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Evolution of the Solar Magnetic Activity over Time and Effects on Planetary Atmospheres

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Abstract. We report on the results of a multi-wavelength program (X-rays to the near IR) of solar analogs with ages covering ~0.1–9 Gyr. The chief science goals are to study the solar magnetic dynamo and to determine the radiative and magnetic properties of the Sun during its evolution across the main sequence. The present paper focuses on the latter goal, which has the ultimate purpose of constructing spectral irradiance tables to be used to study and model planetary atmospheres. The results obtained thus far indicate that the young Sun was extremely active, with large flares, massive winds, and high-energy emissions up to 1000 times stronger than presently. The strong radiation and particle emissions inferred should have had major influences on the photochemistry and photo-ionization of paleo-planetary atmospheres and also played an important role in the development of primitive life in the Solar System. Some recent results of the effects of the young Sun's enhanced radiation and particle emissions on the early Solar System planets are discussed.

1. Introduction

Studies of solar proxies (G0–G5 V stars) across the electromagnetic spectrum have been carried out over the last decade as part of the "Sun in Time" program. The primary aims of the program are: *1)* To test solar dynamo models of the Sun in which rotation is the only significant variable parameter, and *2)* to determine the spectral irradiance of Sun over its main sequence lifetime. This program shows that ZAMS solar-type stars rotate over 10 times faster than today's Sun (see Fig. 1). As a consequence of this, young solar-type stars, including the Sun, had vigorous magnetic dynamos and correspondingly strong coronal X-ray and EUV emissions and chromospheric FUV and UV emissions up to 10–1000 times stronger than observed for the present Sun. Also, observations of the youngest solar proxies indicate that the young Sun had frequent and powerful flares (Audard et al. 1999) and a more massive wind (Wood et al. 2002).

Here we discuss the results of the "Sun in Time" program, chiefly focused on the study of the varying spectral irradiance of the Sun. Included is the characterization of chromospheric, transition region, and coronal emissions of these solar-type stars as a function of age and rotation. Also discussed are the

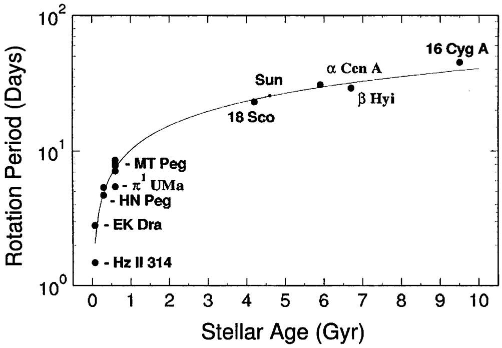

Figure 1. Plot of the rotation period vs. stellar age for a sample of solar-type stars (including the Sun), with a power law fit indicating indicates a spindown of solar-type stars with age.

major effects that the young Sun's strong XUV radiation may have had on the photoionization, photochemistry, and erosion of paleo-planetary atmospheres. Some examples briefly addressed are the possible erosion of Mercury's mantle, the loss of water and the oxidation of the Martian surface, and the evolution of the Earth's atmosphere.

2. High-energy irradiances, flares, and winds of solar-type stars

The "Sun in Time" solar proxies constitute a homogeneous sample of single, nearby, G0–5 stars that have known rotation periods and well-determined ages, temperatures, luminosities, and metallicities (see Guinan et al. 2003). Also, the fits to evolution models yield estimates of the stellar masses and all the stars in the sample are within 10% of 1 $M_\odot$. Our sample stars cover most of the Sun's main-sequence lifetime from 130 Myr up to 9 Gyr.

One of the primary goals of the program is to reconstruct the spectral irradiance evolution of the Sun. To this end, a large number of multiwavelength (X-ray, EUV, FUV, UV, optical) have already been collected. The observations, secured with the ASCA, ROSAT, EUVE, FUSE, HST, and IUE satellites, cover 1 Å (12 keV) to 3300 Å, except for a gap between 360 Å and 920 Å, which is a region of very strong ISM absorption, thus far largely unexplored for stars other than the Sun. Details of the datasets and the flux calibration procedure employed will be provided in forthcoming publication. Full spectral irradiance tables have already been completed for five of the stars in our sample: EK Dra (130 Myr), π^1 UMa (300 Myr), κ^1 Cet (750 Myr), β Com (1.6 Gyr), and β Hyi (6.7 Gyr). This study of solar proxies show an excellent correlation between the emitted flux and stellar age. An illustrative example is given in Fig. 2, where the surface fluxes of two O VI strong transition region emission features in the FUV are shown to decrease with increasing age.

A detailed quantitative analysis reveals that the stellar fluxes can be very well approximated by power law relationships. This is illustrated in Fig. 3.

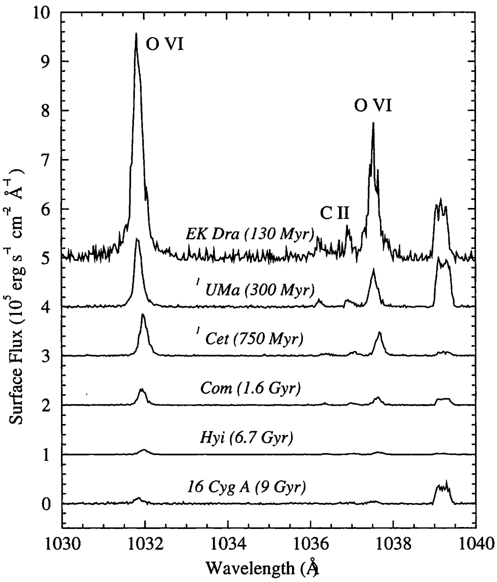

Figure 2. Comparison of the surface fluxes for all targets in our FUSE programs in the region around the O VI $\lambda\lambda$1032,1038 doublet. Note the obvious trend of decreasing flux with increasing stellar age.

Interestingly, the slopes of the best-fitting relationships are seen to decrease monotonically from the X-rays to the UV (i.e. decreasing energy or increasing wavelength). Emissions associated with hotter plasmas diminish more rapidly as the stars spin down with age. The results from the "Sun in Time" program suggest that the coronal X-ray–EUV emissions of the young main-sequence Sun were ~100–1000 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 10–100 and 5–10 times stronger, respectively, than presently. When considering the integrated high-energy emission from 1 to 1200 Å the resulting relationship indicates that the solar high-energy flux was about 3 times the present value 2.5 Gyr ago and about 6 times the present value about 3.5 Gyr ago (when life arose on Earth). Note also that the high-energy flux of the ZAMS Sun was stronger by as much as a hundred-fold. These results are in general agreement with those reported by Zahnle & Walker (1982) and Ayres (1997).

To fully characterize the evolution of high-energy radiation one must also estimate the flux contribution of the strong H I Lyα emission line. From the available observations we find that Lyα is the dominant source of short-wave emission in the Sun and solar-type stars contributing about 80–90% of the total FUV flux and 30–60% of the total flux between 1 and 1500 Å. The Lyα flux is strong enough to penetrate the planetary exospheres into their mesospheres. The intermediate atmospheric layers of planets, richer in molecules, are susceptible to photochemical reactions that could significantly alter their compositions. Preliminary estimates using spectra of two solar proxies indicate that Lyα flux

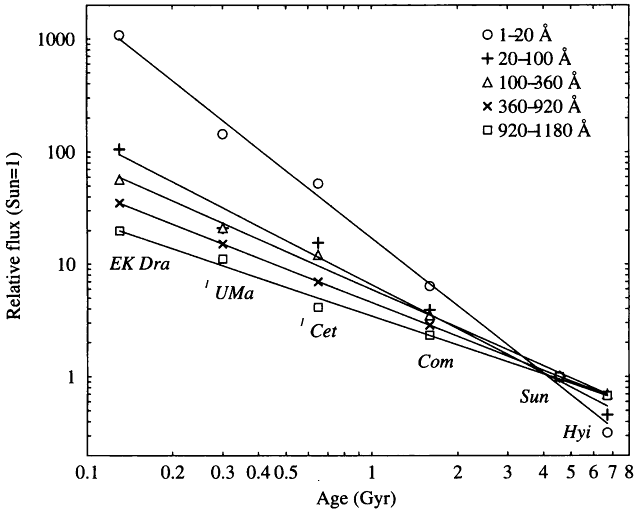

Figure 3. Relative fluxes vs. age for five "Sun in Time" targets. Plotted here are measurements for different wavelength intervals and the corresponding fits using power law relationships (decreasing slope with increasing emission wavelength). The fluxes in the 360–920 Å interval have been inferred by interpolation because of the lack of observations.

of the young Sun was also much stronger, by up to a factor of 15. Planned observations for the remaining targets within the "Sun in Time" will allow for a much better characterization of the emissions from such important flux source.

In addition to intense levels of dynamo generated coronal and chromospheric XUV emissions, the young Sun and young solar analogues are also expected to have stronger and more frequent flares and to have stronger (more massive) stellar winds. Observations of the flare activity of young solar proxies strongly suggest that flare events are frequent and up to 1000 times more powerful than observed for the present Sun (Audard et al. 1999). The high frequency of large flares (~2–3 major flares per day) could indicate explosive episodic releases of plasma. These could be like coronal mass ejections (CMEs) observed in the Sun today, but much stronger and more frequent.

Although winds from solar proxies have not been observed directly, their characteristics can be inferred from observations of the interaction between fully ionized coronal winds with the partially ionized local interstellar medium (Wood et al. 2002). Modeling the associated spectral line absorption features which are formed in these "astrospheres" provides empirical estimates of coronal mass loss rates. The mass loss rate appears to increase with stellar activity. Wood et al. (2002) suggest that the wind in the active young Sun may have been around 1000 times more massive than it is today.

In summary, compelling observational evidence indicates that the Sun underwent a much more active phase in the past. The enhanced activity revealed itself in the form of strong high-energy emissions, frequent flares and CME events, and a powerful stellar wind. Such energy and particle environment certainly had an impact on the genesis and evolution of Solar System planets and planetary atmospheres. In the subsequent sections we address the question of the influence of the young Sun emissions on the planetary system through a few selected examples. While we focus here on the Solar System, the "Sun in Time" data have also been applied to investigate the atmospheric loss of exoplanets resulting from XUV heating, which can eventually lead to the evaporation of "hot Jupiters" (Lammer et al. 2003a).

3. Erosion and sublimation effects on Mercury's surface

Mercury is often referred to as the "iron" planet. Mercury's core is large compared to other terrestrial planets, extending out to over 60 percent of its radius. Mercury has the greatest exposure to solar radiation and winds because of its location near to the Sun (0.39 AU). One of several hypotheses advanced to explain this anomaly is that strong, dense winds and very high X-ray-FUV fluxes of the young Sun (during the first 0.5–1 Gyr of its life) eroded (swept away) its early atmosphere and much of its outer mantle. Even today (with a much less active Sun) ground based observations of heavy constituents like Na^+, K^+ and O^+ in Mercury's present transient exosphere implicate a strong exosphere-surface interaction related to the particle and radiation environment of the nearby Sun (e.g., Cameron 1985).

Recent studies of isotope anomalies in planetary atmospheres and meteorites, appear to support the results inferred from our solar analog program, and indicate that our early Sun underwent a highly active phase after its origin, including continuous flare events where the particle and radiation environment was several hundred times higher than today. Because Mercury is the closest planet to the Sun, its surface was exposed more than all other Solar System bodies by such an enhanced solar wind particle and radiation flux. This problem is being addressed in collaboration with Helmut Lammer and the astrobiology group at Graz (Austria). In this initial study, irradiance values (X-ray/FUV) determined from the "Sun in Time" program and solar wind estimates of the young Sun from Wood et al. (2002) were used as inputs for the modeling. Lammer et al. (2002) have carried out initial calculations that indicate that enhanced solar wind and XUV emissions could be sufficient to explain the present relatively thin mantle and relatively large iron core. If this hypothesis is correct, young Mercury may have started out similar in size to the Earth but lost much of its less dense mantle from radiation and particle interactions (ion pick-up) with the young Sun. Other viable mechanisms that produce similar results are a young Sun that was significantly more massive (and thus more luminous) than today or from loss of volatiles through collisional processes.

4. The Martian water inventory

The results from the "Sun in Time" program were employed by Lammer et al. (2003b) to study the evolution of the Martian water inventory. A gas dynamic test particle model was used to study the various atmospheric escape processes, including an estimate of the pick-up ion loss rates. In these calculations the authors also considered pick up ion sputtering, as well as dissociative recombination. The loss of H_2O from Mars over the last 3.5 Gyr was estimated to be equivalent to a global martian H_2O ocean with a depth of about 12 m, which is smaller than the values reported by previous studies. If ion momentum transport, a process to be studied in detail by Mars Express, is significant on Mars, the water loss may be enhanced by a factor of about 2.

Lammer at al. (2003b) also found that the sum of thermal and non-thermal atmospheric loss rates of H and all non-thermal escape processes of O to space are not compatible with a ratio of 2:1, and is currently close to about 20:1. Escape to space cannot therefore be the only sink for oxygen on Mars. These results suggest that the missing oxygen (needed for the validation of the 2:1 ratio between H and O) can be explained by the incorporation into the Martian surface by chemical weathering processes since the onset of intense oxidation about 2 Gyr ago. Based on the evolution of the atmosphere-surface-interaction on Mars, an overall global surface sink of about 2×10^{42} oxygen particles in the regolith can be expected. Because of the intense oxidation of inorganic matter, this process may have led to the formation of considerable amounts of sulfates and ferric oxides on Mars. To model this effect several factors were considered: *1)* The amount of incorporated oxygen, *2)* the inorganic composition of the martian soil, and *3)* meteoritic gardening. Lammer et al. show that the oxygen incorporation has also implications for the oxidant extinction depth, which is an important parameter to determine required sampling depths on Mars aimed at finding putative organic material. The oxidant extinction depth is expected to lie in a range between 2 and 5 m for global mean values.

5. The paleoatmosphere of the Earth and the Faint Sun Paradox

As discussed by Canuto et al. (1982, 1983), Ayres (1997), Guinan et al. (2003) and others, the strong XUV and particle emissions of the young, more active Sun could have played a major role in the early development and evolution of planetary atmospheres – especially those of the terrestrial planets. The expected strong X-ray–UV irradiance of the young Sun can strongly influence the photochemistry and photoionization (and possible erosion) of the early planetary atmospheres and also may play a role in the origin and development of life on Earth as well as possibly on Mars. For example, Canuto et al. discuss the photochemistry of O_2, O_3, CO_2, H_2O, etc, in the presumed CO_2-rich early atmosphere of the Earth. A sketch showing the effects of the enhanced solar emissions in the past on the atmosphere of the Earth is presented in Fig. 4.

The "Sun in Time" data can also provide insights into the so-called Faint Sun Paradox. The paradox arises from the fact that standard stellar evolutionary models show that the Zero-Age Main Sequence Sun had a luminosity of ~70% of the present Sun. This should have led to a much cooler Earth in the past while geological and fossil evidence indicate otherwise. A solution to the Faint Sun Paradox proposed by Sagan & Mullen (1972) was an increase of the greenhouse effect for the early Earth. The gases that have been suggested to account for this enhanced greenhouse effect are CO_2, NH_3 or CH_4 (see, e.g., Rye et al. 1995; Sagan & Chyba 1997; Pavlov et al. 2000).

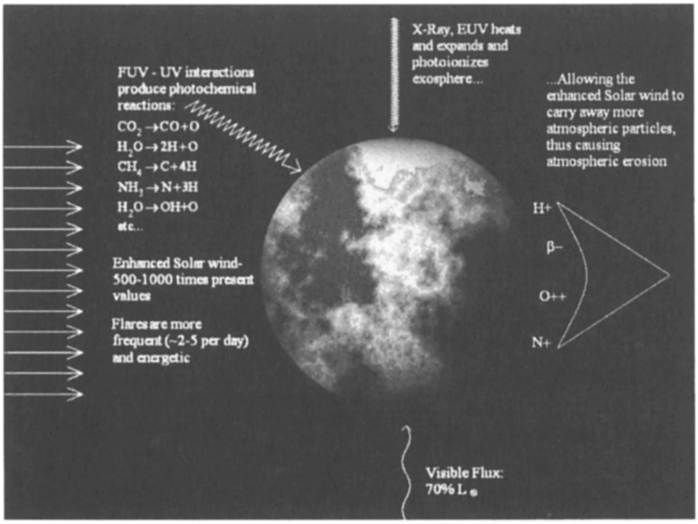

Figure 4. A sketch showing the various effects of the enhanced high-energy emissions, wind strength, and flare rate of the young Sun on the paleoatmosphere of the Earth.

In addition to the stronger greenhouse effect, the expected higher X-ray–UV irradiance of the young Sun should heat up the upper atmosphere of the early Earth. Although the stronger high-energy solar radiation cannot by itself explain the Faint Sun Paradox, the photoionization and photodissociation reactions triggered could play a major role in what greenhouse gases are available. For example, the high levels of FUV–UV radiation of the young Sun could strongly influence the abundances of ammonia and methane in the pre-biotic and Archean planetary atmosphere some 2-4 Gyr ago. Similarly, the photochemistry and abundance of O_3 is of great importance to study life genesis on Earth. Ozone is an efficient screening mechanism for the enhanced UV radiation of the young Sun, thus protecting the emerging life on the Earth's surface.

6. Future directions

Because lower mass stars are especially common and hence may host habitable planets, future progress in this area involves expanding the "Sun in Time" program to time sequences of the high-energy emissions, wind, and flare activity of low-mass stars. Work in this direction has already started with the study of XUV spectral irradiances (and flare characteristics and winds) of nearby lower mass dK–M stars. These stars are cooler and much less luminous than the Sun (and solar type stars) but they are far more numerous than the solar-type stars and have main sequence lifetimes 2–10 times that of the Sun. Because of the low luminosities, their "habitable zones" (see Kasting et al. 1993) can be quite close to the host stars.

Low-mass stars stars have deeper outer convective zones (where the magnetic dynamo operates) than sun-like stars and thus possess very efficient magnetic dynamos. The initial studies of dK and dM stars have found that they have very strong coronal/chromospheric XUV emission fluxes compared to solar-type with similar rotation periods or ages. Even a relatively old dM star like Proxima Cen (age$\sim$5.5 Gyr) shows strong XUV emissions and has powerful flares about once per hour (Walker 1981). Younger dK–M stars seem to flare continuously and have very strong XUV emissions that amount to about 10^{-3} times their total luminosities. These stars are very numerous and it will be important to search for planets around them as is being done now. However, the investigation of the stars' strong (and fluctuating) coronal/chromospheric XUV emissions, flares, and winds is of great importance as these are expected to play a major role in the development of life on planets located in their habitable zones.

7. Acknowledgments

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