unlikely that favorable ambient temperature alone can support life on a planet. Therefore it is reasonable to consider the terrestrial parameters in order to constrain the habitability of a planet. For \( X_O = 1/3 \) and \( X_H = 2/3 \), I obtain \( F_c = 1.43 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1} \) which is two orders of magnitude higher than that calculated by [Watson, Donahue & Walker (1981)] for the Earth irradiated by solar EUV radiation. This ensures the cross over mass \( m_s \) is equal to \( m_O \). The total mass of hydrogen \( (M_H) \) in the atmosphere, Ocean and in the crust of the Earth is about \( 1.9 \times 10^{23} \text{ gm} \) (Anders & Owen 1977; Sharp, Draper & Agee 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.

Taking \( A_B = 0.306 \), \( T_g = 287 \text{ K} \), \( M_P = 5.9726 \times 10^{27} \text{ gm} \), \( R_P = 6.378 \times 10^{8} \text{ cm} \), \( \tau_g = 0.83 \) (Scharf 2009) and \( \epsilon = 0.15 \) (Watson, Donahue & Walker 1981), we find from equation (13) the necessary condition for a star that allows a planet to have terrestrial environment is

\[
\frac{L_{\text{EUV}}}{L_B} < 2.86 \times 10^{-5}.
\]  

(14)

For the same set of parameters the numerical solution of equation (4) and equation (5) gives \( \frac{L_{\text{EUV}}}{L_B} < 3.35 \times 10^{-5} \) for \( q = 0.7 \). In other words an Earth-like planet should lose all the hydrogen and heavier gases and consequently water and hence should become uninhabitable if the ratio between the present EUV and bolometric luminosities of the parent star is greater than \( 2.86 \times 10^{-5} \). The critical EUV flux \( S_c \) is less than \( 10 \text{ erg cm}^{-2} \text{ s}^{-1} \) which ensures energy-limited escape. Also, equation (9) gives the expanded radius \( r_1 = 1.56R_P \).

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. Out of all such stars, only two of the planet-hosting M stars marginally satisfies the above criteria for planetary habitability. The value of $L_{\text{EUV}}/L_B$ for 2MASS 1207 (spectral type M8) is $1.23 \times 10^{-3}$. For GJ 317 (M3.5), GJ 674 (M2.5), GJ 176 (M2.5V) and for GJ 832 (M1.5V), the values of $L_{\text{EUV}}/L_B$ are $1.78 \times 10^{-3}$, $2.95 \times 10^{-4}$, $4.26 \times 10^{-4}$ and $10^{-4}$ respectively. Therefore, none of these M stars can have a planet with environment similar to the Earth. On the other hand the values of $L_{\text{EUV}}/L_B$ for GJ 436 (M2.5) and GJ 876 (M4V) are $1.58 \times 10^{-5}$ and $1.9 \times 10^{-5}$ respectively. Therefore these two M stars marginally satisfies the EUV habitability criteria. 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 HZ is exposed to strong EUV radiation. It is worth mentioning here that a rocky planet in the HZ 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 \cite{Lissauer2007}. But strong EUV irradiation should make it uninhabitable. Interestingly, quite a few K-type stars that are brighter than M0 stars marginally satisfy the habitability condition presented here. The values of $L_{\text{EUV}}/L_B$ for GJ 86 (K1V) is $9.77 \times 10^{-5}$. The values of $L_{\text{EUV}}/L_B$ for HD 87883 (K0V), $\epsilon$ Eridani (K2V), HD 46375 (K1V), HD 93083 (K3V), HD 130322 (K0V), HD 189733 (K1-K2) and HD 218566 (K3V) are $2.75 \times 10^{-5}$, $2.19 \times 10^{-5}$, $1.02 \times 10^{-5}$, $1.479 \times 10^{-5}$, $1.95 \times 10^{-5}$, $2.4 \times 10^{-5}$ and $1.66 \times 10^{-5}$ respectively. So, they marginally satisfy the upper limit for $L_{\text{EUV}}/L_B$ presented here. However, if we include X-ray irradiation as well, none of this planets will be habitable. On the other hand, planet hosting stars of all other spectral types except HD 49674 (G5V) ($L_{\text{EUV}}/L_B = 7.08 \times 10^{-5}$) listed by \cite{Sanz-Forcada2011} have $L_{\text{EUV}}/L_B$ much lower than the upper limit provided here. Therefore, the upper limit presented here is important in deciding the habitability of planets around K and 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 g 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. More massive planets are Neptune and Jupiter types of gaseous planets \cite{Marcy2014}. Further, $A_B$ and $\tau_g < 1$. The variation of $T_g$ for the habitability is limited within an order of magnitude. Therefore, a large value of $L_{\text{EUV}}/L_B$ 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 definition of a habitable planet 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
c Condition along with the other two existing conditions, e.g., size and temperature. Spectra
Of habitable planets around M-type stars and early K-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 or improve the limit presented here.

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

$S_c$ (erg cm$^{-2}$ s$^{-1}$)