

## A BRIEF HISTORY OF THE SOLAR RADIATION AND PARTICLE FLUX EVOLUTION

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**Abstract.** Many evolutionary processes in solar-planetary relations and the evolution of planetary atmospheres can only be understood if one recognizes the fact that the radiation and particle environment of the Sun was not always in the same order than at present. We review and summarize the latest research regarding the evolution of the solar radiation and particle environment from the observations of solar proxies - Sun-like stars - with different ages. Observations by various satellites and studies on solar proxies show that the early Sun was rotating more than 10 times its present rate and had correspondingly strong dynamo-driven high energetic emissions. It can be inferred that the early Sun may have had strong X-ray and extreme ultraviolet (XUV) emissions up to several 100 times stronger than the present Sun (Guinan & Ribas, 2002). Further, evidence of a much denser early solar wind and the mass loss rate of the early Sun can be determined from collision of ionized stellar winds of solar-like stars with different ages, with the

partially ionized gas in the interstellar medium (Wood *et al.*, 2002). This collision creates a population of hot decelerated neutral hydrogen atoms, whose blue-shifted absorption component can be observed in the *Lyman- $\alpha$*  emission line by the *Hubble Space Telescope* (HST). Empirical correlations of stellar mass loss rates with X-ray surface flux values allows one to estimate the solar wind mass flux at earlier times, when the solar wind may have been as as more than 1000 times more massive. We mention also briefly some important implications for the history of planetary atmospheres in our solar system and newly discovered exoplanets.

**Key words:** Solar proxies - radiation environment - Sun: solar wind - Sun: mass loss - Sun: solar planetary-relations

## 1. Introduction

The Sun have always played a dominant role in solar-planetary relations of planetary atmospheres. The evolution of the solar radiation and particle environment must therefore, bear strongly considered for evolutionary aspects on planets. The increase in solar luminosity over the history of geologic time periods and its effect on the Earth's climate have been discussed by various authors in the past (e.g., Sagan & Mullen, 1972; Newman & Rood 1977; Owen *et al.*, 1979; Walker, 1981; Guinan & Ribas, 2002). The early Sun, with a luminosity of about 70% of that today, should have been too faint to prevent the early Earth from freezing. However, paleoclimate studies show that the young Earth always had liquid water and was therefore, typically warmer and possibly heated by greenhouse gases such as (CO<sub>2</sub> and CH<sub>4</sub>), than during recent times. On the other hand solar evolution models indicate that the Sun shall be about 10 % brighter in about 1 Gyr from now, that the Earth's oceans will start to evaporate.

On the other hand the impact of the solar radiation and particle fluxes on the evolution of planetary atmospheres and their water inventories has received not so much attention. Previous observational based studies indicated that the early Sun was a far stronger source of energetic particles and electromagnetic radiation (e.g., Kraft, 1967; Smith, 1979; Newkirk, 1979; Geyer, 1981; Skumanich & Eddy, 1981; Zahnle & Walker, 1982). This early studies are now more and more supported by a large number of multiwavelength (X-ray, EUV, FUV, UV, optical) observations of solar proxies as a solid evidence that the early Sun was a much more active star than it is present (e.g., Guinan & Ribas, 2002; Wood *et al.*, 2002).

Solar XUV radiation is of particular interest, because it can dissociate molecules, that would otherwise be relatively inert, thereby initiating photochemistry that can alter an atmosphere's bulk composition as well as creating a class of radiation-dependent trace chemicals and ionize atmospheric species. Moreover, solar XUV radiation controls the temperature structure of the upper atmospheres and may have played an important role for large-scale atmospheric escape on Venus, Earth,

Mars and Saturn's large satellite Titan.

A much stronger magnetic activity of the early Sun would also have resulted in increased flaring activity and stronger, more energetic solar wind and particle fluxes. Enhanced flares and a strong solar wind should have also played an important role in the erosion and evaporation processes of the primitive planetary atmospheres.

## 2. Solar X-ray and extreme ultraviolet radiation

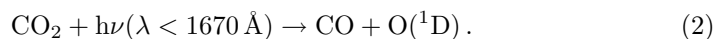
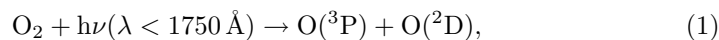
The extreme ultraviolet (EUV) radiation nominally spans the wavelength range from 1000–100 Å, although the edges are often somewhat indistinct defined and extend shortward into the soft X-ray or longwards into the far ultraviolet (FUV).

Until the early 70ies the conventional view was, that EUV astrophysics was not a practical proposition, because most elements have outer electron binding energies in the range of 10 – 100 eV; photons in the corresponding energy range will be strongly absorbed in any photon-atom interaction when the ionization potential  $IP < hc/\lambda$ , where  $\lambda$  is the photon wavelength,  $h$  the *Planck's constant* and  $c$  the speed of light when  $10 < IP < 100$  eV,  $\lambda$  lies in the range between 1000–100 Å, i.e., within the EUV band (Barstow & Holberg, 2003). As a result, a planetary atmosphere is opaque to EUV radiation as in the case of Earth due to photoabsorption by N<sub>2</sub>, O<sub>2</sub> and O, so that the 1/e absorption depth at 100 Å is at an altitude of about 130 km.

The source of the EUV (1750–70 Å) and X-ray radiation (170–1 Å) of a solar-like G star as the Sun is produced in the various layers of the stars' atmosphere. Table 1 lists the appropriate wavelengths at their point of origin (e.g., de Jager, 1964; Ivanov-Kholodnyi & Nikolski, 1969; Bauer & Lammer, 2004).

The absorption of the XUV radiation in a planetary atmosphere leads to photoionization and photodissociation of atmospheric constituents. Table 2 lists the penetration depth of the solar radiation and particles as well as their energy fluxes (Bauer & Lammer, 2004).

The relevant wavelengths for the heating of upper atmospheres of planets are the ionizing ones less than 1000 Å (e.g., Hunten, 1993), which contain only a small fraction of the present solar spectral power as shown in Table 2. The molecular constituents H<sub>2</sub>O, CO<sub>2</sub> and O<sub>2</sub> can be dissociated by relatively long wavelength radiation in the *Schumann-Runge continuum* range of 1750–1300 Å, according to



The wavelength range with an energy flux of  $\geq 2 \text{ erg cm}^{-2} \text{ sec}^{-1}$  represents the predominant XUV heat source for the terrestrial thermosphere. Dissociation can also take place below the true dissociation limit due to excitation of molecules

**Table I:** Wavelength region and source of solar XUV radiation (Bauer & Lammer, 2004).

$\lambda$ [Å]	Source of radiation
>1800	Photosphere
1200–2000	Transition Photosphere-Chromosphere
900–1800	Chromosphere
100–1000, Ly $\alpha$ (1216)	Transition to Corona
10–200	Quiet Corona
5–100	Coronal active region
1–50	Thermal Radiation
0.01–10	Non-thermal Burst

} Solar Flares

**Table II:** Penetration depth of solar XUV radiation in the Earth atmosphere (Bauer & Lammer, 2004).

$\lambda$ [Å]	Penetration depth	Energy flux [ $10^3$ erg cm $^{-2}$ sec $^{-1}$ ]
> 3000 visible + IR	Troposphere	1360 (outside the atmosphere)
2000 – 3000	Stratosphere	14
UV	Mesosphere	
1500 – 2000	Mesosphere	
EUV	Thermosphere	0.25
	Ionosphere	
1000 – 1500	Thermosphere	$8 \times 10^{-3}$
EUV	Ionosphere	
100 – 1000	Thermosphere	$2 \times 10^{-3}$
XUV	Ionosphere	
10 – 100	Thermosphere	$5 \times 10^{-5}$
X-rays	Ionosphere	
1	Mesosphere	$10^{-4}$
X-rays	Ionosphere	
Particles		
Solar protons	Stratosphere	$10^{-3}$
(MeV)	Mesosphere	
Solar wind	Magnetosphere	$10^{-4}$
(keV)		

**Table III:** Solar photon fluxes at 1 AU (Bauer & Lammer, 2004).

$\lambda$ [Å]	$\Phi_{\infty}$ [ $10^9$ ph cm $^{-2}$ sec $^{-1}$ ]	$I_{\infty}$ [erg cm $^{-2}$ sec $^{-1}$ ]
1215.7 (Ly $\alpha$ )	300	5
1027–911	11.61	0.23
(1025.7, Ly $\beta$ )	(3.5)	(0.067)
(977, C III)	(4.4)	(0.090)
911–800	8.3	0.20
800–630	2.4	0.064
630–460	4.7	0.17
(584.3, He I)	(0.9)	(0.03)
460–370	0.63	0.03
370–270	10.3	0.65
(303.8, He II)	(5.4)	(0.35)
270–205	4.5	0.36
205–153	4.6	0.49
153–100	0.4	0.06
120–80	0.3	0.066
80–40	0.33	0.108

into a state which dissociates. This predissociation process occurs for O<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>, but not significantly for N<sub>2</sub> accounting for its apparent stability against photodissociation.

For H<sub>2</sub>, radiation  $\lambda < 850$  Å leads to either dissociation or ionization. Atomic hydrogen possesses a strong continuum absorption cross section below 912 Å and strong *Lyman-series* lines, principally the intense *Lyman- $\alpha$*  line at 1216 Å. XUV radiation of wavelengths below the *Lyman- $\alpha$*  line (1216 Å) is primarily responsible for the formation of planetary ionospheres and thermospheric heating.

Rocket and satellite observations have led to a detailed identification of the solar emission line spectrum; relatively accurate values for the intensities of these radiations have become available by now (e.g., Hall *et al.*, 1969; Tobiska, 1993; Tobiska *et al.*, 1998). Solar photon fluxes at Earth for moderate activity are summarized in Table 3 (Bauer & Lammer, 2004). The solar photon flux  $\phi_{\infty}$  is used for the ionization process, while the XUV energy flux  $I_{\infty} = (h\nu)\phi_{\infty}$  is applicable to thermospheric heating.

The solar photon fluxes vary both over a long period (11 year solar cycle) as well as over short periods (27 days) during disturbances. Although the exact amplitude of these variations is not yet fully established, it appears to be for

the EUV range of the order of 2. The 10.7 cm solar radio flux  $F_{10.7}$  is usually considered to be an excellent indicator of solar activity; according to limited data the integrated flux in the range 1310–270 Å changes by a factor of 1.4–1.5 for a change in  $F_{10.7}$ , by a factor of 2 (e.g., Tobiska *et al.*, 1998).

The solar cycle variation for the spectral range between 100–10 Å amounts to a factor of 7, the energy flux in this range is  $\sim 0.9 \text{ erg cm}^{-2} \text{ sec}^{-1}$  at solar maximum. The X-ray energy flux  $I_X$  at 8 Å in the absence of flares and varies over the solar cycle by a factor of 300; the variation in the range from 8–2 Å from a completely quiet Sun to a class 3 flare can amount to five orders of magnitude ( $10^5$ ).

### 3. The time evolution of the solar XUV radiation

This active phase of the Sun, which lasted about 0.5–1.0 Gyr, included continuous flare events where the particle and radiation environment was several hundred times more intense than today. The high radiation levels of the young Sun were triggered by strong magnetic activity. The magnetic activity of the Sun is expected to have greatly decreased with time (Skumanich, 1972; Simon *et al.*, 1985; Guinan & Ribas, 2002) as the solar rotation slowed down through angular momentum loss. Observational evidence and theoretical models suggest that the young Sun rotated about 10 times faster than today and had significantly enhanced magnetically generated coronal and chromospheric activity (Keppens *et al.*, 1995; Guinan & Ribas, 2002).

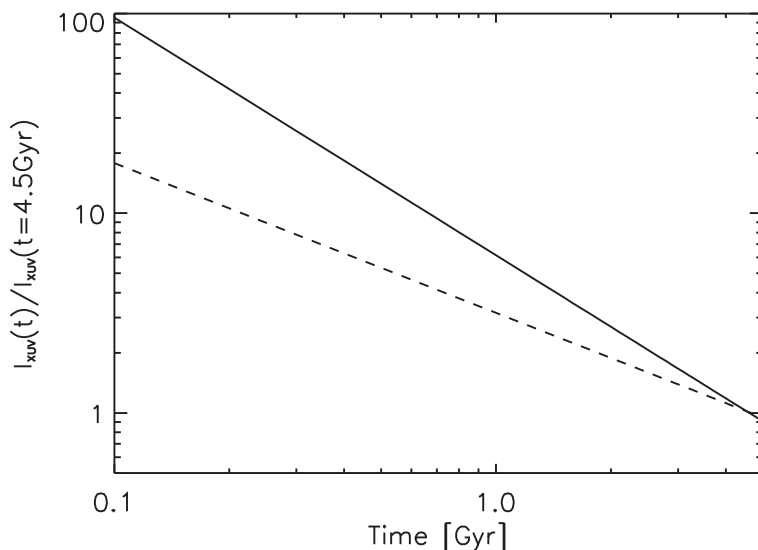
The *Sun in Time* program (Dorren & Guinan, 1994) was established to study the magnetic evolution of the Sun using a homogeneous sample of single nearby G0–V main sequence stars which have known rotation periods and well-determined physical properties, including temperatures, luminosities, metal abundances and ages. As can be seen in Table 1, the sample of solar proxies contains stars that cover most of the Sun’s main sequence lifetime from 130 Myr to 8.5 Gyr. One of the primary goals of the *Sun in Time* program is to reconstruct the spectral irradiance evolution of the Sun. To this end, a large amount of multiwavelength (X-ray, EUV, FUV, UV, optical) data have already been collected.

The observations, obtained with the ASCA, ROSAT, EUVE, FUSE and IUE satellites, cover a range between 1 Å and 3300 Å, except for a gap between 360 Å and 920 Å, which is a region of very strong interstellar medium absorption. Details of the data sets and the flux calibration procedure employed are provided in Guinan & Ribas (2002). Full spectral irradiance tables have already been completed for five of the stars in the *Sun in Time* sample (*EK Dra* [130 Myr],  $\pi^1$  UMa [300 Myr],  $\kappa^1$  *Cet* [750 Myr],  $\beta$  *Com* [1.6 Gyr],  $\beta$  *Hya* [6.7 Gyr]) and show an excellent correlation between the emitted flux and stellar age.

The coronal XUV emissions of the young main-sequence Sun were about 100 to 1000 times stronger than those of the present Sun. Similarly, the transition region and chromospheric FUV–UV emissions of the young Sun are expected to

be 10 to 100 and 5 to 10 times stronger, respectively, than present and the flux variation over age is therefore a steep wavelength function. As discussed above, for the present work we have focused on the spectral range with  $\lambda < 1000 \text{ \AA}$ , which includes X-rays and EUV. We have computed integrated fluxes for the stars with complete irradiance and scaled the resulting values to a distance of 1 AU.

Fig. 1 shows the time evolution of the spectral range with  $1 \text{ \AA} < \lambda < 1000 \text{ \AA}$ , which includes X-rays and EUV and the *Lyman- $\alpha$*  line at  $1215.6 \text{ \AA}$  (Lammer *et al.*, 2003a; 2003b) at a distance of 1 AU.



*Figure 1:* Time evolution of the  $I_{XUV}$  energy flux for solar-like G stars (Solid line:  $\lambda = 1000\text{--}1 \text{ \AA}$ ; dashed line: *Lyman- $\alpha$*  =  $1215.6 \text{ \AA}$ ).

The resulting relative XUV fluxes shown in Table 4 yield an excellent correlation between the emitted flux and stellar age. In the  $1000\text{--}1 \text{ \AA}$  interval, the fluxes follow a power-law relationship (Lammer *et al.*, 2003a; 2003b).

$$\frac{I_{XUV}(t)}{I_{XUV}} = 6.16 \times (t[\text{Gyr}])^{-1.19}. \quad (3)$$

At longer wavelengths, the *Lyman- $\alpha$*  emission feature can contribute to a significant fraction of the XUV flux. High-resolution *Hubble Space Telescope* (HST) spectroscopic observations were used to estimate the net stellar flux. These measurements, together with the observed solar *Lyman- $\alpha$*  define the following power-law relationship with high correlation

**Table IV:** Solar-like G-type stars studied within the *Sun in Time* program. The parameters of the solar proxies shown below are: luminosity, distance, age, the XUV energy flux relative to the present value at 1 AU in the 1000 – 1 Å interval and *Lyman-α* (Guinan & Ribas, 2002).

Star	Lum [ $L_{\odot}$ ]	Dist. [pc]	Age [Gyr]	$P_{rot}$ [d]	$\frac{I_{XUV}(t)}{I_{XUV}}$	$\frac{I_{L_{\alpha}}(t)}{I_{L_{\alpha}}}$
EK Dra	0.94	34	0.13	2.75	69.8	14.6
$\pi$ 1 UMa	0.98	14.3	0.3	4.68	25.8	7.8
$\chi$ 1 Ori	1.07	8.7	0.3	5.08	25.8	7.8
9 Cet	0.98	20.4	0.65	7.6	10.3	4.4
$\kappa$ 1 Cet	0.84	9.2	0.75	9.2	8.7	3.9
$\beta$ Com	1.36	9.2	1.6	12.4	3.5	2.2
15 Sge	1.25	17.7	1.9	13.5	2.9	1.9
Sun	1.00	–	4.6	25.4	1	1
18 Sco	1.05	14.0	4.9	23.0	0.9	0.96
$\beta$ Hyi	3.58	7.47	6.7	28.0	0.6	0.76
16 Cyg A	1.62	21.6	8.5	35.0	0.5	0.63

$$\frac{I_{L_{\alpha}}(t)}{I_{L_{\alpha}}} = 3.17 \times (t[\text{Gyr}])^{-0.75}. \quad (4)$$

In both power-laws, the XUV and *Lyman-α* expressions, are valid for ages between 0.1 – 7 Gyr,  $I_{XUV}$  and  $I_{L_{\alpha}}$  are the present integrated fluxes at 1 AU and  $I_{XUV}(t)$  and  $I_{L_{\alpha}}(t)$  are the integrated fluxes as a function of time. One finds fluxes of  $\approx 6 \times I_{XUV}$  and  $\approx 3 \times I_{L_{\alpha}}$  about 3.5 Gyr ago, and  $\approx 100 \times I_{XUV}$  and  $\approx 20 \times I_{L_{\alpha}}$  about 100 Myr after the Sun arrived on the *Zero-Age-Main-Sequence* (ZAMS).

#### 4. The solar wind history of the Sun

HST high-resolution spectroscopic observations of the H *Lyman-α* feature of several nearby main-sequence G and K stars carried out by Wood *et al.* (2002) have revealed neutral hydrogen absorption associated with the interaction between the stars' fully ionized coronal winds with the partially ionized local interstellar medium. Wood *et al.*, 2002 modelled the absorption features formed in the astrospheres of these stars and provided the first empirically-estimated coronal mass loss rates for solar-like G and K main sequence stars.

They estimated the mass loss rates from the system geometry and hydrodynamics and found from their small sample of stars where astrospheres can be observed, that mass loss rates increase with stellar activity. This study suggests that the early Sun had a much denser solar wind than today. The correlation between mass loss and X-ray surface flux follows a power law relationship, which indicates an average solar wind density up to 1000 times higher than today during the first 100 Myr after the Sun reached the ZAMS.

Mass loss rates of cool main sequence stars depend on their rotation periods, which are in turn correlated with the star's ages. To obtain the evolution of the stellar wind velocity  $v$  and stellar wind density  $n$  of solar-like stars, one can use the scaling for stellar mass loss rates provided by Wood *et al.*, (2002) as well as the scaling for the velocity developed by Newkirk (1980).

The mass loss as function of the X-ray flux  $\phi_X$  observed on solar-like stars, when the coronal activity is at its maximum can be written as a power-law (Wood *et al.*, 2002)

$$\dot{M} \propto \phi_X^{1.15}. \quad (5)$$

Mass loss rates of cool main sequence stars depend on their rotation periods  $P_{rot}$ , which are in turn correlated with the star's ages. According to Wood *et al.* (2002) these relations can be expressed as

$$\phi_X \propto P_{rot}^{-2.9} \quad (6)$$

and

$$P_{rot} \propto t^{-0.6}, \quad (7)$$

respectively.  $t$  denotes the time elapsed since the formation of the stellar system. For the present day solar system,  $t = 4.6$  Gyr. From eqs. (5) and (6), one obtains a power law relationship for the mass loss rate as a function of rotation period,  $\dot{M}(P_{rot})$  (Grießmeier *et al.*, 2004). Here, a complication occurs. Equation (5) does look like a scaling for the mass loss, but what is really measured by Wood *et al.*, (2002) is the total ram pressure, i.e. the *product* of mass loss and solar wind velocity. The mass loss given by Wood *et al.* (2002) was obtained by assuming a constant velocity  $v_{sw}$ . As one try to find scalings for both  $n_{sw}$  and  $v_{sw}$ , one has to correct for this by writing  $\dot{M}v_{sw}$  rather than  $\dot{M}$  in eq. (5)

$$\dot{M}v_{sw} \propto P_{rot}^{-3.3}. \quad (8)$$

To obtain the time dependence, one has to insert a function for  $P_{rot}(t)$  into eq. (8). In principle, eq. (7) could be used, but for sake of consistency with the velocity scaling given below we take the scaling derived by Newkirk (1980)

$$P_{rot} \propto \left(1 + \frac{t}{\tau}\right)^{0.7}, \quad (9)$$

with the time constant  $\tau = 2.56 \times 10^7$ yr. By combining eqs. (8) and (9) it is possible to derive a power law formula for the stellar mass loss as

$$\dot{M}v_{sw} \propto \left(1 + \frac{t}{\tau}\right)^{-2.3}. \quad (10)$$

On the other hand, the solar mass loss linearly depends on  $v_{sw}$  and  $n_{sw}$ :

$$\dot{M} = An_{sw}v_{sw}m_p, \quad (11)$$

where  $A$  is the solar surface and  $m_p$  the mass of the solar wind protons. So, by finding an independent scaling for the solar wind velocity, the solar wind density directly follows from eq. (10). The time-behaviour of the solar wind velocity can be achieved by Newkirk (1980)

$$v_{sw} = v_* \left(1 + \frac{t}{\tau}\right)^{-0.4}. \quad (12)$$

From the mass loss formula eq. (10) and with eq. (11) we can determine the particle density:

$$n_{sw} = n_* \left(1 + \frac{t}{\tau}\right)^{-1.5}. \quad (13)$$

The proportionality constants are determined by average present-day solar wind conditions. With  $v_{sw} = 400$  km/s and  $n_{sw} = 10^7$  1/m<sup>3</sup> for  $t = 4.6$  Gyr and at  $d = 1$  AU (Schwenn, 1990) one obtains  $v_* = 3200$  km/s,  $n_* = 2.4 \times 10^{10}$  1/m<sup>3</sup> (density at 1 AU). The time constant is  $\tau = 2.56 \times 10^7$ yr (Newkirk, 1980). For distances other than 1 AU, eq. (13) is scaled with a  $1/r^2$  dependency. The time variation of  $n(t)$  at Earth orbit of 1 AU is shown in Fig. 2. One can see from Fig. 2 that the observational data for solar-like G and K stars suggest that more active stars have higher mass loss rates and solar wind number density. However, observations of the M dwarf star *Proxima Cen* and the *RS CVn* system  $\lambda$  *And* (G8 IV + M V) are inconsistent with this relation and show lower mass loss rates. An other recent observation of the  $\xi$  *Boo* binary system shows also a lower mass loss rate, which is consistent with the mass loss rates previously found for *Proxima Cen* and  $\lambda$  *And* (J. L. Linsky, private communication, 2004).

The common feature of these three stars is that they are all very active in X-ray surface fluxes at about  $10^6$  erg cm<sup>-2</sup> s<sup>-1</sup>, which is about a factor 30 larger than the Sun and corresponds to a time of about 700 Myr after solar-like stars arrived at the ZAMS. This observations indicate the uncertainty of early mass loss and solar wind estimations, because both stars in the  $\xi$  *Boo* system are usual but very active G and K stars, while *Proxima Cen* and  $\lambda$  *And* are different types than normal G and K stars. Linsky and his team suggest that there may be a high-activity cutoff to the mass-loss/activity relation obtained by Wood *et al.* (2002),

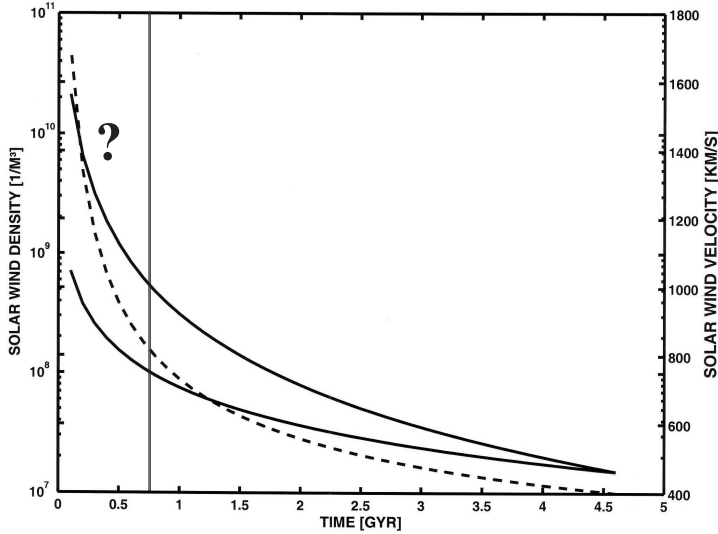


Figure 2: Time evolution of the observational based minimal and maximal stellar wind densities scaled to 1 AU (left scale: solid lines) obtained from several nearby solar-like G and K main-sequence stars. On the right scale one can see the temporal evolution of the stellar wind velocity (right scale: dashed curve) More observations or early active stars with ages less than 700 Myr are needed to obtain a better picture of the mass-loss/activity relation.

although more active young solar-like G and K stars with X-ray surface fluxes larger than  $10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$  must be studied in the future. More observations of solar-like G and K stars with lower X-ray surface fluxes are also needed to better determine the mass-loss/activity relation.

## 5. Evolutionary aspects for planetary atmospheres

The known terrestrial planets with substantial atmospheres are Venus, Earth and Mars and as a special case Saturn’s large satellite Titan. The initial major atmospheric gases on the three classic early terrestrial-type planets Earth, Venus and Mars were most probably  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{N}_2$ . Most of the Earth’s  $\text{CO}_2$  was transformed into surface by chemical weathering and Venus has lost most of its  $\text{H}_2\text{O}$

so that CO<sub>2</sub> remained. The Martian atmosphere may have been eroded mainly by impacts due to large asteroids and comets during the first 500 Myr after the planets origin.

From the current knowledge of the atmospheres of the terrestrial planets and the evolution of the solar radiation and particle environment as discussed in this work one can suggest that the critical phase if a H<sub>2</sub>O-bearing planet can evolve into a habitable world like Earth is its survival during: (1) The period of heavy bombardment by asteroids and comets (Melosh & Vickery, 1989; Brain & Jakosky, 1998) and (2) the active XUV period of and strong stellar wind of the early active Sun or stars (Lammer *et al.*, 2003b; Bauer & Lammer, 2004).

The main criteria for the survival of a planetary atmosphere and its water inventory are the high X-ray and extreme ultraviolet fluxes of young stars. In fact XUV-driven hydrodynamic *blow off* and expansion of the rich hydrogen atmosphere of the Jupiter-class short periodic exoplanet HD209458 b was observed recently by Vidal-Madjar *et al.* (2003) and Vidal-Madjar *et al.* (2004) and studied theoretically by Lammer *et al.* (2003b).

Atmospheric loss rates caused by planetary winds are orders of magnitudes higher than thermal escape by the *Jeans treatment*. The loss of heavier constituents by planetary hydrogen winds is essentially aerodynamic drag (Hunten, 1993; Chassefiere, 1996). For water bearing terrestrial planets with early CO<sub>2</sub> atmospheres the escape flux of the light gas in the upper atmosphere may be limited by the rate at which it can diffuse through the upper atmosphere. However, long-time XUV radiation in the order of about 50 – 100 times the present value can effect the water inventory of a terrestrial planet and may have been the main process of water-loss during the first 100 Myrs on Mars after the planets origin.

## 6. Conclusion

Studies of solar proxies with different ages obtained from observational data with the ASCA, ROSAT, EUVE, FUSE and IUE satellites, indicate that the early Sun had much stronger X-ray and EUV emissions up to several hundred times stronger, than the present Sun. Observations of flare activity of these young solar-like stars, such as the 130 Myr old *EK Dra* with EUVE strongly suggest that flare events are frequent and more powerful than observed on the present Sun. This radiation ( $\lambda \leq 1000 \text{ \AA}$ ) is expected to be the most greatly enhanced at 100 Myr of about 100 times the present value (Zahnle & Walker, 1982; Ayres, 1997; Guinan & Ribas 2002) and is therefore the most interesting in the evolution of hydrogen-rich primordial atmospheres. This radiation can strain the energy balance in a planets thermosphere and supply energy for rapid atmospheric escape of hydrogen and heavier gases due to aerodynamic drag (Chassefiere, 1996; Lammer *et al.*, 2003b). Further, a recent analysis of astrospheric absorbtion features seen in *Lyman- $\alpha$*  lines toward nearby solar-like G and K stars can be used for the estimation of stellar

mass loss rates and the time evolution of the solar wind (Wood *et al.*, 2002). This corroborates that the solar wind of the young Sun could possibly be 100 – 1000 times more intense than today, which may also have played a major role in the evolution of planetary atmospheres.

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