

Session I

Introduction

Chair: C. Fang

The Sun and stars as the primary energy input in planetary atmospheres

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Abstract. Proper characterization of the host star to a planet is a key element to the understanding of its overall properties. The star has a direct impact through the modification of the structure and evolution of the planet atmosphere by being the overwhelmingly larger source of energy. The star plays a central role in shaping the structure, evolution, and even determining the mere existence of planetary atmospheres. The vast majority of the stellar flux is well understood thanks to the impressive progress made in the modeling of stellar atmospheres. At short wavelengths (X-rays to UV), however, the information is scarcer since the stellar emission does not originate in the photosphere but in the chromospheric and coronal regions, which are much less understood. The same can be said about particle emissions, with a strong impact on planetary atmospheres, because a detailed description of the time-evolution of stellar wind is still lacking. Here we review our current understanding of the flux and particle emissions of the Sun and low-mass stars and briefly address their impact in the context of planetary atmospheres.

Keywords. Sun: activity, Sun: particle emission, stars: activity, planetary systems, ultraviolet: stars, X-rays: stars, planets and satellites: general

1. Introduction

Our knowledge of planets, including our Earth, is directly driven by our knowledge of the parent star. Indeed, the host star to a planet is the overwhelmingly larger source of energy and its emissions critically affect the composition, thermal properties and the mere existence of planetary atmospheres. Our current description of the internal structure, evolution and radiative flux of stars has reached a relatively mature level and theoretical models can now predict stellar attributes to fairly good accuracy. While this refers to the bulk properties of stars, some other components related to stellar emissions still defy detailed understanding. This is the case of the emissions related to magnetic activity, a common feature of all low-mass stars. High-energy emissions of solar-type stars and their variations over different timescales are now quite well characterized but not so active stars in general. The situation for particle winds is even more frustrating, with a lack of direct detections and large uncertainties on the predicted wind of active stars from indirect measurements. However, all evidence collected so far supports the fact that low-mass stars undergo an early phase of strong magnetic activity (lasting from tens of Myrs to Gyrs) in which their high-energy and particle emissions are enhanced by orders of magnitude with respect to our current Sun. If the effects of the active Sun are even noticeable today on our Earth, it is undeniable that such effects *must* have been even stronger for our planet and all Solar System planets in the past. In general, all planets orbiting low-mass stars are affected by the magnetic evolution of their parent star.

In the following sections we review the current state of knowledge of the properties of stars from the point of view of planet hosts, including their bulk emissions and those related with magnetic activity. Further, we discuss the possible impact that long-term

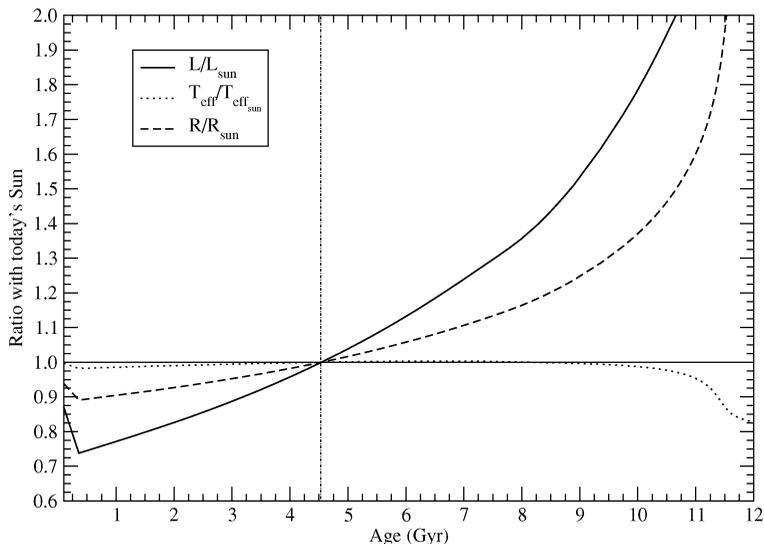


Figure 1. The evolution of the effective temperature, radius, and luminosity of the Sun from the zero-age main sequence to the start of its red giant phase. The vertical line marks the current age of the Sun. Based on the Yonsei-Yale evolutionary sequences (see text for references).

variability of high-energy radiations and particle fluxes has on the Solar System planets and exoplanets around solar-type and lower-mass stars.

2. The structure and evolution of the Sun and stars

Much progress has been made in understanding the internal structure and evolution of stars. Stellar models are now able to predict with relatively good accuracy the fundamental properties of stars over a wide range of masses and a large fraction of the Hertzsprung-Russell diagram. This is especially true for the better-behaved evolutionary stages (i.e., main sequence and giants) thanks to great advances in our knowledge of the physical processes that govern the interiors of stars, such as opacities, nuclear reaction rates, energy transport, equation of state, etc (see, e.g., Lebreton 2000; Chabrier & Baraffe 2000). Grids of stellar evolution models have been proposed by a number of different groups and they mostly manage to reproduce the observable properties of main sequence and giant stars satisfactorily. In spite of the long-lasting major concern that our understanding of the interior of the Sun (and, by extension, of stars) was incomplete, the resolution of the so-called “solar neutrino problem” (Ahmad *et al.* 2001; Bahcall 2004) ultimately vetted the calculations and lent confidence on the ability to model stellar interiors.

The relative good performance of stellar models has permitted the calculation of the past and future evolution of the Sun, and thus the variation of its main properties over time. An illustration of this is given in Fig. 1, where the normalized luminosity, effective temperature, and radius of the Sun are plotted as a function of age as calculated from the Yonsei-Yale theoretical models (Kim *et al.* 2002; Yi *et al.* 2003). The plot shows how the luminosity of the Sun is found to be some 75% of today’s when life supposedly arose on Earth, thus giving rise to the so-called “Faint Young Sun” paradox (e.g., Sagan & Mullen 1972).

The optimistic picture of the theory of stellar evolution is not without its blemishes. There are still nagging deficiencies in the models linked to our poor understanding of

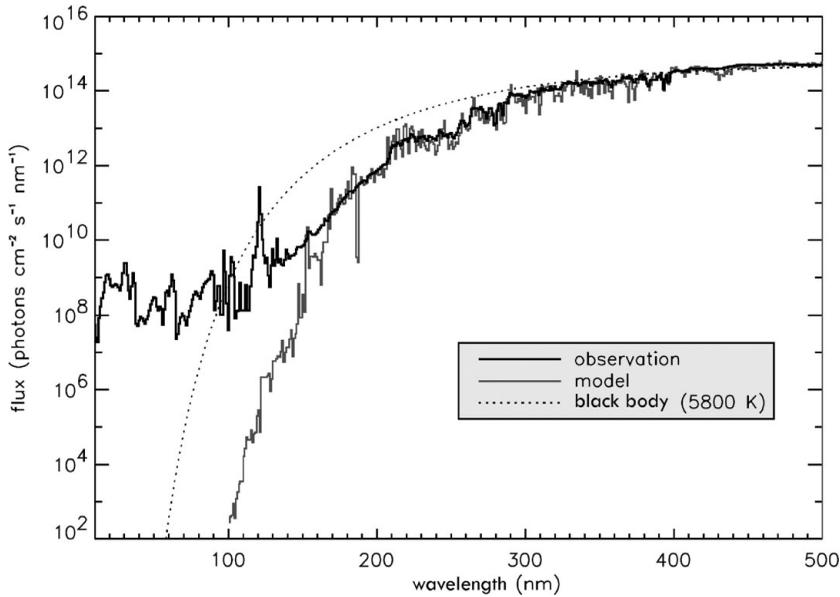


Figure 2. Comparison of the observed solar energy distribution with the prediction of a matching photospheric model and a black body. Note the divergence below 170 nm when the contribution from the chromosphere dominates. Adapted from Selsis (2000).

phenomena such as convective energy transport or mass loss (e.g., Lafon & Berruyer 1991; Cassisi 2009). While these have a stronger impact on high-mass stars, the effects of mass loss have also been considered in low-mass stars such as the Sun (Sackmann & Boothroyd 2003). Also in the case of the Sun, an apparent victory of theory was the almost perfect agreement with the results of helioseismology, but the idyllic situation broke down, so far irreversibly, with the revision of the solar abundances (see Christensen-Dalsgaard *et al.* 2009; Asplund *et al.* 2009). In the particular case of the cool end of the main sequence, the chief open issues are related to the inability of theory to correctly predict the radii and effective temperature of stars, presumably because of the complete absence of the effects of magnetic activity in the model calculations (e.g., Ribas *et al.* 2008).

Besides the integrated radiative flux of stars, models have also come a long way in trying to reproduce the spectral energy distribution of the emissions. Theoretical atmosphere models provide today a fairly realistic picture of the bulk energy output of stars thanks to intensive efforts in compiling large databases of atomic and molecular transitions and in including fine details in the calculations of radiative transfer. Direct comparison with the spectral energy distribution of the Sun (arguably the star for which the best data are available) shows that models are able to predict the spectral distribution of flux near the peak of the emission within 5%, as shown by Edvardsson (2008) in the case of the MARCS models and Bohlin (2007) in the case of the Kurucz models. Such models consider the radiation from the photosphere, which dominates over the visible and near-IR spectrum. However, at shorter wavelengths (X-rays to UV) the predictions start to deviate from the calculations. This is nicely illustrated in Fig. 2, where the synthetic model and real data diverge below 170 nm. The reason for the divergence is the contribution from the hot atmosphere layers of the Sun, which are associated to magnetic activity. This is addressed in the following section.

3. The magnetic Sun and stars

Activity in late-type stars has been the subject of attention for many years. Early studies already pointed out a strong correlation between the rotation rate of a star and its activity level (Wilson 1966; Kraft 1967). This evidence, together with the growing body of information on our nearest active star, the Sun, has shaped up the currently accepted model of stellar activity in cool stars as being a consequence of the operation of a magnetic dynamo (Parker 1970). In this model, the interplay between the stellar rotation and the gas motions in the convective layer of the star generates magnetic fields that give rise to the observed phenomena. It is well established for the Sun that active regions arise from magnetic field lines emerging from (and plunging into) the surface and the same is probably true for other active stars.

The observational manifestations of stellar activity are plentiful and include modulations of the stellar photospheric light due to stellar spots, high-energy emissions, and flares. The magnetic dynamo generates energy that heats up the upper stellar atmosphere creating a vertical temperature profile with distinct regions such as the chromosphere and the corona. These layers, with estimated temperatures of $10^4 - 10^7$ K, are the source of the high-energy emissions (from X rays to the UV) observed in active cool stars. The stratified nature of the solar atmosphere makes that observations at different wavelengths are typically associated with the various layers (X-rays & EUV – corona, FUV – transition region; UV – chromosphere) and thus serve as probes for their physical conditions. A consequence of a hot upper layer in the Sun is the existence of a particle wind, for which there is ample evidence and has been subject to intensive scrutiny (e.g., Zurbuchen 2007).

A component intimately associated with stellar activity is its pronounced variability over time. Such variations cover nearly all timescales, including hours (flares), days (rotational modulation; Fröhlich & Lean 2004), years (the 11-yr sunspot cycle; Fröhlich & Lean 2004), centuries (Maunder minima and the likes; e.g., Soon & Yaskell 2004), and up to billions of years. The latter is of the same order as the nuclear evolution timescale and it is related with the rotational spin down from magnetic braking. This is discussed in more detail in the following section.

4. Long-term evolution of solar/stellar activity

4.1. High-energy emissions

Compelling observational evidence (Güdel *et al.* 1997) shows that zero-age main sequence (ZAMS) solar-type stars rotate over 10 times faster than today's Sun. As a consequence of this, young solar-type stars, including the young Sun, have vigorous magnetic dynamos and correspondingly strong high-energy emissions. From the study of solar type stars with different ages, Skumanich (1972), Simon *et al.* (1985), and others showed that the Sun loses angular momentum with time via magnetized winds (magnetic braking) thus leading to a secular increase of its rotation period (Durney 1972). This rotation slow-down is well fitted by a power law roughly proportional to $t^{-1/2}$ (e.g., Skumanich 1972; Soderblom 1982; Ayres 1997; Barnes 2007; Mamajek & Hillenbrand 2008). This is illustrated in Fig. 3. Note that the age–rotation period relationship is tighter for intermediate/old stars, while young stars (a few 10^8 yr) show a larger spread in rotation periods. In response to slower rotation, the solar dynamo strength diminishes with time causing the Sun's high-energy emissions also to undergo significant decreases. Comprehensive studies on this subject were published by Zahnle & Walker (1982) and Ayres (1997).

The *Sun in Time* program (Dorren & Guinan 1994; Ribas *et al.* 2005) was established to study the magnetic evolution of the Sun using a homogeneous sample of single, nearby

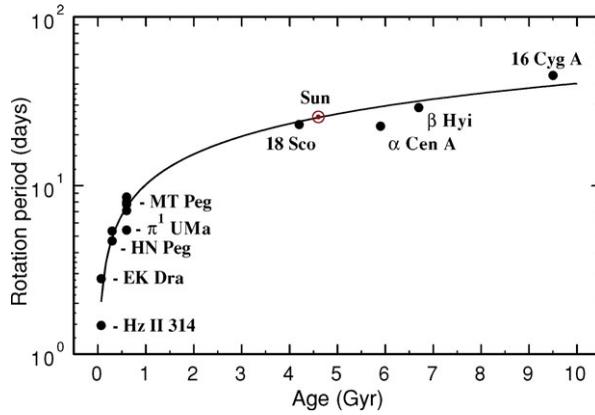


Figure 3. Rotation period as a function of age for a sample of solar-type stars. The solid line represents a power-law fit.

G0-5 main sequence stars, which have known rotation periods and well-determined physical properties, including temperatures, luminosities, metal abundances and ages. Such stars could be used as proxies for the Sun at evolutionary stages covering from 0.1 up to about 7 Gyr. Detailed analyses indicated that all proxies have masses within 10% of that of the Sun.

One of the primary goals of the *Sun in Time* program was to reconstruct the spectral irradiance evolution of the Sun. To this end, a large amount of multiwavelength (X-ray, EUV, FUV, UV, optical) data was collected using various space missions (ASCA, ROSAT, EUVE, FUSE, IUE, HST) covering a range between 0.1 and 330 nm†. Details of the data sets and the flux calibration procedure employed are provided in Ribas *et al.* (2005). Full spectral characterization was completed for five of the stars in the sample, which cover key stages in the evolution of the Sun (and solar-type stars): EK Dra – 0.1 Gyr, π¹ UMa – 0.3 Gyr, κ¹ Cet – 0.6 Gyr, β Com – 1.6 Gyr, and β Hyi – 6.7 Gyr. The reconstructed irradiances of these solar proxies indicate that the X-ray and EUV emissions of the young main-sequence Sun were about 100 to 1000 times stronger than those of the present Sun. Similarly, the FUV and UV emissions of the young Sun were 10 to 100 and 5 to 10 times stronger, respectively, than today. The spectral energy distribution of the Sun and its time evolution is illustrated in Fig. 4 (top).

But, additionally, the results suggest a very good correlation of the emitted flux with age that can be modeled accurately by power laws (see Fig. 4 bottom). A fit to the overall XUV flux (integrated between 0.1 and 120 nm) as a function of age (τ) and normalized to a distance of 1 AU yields the following expression:

$$F_{\text{XUV}} = 29.7 [\tau(\text{Gyr})]^{-1.23} \text{ erg s}^{-1} \text{ cm}^{-2} \quad (4.1)$$

The equation reveals that the XUV emissions of the Sun were about 3 times higher 2.5 Gyr ago and 6 times higher 3.5 Gyr ago, roughly when life appeared on Earth. Also, the young 0.1-Gyr old Sun could have had up to 100 times stronger XUV radiation (albeit for a short period of time). At longer wavelengths, the H Lyman- α emission feature can contribute to a significant fraction of the XUV flux (over 50% in the case of the Sun; Woods *et al.* 1998). High-resolution Hubble Space Telescope spectroscopic

† Note the existence of a gap between 36 and 92 nm that is unobservable because of the very strong interstellar absorption

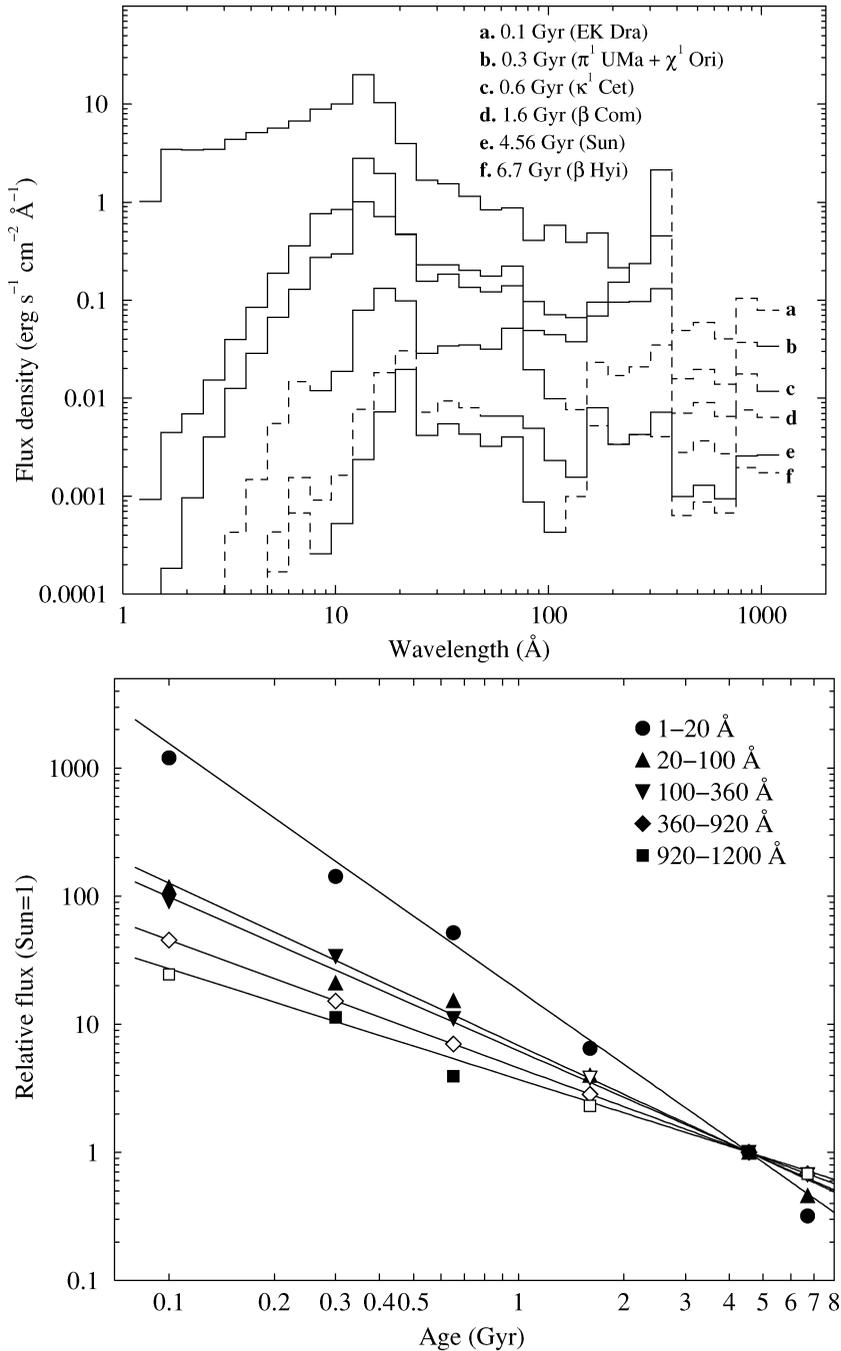


Figure 4. *Top:* Full spectral energy distribution of the solar-type stars at different stages of the main sequence evolution. The solid lines represent the measured fluxes while the dotted lines are fluxes calculated by interpolation using a power-law relationship. *Bottom:* Solar-normalized fluxes vs. age for different stages of the evolution of solar-type stars. Plotted here are the measurements for different wavelength intervals (filled symbols) and the corresponding fits using power-law relationships. Represented with empty symbols are the inferred fluxes for those intervals with no available observations. Adapted from Ribas *et al.* (2005).

observations were used to estimate the net stellar flux. These measurements, together with the observed solar Lyman- α define the following power-law relationship with high correlation:

$$F_{L_{y\alpha}} = 19.2 [\tau(\text{Gyr})]^{-0.72} \text{ erg s}^{-1} \text{ cm}^{-2} \tag{4.2}$$

While the long-term variation of the high-energy emissions of the Sun and solar-type stars is now well characterized, the same is not true for stars of lower mass. The situation is further aggravated by the fact that K- and M-type stars are known to be more active than their solar counterparts. We are currently generalizing the Sun in Time study to all stars of GKM spectral types (Garcés *et al.* 2010). For an initial estimate of the evolution of XUV irradiances we have used a proxy indicator, which is the ratio of the X-ray luminosity to the bolometric luminosity ($\log [L_X/L_{\text{bol}}]$). This ratio is highest for the more active stars (i.e. fastest rotation period) and decreases monotonically with decreasing level of chromospheric activity (e.g., Stelzer & Neuhäuser 2001; Pizzolato *et al.* 2003). From the analysis of open cluster stars it is now well established that all single GKM stars spin down as they age, their activity decreases with time, and so does the ratio $\log(L_X/L_{\text{bol}})$. It is also a well-known effect that $\log(L_X/L_{\text{bol}})$ cannot reach values arbitrarily close to unity (in quiescence) for very active stars. A “saturation” phenomenon occurs at $\log(L_X/L_{\text{bol}}) \approx -3$ (e.g., Vilhu & Walter 1987; Stauffer *et al.* 1994). Qualitatively, the evolution of $\log(L_X/L_{\text{bol}})$ for a late-type star has a flat plateau from its arrival on the main sequence up to a certain age (end of saturation phase) and then decreases monotonically with age.

Assuming that all active stars share the same underlying physical mechanism responsible for the emission and a supposedly similar spectral energy distribution, one can infer that stars with similar values of $\log(L_X/L_{\text{bol}})$ will also have similar $\log(L_{\text{XUV}}/L_{\text{bol}})$. From this assumption and the available results for solar analogs, estimates of stellar ages for late G-, K-, and M-type stars yield the following preliminary expressions, generalizing Eq. 4.1:

$$\begin{aligned} F_{\text{XUV}} &= 4.04 \cdot 10^{-24} L_{\text{bol}}^{0.79} && \text{for } 0.1 \text{ Gyr} < \tau < \tau_i \\ F_{\text{XUV}} &= 29.7 \tau^{-1.23} && \text{for } \tau < \tau_i \\ \tau_i &= 1.66 \cdot 10^{20} L_{\text{bol}}^{-0.64} \end{aligned} \tag{4.3}$$

with F_{XUV} (0.1–120 nm) in $\text{erg s}^{-1} \text{ cm}^{-2}$ at 1 AU, τ in Gyr and L_{bol} in erg s^{-1} . The expression indicates that, solar-type stars stay at saturated emission levels until ages of ~ 0.1 Gyr and then their XUV flux rapidly decreases following a power law relationship as a function of age. Early K-type stars stay at saturated emission levels for a little longer and then also decrease following a power law relationship of very similar slope. Finally, early M-type stars have saturated emission levels for up to 1 Gyr (and possibly longer) and then decrease in an analogous way to G- and K-type stars. More quantitatively, our preliminary results (to be further discussed in Garcés *et al.* 2010) indicate that early K-type stars and early M-type stars may have XUV fluxes that are 3–4 times higher and 10–100 times higher, respectively, than solar-type stars of the same age.

4.2. Particle winds

High energy fluxes are not the only trait of active stars. As mentioned above, particle emissions (winds) are also associated with the hot coronal plasma. If the Sun was more active in the past one may intuitively assume that its particle wind was also more intense. This agrees with evidence from lunar rocks (Newkirk 1980) and from the relative nitrogen isotopic abundances in the atmosphere of Titan (Lammer *et al.* 2000). Unfortunately, the direct detection of the stellar counterparts to the solar wind has, so far, remained

elusive even for the nearest and more active stars (Gaidos *et al.* 2000; Ayres *et al.* 2001). However, indirect evidence for the existence and strength of stellar winds was obtained by the pioneering work of Wood *et al.* (2002). The authors devised a technique based on the detailed modeling of the H Lyman- α emission feature that reveals an absorption component associated with the interaction between the stellar wind and the surrounding interstellar medium. Quantitative analysis yielded an estimate of the mass loss rate of the stars in the most favorable cases (appropriate geometry, clean line of sight). Wood *et al.* (2002) proposed the existence of a correlation between the X-ray surface flux (as activity indicator) and the mass loss rate, which was found to be proportional to τ^{-2} . This would imply a much stronger (up to 1000 times) solar wind in the past. Recent results from the same team (Wood *et al.* 2005) have casted doubt on the validity of the results for the younger stars, with a break down of the relation for ages below ≈ 0.7 Gyr. In addition, Holzwarth & Jardine (2007) agree that K- and M-type stars should not be considered jointly and propose a new, much shallower power law.

The question of the strength of the wind of single active stars remains unsolved. Current best estimates for the young Sun suggest a stronger wind by a very uncertain factor between 10–1000. All these results are based on a few observations taken before the demise of the STIS spectrograph on board HST. The recent recovery of the instrument should permit the continuation of the observations and, hopefully, provide the needed proof to constrain the time-evolution of the mass loss of the Sun and active stars in general. On the down side, other important parameters will remain unknown for the active stellar phases, such as the geometry of the wind or the intensity of the interplanetary magnetic field. For example, active stars are known to present active regions at high latitudes (e.g., Strassmeier 2009) and the simple scaling of the geometry of the current solar wind may just be incorrect.

5. Short-term variability

Magnetic activity phenomena have characteristic variations over a very wide range of timescales. In mid-range timescales (years and decades), the variations are associated with activity cycles, which in the case of the Sun is of the order of 11 years. Over this time period, the amplitude of the variations is of about 20–50% in the UV range up to a factor 10–20 in X-rays (Rottman 1988; Lean 1997). Most of what we know about activity cycles in field stars is due to the Mount Wilson, based on the monitoring of the Ca II H&K emission lines (e.g., Donahue *et al.* 1996). The data collected has shown the existence of activity cycles in many stars which, interestingly, have periods similar to that of the Sun (Baliunas & Vaughan 1985). Even in the case of very active stars, such as EK Dra, the activity cycle seems to be around 10 years (Güdel *et al.* 2003; Järvinen *et al.* 2005). But the most relevant factor to the potential impact on planets is the amplitude of the variations. Such amplitude is seen to decrease with increasing activity. Thus, a young solar analog has peak-to-peak variations of a factor 2–2.5 in X-rays (some 4 times smaller than those of the Sun; Micela & Marino 2003). This apparent contradiction is probably explained by the lower contrast between the epochs of maximum and minimum activity for stars that are already strongly active in quiescence.

At short timescales, variability is driven by spot modulation and, more interestingly, by flare events. Thanks to our privileged view of the Sun, links have been established between these flares, high-energy emissions and particle emissions (coronal mass ejections) (e.g., Aschwanden *et al.* 2001). Flares can be very energetic phenomena that trigger rapid increases over the quiescent high-energy and particle emissions. For example, the increase

in the flux for strong solar flares can be of 20–50% in the FUV–UV and 2–10 fold in X-rays.

A relevant question is whether flare rates change over the course of the stellar lifetime. Indeed, observations by the EXOSAT X-ray satellite revealed a strong flare (10-fold increase in flux) of the 0.3-Gyr-old solar analog π^1 UMa (Landini *et al.* 1986), thus suggesting an enhanced flare activity in young stars. This was corroborated by the thorough analysis carried out by Audard *et al.* (2000) using EUVE data, who found a well-defined correlation between the rate of flare occurrence and magnetic activity (using L_X as proxy). The expressions in Audard *et al.* (2000) indicate that the cumulative flare distribution follows the power law:

$$N(> E) \approx 0.08 L_X^{0.95} E^{-0.8} \text{ day}^{-1} \quad (5.1)$$

with E being the flare energy. The expression indicated that a young, active solar-type star ($L_X \approx 10^{30} \text{ erg s}^{-1}$) can undergo several tens of large ($E > 10^{32} \text{ erg}$) flares per day, while the current Sun at its peak of activity experiences such strong flares once every two weeks on average.

Flares are an important addition to the high-energy fluxes and particle emissions in quiescence. The high flare rates of active stars indicate that this is a factor that needs to be taken into account for a complete picture of stellar activity and its potential impact on planets.

6. Effects of solar/stellar activity on planets

The evidence discussed above unambiguously draws a picture of the young Sun (and young, active stars in general) of enhanced high-energy and particle emissions, with frequent energetic flares. To put these results in context it is useful to consider that high-energy emissions of the Sun today account for about 3 millionths of the total radiative flux that the Earth received. Even in the most active phase of the young Sun, this high-energy emissions just amount to 5 parts in ten thousand, a very small fraction of the total flux. This implies, for example, that the higher flux cannot explain the Faint Young Sun paradox using arguments related to the radiative budget. However, an important feature of high-energy emissions is that they are absorbed at very high altitude in the planetary atmosphere (because of the large cross section), in a region, the exosphere, where the density is low. Even the relatively small contribution of energetic photons can increase the temperature of this atmospheric layer dramatically, leading to the onset of escape processes. This illustrates the often non-linear behavior of Nature, in which it can be the process instead of sheer power what explains physical phenomena. Besides, the enhanced UV radiation can trigger photochemical reactions thus altering the chemical composition (see Hunten *et al.* 1991 for a review). Finally, particle emissions also play their role by contributing to the erosion of planetary atmospheres via non-thermal processes, mostly through so-called sputtering and ion pick-up. Only the strength of the planetary magnetic field can offer some protection by diverting the incoming charged particles. All the loss processes, both thermal and non-thermal, are thoroughly covered in the monograph by Bauer & Lammer (2004).

All the evidence discussed so far compellingly demonstrates that radiation and particle emissions from active stars (including the young Sun) can be orders of magnitude stronger than those of the current Sun and thus potentially have an impact on the properties of planetary atmospheres. In the following sections we review some of these effects on both Solar System planets and exoplanets.

6.1. *Mars and Venus*

An immediately obvious application of the time-evolution of solar magnetic emissions is the study of the volatile inventory of planet Mars. The small mass of the planet and the lack of a protecting magnetic field make it specially vulnerable to the charges from the active Sun. Relevant processes include the loss of atmospheric constituents to space (basically molecules and H, He, C, N and O ions) and the balance with the incorporation in the Martian soil via weathering processes. Recent sophisticated studies based on 2D and 3D modeling (Lammer *et al.* 2003a; Donahue 2004; Terada *et al.* 2009) suggest that the loss of volatiles from Mars could amount to a global water ocean with a depth of several tens of meters. This is in agreement with the inference from the water-related features visible on the Martian surface as shown by the images of the Mars Global Surveyor (Carr & Head 2003). The loss of water was driven by photolysis in the atmosphere and subsequent loss of oxygen and hydrogen ions by thermal escape. Instead of the expected 2:1 (H:O) loss ratio, the observed and modeled value is 20:1 because of hydrogen being lighter and escaping more easily. The remaining O is incorporated in the Martian surface giving it the characteristic rusty aspect. The thickness of the oxidized layer is relevant to future searches for organic matter and the calculations indicate that it could be at least of 2–5 m.

A related aspect is the investigation of the conditions of the Martian atmosphere that allowed the presence of liquid water on the surface 3.8 Gyr ago, as indicated by the observations (Baker 2001). The studies that account for the effects of the solar high-energy emissions show that a greenhouse effect driven by CO₂ could have provided the necessary conditions (Kulikov *et al.* 2007), although there are still numerous uncertainties. At the same time, Mars should have been protected by a magnetic field to avoid massive erosion of its atmosphere from non-thermal processes. The subsequent evolution of Mars can just be guessed. Its core possibly ceased to generate a magnetic dynamo because of several possible reasons (Stevenson 2009) and the loss of the magnetic field exposed the atmosphere of the planet to intense erosion. The atmosphere started to evaporate (including the water and volatile inventory) and the planet eventually cooled down because of the lack of a greenhouse effect. During this cooling process, which could have been quite rapid, part of the water could have been incorporated into the Martian soil as water ice and explain the observations from several probes (Murray *et al.* 2005).

The other interesting terrestrial planet of the Solar System is Venus, with a mass similar to the Earth's but at the same time with a very different atmosphere. The question is whether Venus was once a wet planet and, if so, why it is now so dry. The past of Venus is still quite mysterious but there is strong evidence that Venus had a significant water inventory, both from the current understanding of the formation of the Solar System planets and from certain isotope ratios. Estimates using D/H ratios suggest that the water content of Venus was at least 0.3% of an Earth ocean (Hartle *et al.* 1996), and possibly closer to the total Earth water inventory. The combination of a runaway greenhouse effect caused by the increasing solar flux with the high-energy emissions heating up the upper atmosphere and producing photolysis led to the loss of water to space. Depending on different assumptions, the loss of water could easily amount to over an Earth ocean in just a few tens or hundreds of Myr (Kulikov *et al.* 2006). This was probably further exacerbated by non-thermal losses caused by the lack of a protecting magnetic field in Venus. The current CO₂ rich atmosphere could come from out-gassing processes resulting from volcanism.

Similar investigations can be carried out on the satellites of the Solar System with an atmosphere, such as Titan. An excellent review on the atmospheric escape processes in

terrestrial planets (Venus, Mars and Earth) and satellites (Titan) was published recently by Lammer *et al.* (2008).

6.2. Earth

The question of the influence of variations in the Sun on Earth's climate has been a recurrent one. Correlations between climate variations (temperature, rainfall) and solar activity have been proposed even on short timescales, such as those related to the 11-yr solar cycle (see, e.g., Hoyt & Schatten 1997). The overall solar irradiance variations over the sunspot cycle are of about 0.1–0.2% (Fröhlich & Lean 2004). This translates into a cyclic temperature variation of the Earth of about 0.1°C when computed from simple black body considerations, which does not seem sufficient by itself to produce observable climate changes.

Even though the observed global light variations of the Sun are very small over its activity cycle, these are much larger at shorter wavelengths (e.g., Lean 1997). For example, the typical variations of solar X-ray and EUV emissions from the minimum to the maximum of the ~11 year activity cycle are over a factor of 5, while at FUV and UV they range from 10 to 50 percent. Also the frequencies and intensities of flaring events and coronal mass ejections (CME) are strongly correlated with the Sun's activity cycle. For example, the rate of CME occurrences is larger during the sunspot maxima than during the times sunspot minima (Webb & Howard 1994). An interesting – and perhaps definitive – proof of forcing from solar activity cycle on Earth's climate was presented recently by Meehl *et al.* (2009). The authors link rainfall and temperature anomalies in the Pacific to the response of the stratosphere to ozone fluctuations caused by solar high-energy emissions. This mechanism illustrates how a small change in the energy budget can amplify via feedback mechanisms to measurable variations in the Earth climate.

One of the most tantalizing hypotheses on possible climate–solar activity connection is the coincidence of the extended low solar activity level that occurred during ~1450–1850 with an interval of cooler/stormier weather known as the “The Little Ice Age”. The early observations of sunspot number have been reconstructed from historical sources starting from the telescopic observations of sunspots by Galileo in 1610/11. There is a paucity of sunspots during 1645–1715 and, to a lesser extent, again during 1800–1840. These intervals of low sunspot numbers are known as the Maunder Sunspot Minimum and the Dalton Sunspot Minimum, respectively. Attempts have been made to compute the solar total irradiance during the Maunder Minimum from sunspot activity (see Lean *et al.* 1995). The reconstruction of the solar irradiance back to 1600 suggests an estimated decrease of 0.24% from the present to the time of the Maunder Minimum in the late 17th century. Using simple radiative laws, this irradiance change should produce a global temperature decrease of about 0.2°C. However, proxies of surface temperature indicate a temperature decrease of about 0.7°C during the Maunder Minimum (Bradley & Jones 1993). The connection of stellar activity and the “Little Ice Age” remains unsolved, but, as before, it could be related to non-linear feedback mechanism in the climate system. There is even controversy over how widespread was the cool period and it has been suggested that the temperature anomaly could just have affected the Northern Hemisphere (e.g., Jones *et al.* 1998), thus lessening its global impact.

Over long timescales, the Earth has suffered the same processes as explained above for Venus and Mars (e.g., Lundin *et al.* 2007), but it is obvious that Earth managed to keep its volatiles, probably thanks to the large mass and protecting magnetic field. In the case of the Earth it is very interesting to study the effects of high-energy radiation on the photochemistry of the early atmosphere. A particularly noteworthy period was the time of appearance of life on Earth, about 3.9 Gyr ago. Remarkably, one of the proxies

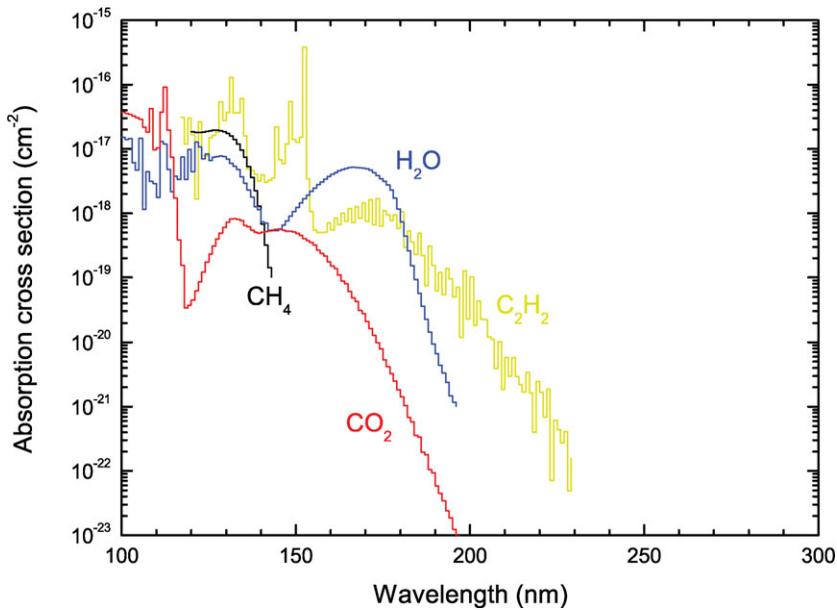


Figure 5. Photoabsorption cross sections of some molecules suspected to have been present in early Earth's atmosphere according to the model by Pavlov *et al.* (2001). Note the sensitivity of these molecules to photodissociation by UV radiation, which is found to be significantly enhanced in active stars, including the young Sun.

used in the Sun in Time program, κ^1 Cet, happens to be an excellent match for the Sun at at key time in Earth's past. As discussed Ribas *et al.* (2010), κ^1 Cet's UV flux is some 35% lower than the current Sun's between 210 and 300 nm, it matches the Sun's at 170 nm and increases to at least 2–7 times higher than the Sun's between 110 and 140 nm. This wavelength regime is important to the photodissociation of some important molecules expected in the atmosphere of the Earth, such as CO_2 , CH_4 , H_2O , and C_2H_2 (Pavlov *et al.* 2001), as shown in Fig. 5. The use of the correct UV fluxes indicate that photodissociation rates should have been several times higher than those resulting from the simplistic “theoretical” solar spectrum, as used in most of the previous calculations of the young Earth's atmosphere. This is likely to trigger a very peculiar atmospheric chemistry that will be investigated by using a photochemical model of the primitive Earth's atmosphere. The enhanced H_2O photolysis would also result in a higher escape rate of hydrogen to space, particularly important for the early evolution of Mars and Venus.

Our calculations vividly show that self-consistent planetary atmosphere calculations must account for the much stronger photodissociating radiation of the young Sun. The resulting chemistry could be markedly different from that assumed in most investigations. This is obviously relevant to a very significant point in the Solar System evolution, when life was developing on Earth.

6.3. Hot Jupiters

Thermal escape in Solar System planets is today almost negligible, but this is not the case of some of the exoplanets discovered. The most suggestive case is that of “Hot Jupiters”, giant planets orbiting at very close distances (a few hundredths of an AU) of their host star. The influence of the stellar radiations can be very important for this class of planets. High-energy emissions heat up the exosphere of the planet and lead to intense

evaporation of hydrogen and other atmospheric constituents through an outflow (Lammer *et al.* 2003b). Initial estimates suggested that the escape rate could be high enough to fully evaporate giant planets over a timescale of 1 Gyr (Baraffe *et al.* 2004), leaving only a naked terrestrial core. Further more refined simulations (Yelle *et al.* 2008, and references therein) indicate lower evaporation rates that, when integrated over time, would not imply significant loss of mass for a planet during the course of its lifetime. Certain processes in the upper atmosphere would provide the necessary cooling to counteract the high-energy flux, such as the creation of H_3^+ ions. However, the expected strong emission associated to H_3^+ has not been detected yet (Shkolnik *et al.* 2006).

Besides thermal losses, evaporation driven by particle winds can also be very relevant. The key element here is the existence of a protecting magnetic field. The uncertainties in this case are difficult to overcome. For example, Grießmeier *et al.* (2004) show that the evaporation rate will depend on the magnetic moment of the planet (which is tidally locked) and different assumptions lead to very different conclusions. Direct observations of mass loss from Hot Jupiters should hold the key to understanding the processes that drive the evolution of these planets. Unfortunately, the only observation that could relate to such evaporation process at play (Vidal-Madjar *et al.* 2003, 2008) has raised significant controversy (Holmström *et al.* 2008; Ben-Jaffel 2008).

6.4. Habitability of terrestrial exoplanets

The milestone of identifying life outside of our planet and, eventually, beyond our own Solar System is of the utmost impact to science and to humanity as a whole. A key component in this direction is to define the main requirements to habitability. There is substantial agreement in pointing out liquid water as a requisite for the existence of life (or, as least, life that could be recognizable to us). Kasting *et al.* (1993) were pioneers in employing a simple climate model to predict the range of distances around a star that could sustain liquid water bodies on the surface of a planet. This led to the definition of the so-called Habitable Zone. However, even today, there are significant uncertainties as to the extension of the habitable zone because processes like CO_2 cloud formation are poorly known and so are their thermal properties. An example is the case of Mars, which is well within the habitable zone according to the calculations yet it does not have liquid water on its surface (at least in a stable condition). Its mass is not sufficient to keep the volatiles neither to possess active plate tectonics providing the necessary climate stabilization feedback. All this is clearly discussed in the review by Kasting & Catling (2003).

It has become evident over time that the simple definition of the habitable zone can be very incomplete. Habitability is influenced by many factors in addition to the incoming stellar radiation, such as the presence of a magnetic field, the mass of the planet, the existence of plate tectonics, the composition of the atmosphere, and even some second order effects like the frequency of catastrophic impacts or the stability of the obliquity. All these further ingredients need to be put in the models to assess the presence and properties of a planet atmosphere and, ultimately, whether the planet could be habitable. A thorough discussion on the wide concept of habitability and its implications can be found in Lammer *et al.* (2009).

A particular case that has raised much attention lately is that of planets around very low mass stars (M-type). Such stars, because of their relative abundance and good prospects for direct study of habitable planets, have become very appealing. There are two main issues that planets around M-type stars need to face. Firstly, according to tidal theory, they would have their rotation captured and thus spin synchronously with the orbital translation motion (implying diurnal and nocturnal hemispheres). Secondly, as

explained above, low-mass stars could have extended periods of strong magnetic activity with accompanying intense high-energy and particle emissions (plus frequent flares with associated coronal mass ejections). Both effects have raised concern whether a terrestrial planet around an M-type star could have a stable atmosphere with a climate allowing for the existence of liquid water. Calculations by Joshi *et al.* (1997) showed that a dense atmosphere with efficient circulation could avoid condensation on the night-side of the planet. Regarding evaporation, several studies have evaluated the different conditions (Scalo *et al.* 2007; Lammer *et al.* 2007; Khodachenko *et al.* 2007). Models seem to suggest that a CO₂ rich and dense atmosphere could survive the strong incoming high-energy radiation by efficient IR cooling, but the degree of uncertainty is still large. Photochemical reactions may also play a key role in the atmosphere of terrestrial planets around M-type stars because of the strong UV radiations (Segura *et al.* 2005). A practical example of habitability criteria applied to the Gl 581 system was presented by Selsis *et al.* (2007).

7. Conclusions

Our planet Earth orbits around a dependable star that has provided a suitable environment for life to thrive. But the apparent stability of the Sun is just an illusion. Thanks to our vantage point we are able to scrutinize the solar properties with exquisite detail. Centuries of observation have shown a variety of effects related to the magnetic activity that reveal our Sun as a variable star. Sunspots, faculae, coronal mass ejections, are all different facets of the active Sun. Firsthand experience on Earth has demonstrated that such phenomena have a powerful influence on our planet's upper atmosphere and, perhaps, even on our climate. But consider the current Sun with an increase of its high-energy and particle emissions by two or three orders of magnitude. This would have been the infant Sun. Our planet and the rest of its Solar System siblings had to endure an epoch of heavy irradiations early in their history. The atmosphere of Mars, once it lost its magnetic shielding, succumbed to the intense erosion. The strong emissions also left their imprint in the isotopic ratios of the atmospheres of Venus and Titan, for example. Fortunately, the mass of the Earth and its magnetic protection helped our planet to keep its volatile inventory and eventually allowed for the development of complex life. While our Sun's wild ages lasted for a few hundred million years, other less massive stars may have kept the strong emissions for much longer. Future research will tell us what could happen to a terrestrial planet orbiting a red dwarf star, which stays active for billions of years, and whether habitability can exist in such hostile environment.

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