THE PARTICLE AND RADIATION ENVIRONMENT OF THE EARLY SUN

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ABSTRACT

Multi-wavelength studies of solar-like G-type stars at several stages of their main sequence evolution indicate that our early Sun must have undergone a highly active phase in its particle and radiation environment 3.5-4.5 Gyr ago. An overview of that problem can be found e.g. in Guinan and Ribas (2002) and Hanslmeier (2002). Detailed observations of such stars by the ROSAT and ASCA X-ray satellites show that the X-ray luminosity may have been several hundred times higher than today. We investigate in our study how these high X-ray fluxes could be connected to the mass loss and particle outflow of these stars and how such an enhanced particle and radiation environment has influenced the evolution of planetary bodies in our solar system at least up to 3.0 Gyr ago.

1. THE SUN IN TIME PROGRAM

The Sun in Time program is a comprehensive project to study the magnetic evolution of the Sun using a sample of single nearby G0-V stars that have known rotation periods and well-determined physical properties and ages (Guinan & Ribas, 2002). Our sample comprises most of the Sun’s main sequence lifetime from 130 Myr up to 8.5 Gyr. To study the evolution of the Sun’s high-energy emissions, we have been collecting a large number of multi-wavelength (X-ray, EUV, FUV, UV, optical) observations, directed towards achieving a full description of the spectral irradiance of the targets. Full spectral irradiance tables covering from 1 Å (12 keV) to 3300 Å have already been completed for five of the stars in the sample: EK Dra (130 Myr), π LMi (300 Myr), κ1 Cet (750 Myr), β Com (1.6 Gyr), and β Hyi (6.7 Gyr). Examples of the resulting data products are shown in Figure 1. An excellent correlation between the emitted flux and stellar age is clearly observed. Our study of solar proxies shows that the coronal X-ray-EUV emissions of the young main-sequence Sun (~EK Dra) were over 1000 times stronger than those of the present Sun (~β Hyi). The data in the figure show that while the NUV/optical flux is similar for all stars, very large differences exist in the high-energy region of the spectrum. Over the past decade, data covering X-ray, EUV, FUV, NUV and optical wavelengths that cover coronal emissions and chromospheric emissions were secured. For our study

Figure 1. ASCA, ROSAT, and IUE irradiances for the five stars of the Sun in Time sample with complete data. While the NUV/optical flux is similar for all stars, very large differences exist in the high-energy portion of the spectrum.

the data of the Extreme Ultraviolet Explorer (EUVE), the Far Ultraviolet Spectroscopic Explorer (FUSE) and the X-ray data obtained by the ASCA and ROSAT satellites are essential. EUVE and FUSE are spectroscopic missions where EUVE provides a moderate resolution of $\Delta \lambda / \lambda \approx 200$ spectroscopy from 80 Å to 760 Å in three band-passes. Because of the strong interstellar medium H extinction wavelengths only in the shorter region 80 Å to 360 Å are useful for our study. The FUSE satellite covers a wavelength range of 920 Å to 1180 Å. Both EUVE and FUSE observations fill an important wavelength and energy gap and complement observations of the X-ray region of the same stars made by ASCA and ROSAT.

Table 1. Stars studied under the Sun in Time program.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectr. Type</th>
<th>$P_{\text{d}}$(d)</th>
<th>Age(Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EK Dra</td>
<td>G0 V</td>
<td>2.75</td>
<td>0.13</td>
</tr>
<tr>
<td>$\pi^1$ Uma</td>
<td>G1.5 V</td>
<td>4.68</td>
<td>0.3</td>
</tr>
<tr>
<td>HN Peg</td>
<td>G0 V</td>
<td>4.86</td>
<td>0.3</td>
</tr>
<tr>
<td>$\chi^1$ Ori</td>
<td>G1 V</td>
<td>5.08</td>
<td>0.3</td>
</tr>
<tr>
<td>BE Cet</td>
<td>G2 V</td>
<td>7.65</td>
<td>0.6</td>
</tr>
<tr>
<td>VB 64</td>
<td>G2 V</td>
<td>8.7</td>
<td>0.6</td>
</tr>
<tr>
<td>$\kappa^1$ Cet</td>
<td>G5 V</td>
<td>9.2</td>
<td>0.75</td>
</tr>
<tr>
<td>$\beta$ Com</td>
<td>G0 V</td>
<td>12.4</td>
<td>1.6</td>
</tr>
<tr>
<td>15 Sge</td>
<td>G2 V</td>
<td>13.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Sun</td>
<td>G2 V</td>
<td>25.4</td>
<td>4.6</td>
</tr>
<tr>
<td>$\alpha$ Cen A</td>
<td>G2 V</td>
<td>$\sim$30</td>
<td>5-6</td>
</tr>
<tr>
<td>$\beta$ Hyi</td>
<td>G2 IV</td>
<td>$\sim$28</td>
<td>6.7</td>
</tr>
</tbody>
</table>

2. PENETRATION OF X-RAYS IN PLANETARY PALEO-ATMOSPHERES

We calculate the absorption of X-rays in a CO$_2$ atmosphere within the range of wavelengths covered by ASCA and ROSAT observations: from 1 to 124 Å. As an example, we used the atmospheric profile (P, T) of the present Martian atmosphere and the cross-section for CO$_2$. Independently of the value of the incoming flux, it gives the altitudes at which 1% and 99% of the photons are absorbed at each wavelength. We found that only the shorter wavelengths of the X-rays penetrate down to below 80 km. The energy deposited, integrated over the wavelength domain, was used for the calculation of the energy that is absorbed with in a planetary atmosphere for 3 young solar-type stars at a distance of 1.5 AU is shown in Figure 2. Our calculations show that the early strong X-ray emitted by young stars is absorbed in the upper part of the atmosphere due to the high interaction cross-sections at these wavelengths. Further, dissociative recombination processes from soft X-rays, EUV and UV radiation in planetary atmospheres could be important contributors to the erosion and removal of primordial atmospheres of solar and extrasolar terrestrial planets. We suggest that the high levels of solar ionising radiation will play an important role in the evolution and heating of upper planetary atmospheres as well as ionospheres, resulting in hydrodynamic thermal escape of light atmospheric constituents from the terrestrial planets (e.g. Hunten, 1973, Kasting & Pollack, 1983), which may have been responsible for the removal of large quantities of water from Mars before 3.5 Gyr ago. The much higher solar wind density and flux related to the high X-ray activity of the young Sun will also remove large quantities of atmospheric constituents and water from planets who were not protected by a strong intrinsic magnetic field (e.g. Bauer, 1983, Chassefière, 1997, Lammer et al., 2000, Lammer et al., 2002) and will contribute to the surface heat input and surface sputtering of planetary bodies who have no dense atmosphere like Mercury (Cameron, 1985, Lammer, 1997, Wurz & Lammer, 2002).

![Figure 2. Energy deposit integrated over the wavelength domain of the X-rays as function of altitude for 3 young solar-type stars at a distance of 1.5 AU.](image-url)

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3. ESTIMATIONS OVER THE HISTORY OF THE SOLAR WIND AND ITS MASS LOSS

The high frequency of large Flares observed with EUVE by Audard et al. (1999) in solar proxies such as EK Dra and 47 Cas β could indicate explosive episodic releases of plasma. These would be like the Coronal Mass Ejections (CME’s) observed on the Sun today but stronger and more frequent. Presently, CME’s contribute significantly to the solar wind, about 3% at the cycle minimum and about 10% at the solar maximum (Howard et al. 1985). It is suggested from SOHO observations that the contributions of CME’s to the solar wind are probably higher. Lammer et al. (2000) and Lammer et al. (2002) studied an observed $^{15}$N/$^{14}$N isotope ratio in the atmosphere of Saturn’s large satellite Titan and attributed the isotope enrichment of $^{15}$N compared to $^{14}$N of about 4.5 relative to the terrestrial value to an enhanced solar wind exposure and resulting loss of the lighter constituent. For getting an idea about the early solar wind density one must estimate the solar mass loss rate.

\[
\frac{dM}{dt} = 1.0 \times 10^{-9} P_{\text{rot}}^{-2.5} \left( \frac{M_\text{Sun}}{M_\odot} \right) \]

\( P_{\text{rot}} \) is the daily rotation period of the star and the mass loss is in Sun masses per year. By using the rotation period data of the Sun in Time program stars one gets the evolution of the solar mass loss and the solar wind density with time. One can see from the Figures 3 and 4 that the early solar wind may have been 10000 times denser at 1.0 AU during the time as the Sun reached the main-sequence. One can also see from our study in Figure 5 that the early Sun may have been slightly heavier as it reached the main-sequence. The resulting mass-luminosity relation of the Sun could contribute to a solution of the so-called faint young Sun paradox, which is one of the outstanding problems in understanding the early climates of Earth and Mars. Standard stellar evolution theory predicts a solar luminosity 3.8 Gyr ago of about 75% of its present value (e.g. Gough, 1981). By using the solar standard model, including the maximum possible greenhouse effect one cannot easily explain the Martian valley.

![Figure 3. Modelled mass loss history of the Sun based on the observations of solar-like stars by Wood et al. (2002). The dashed line shows the minimum mass loss rate, the dashed-dotted line the average mass loss and the solid line shows the maximum mass loss rates.](image)

![Figure 4. The history of the solar wind density with an assumption of 6 protons cm$^{-3}$ at present and at 1 AU for the three cases resulting from Figure 3.](image)

![Figure 5. Initial Sun masses based on an integration of the mass loss rates of Figure 3. The studies from young solar proxies suggest that the early Sun could have had a maximum mass of 1.026 M$_{\odot}$.](image)
networks (e.g. Baker, 2001). Even if subsurface sapping of groundwater formed the water channels, the Martian surface temperatures must have been significantly higher than today to allow groundwater to be mobile near the surface. Wilson (1987) has given evidence suggested that main sequence dwarfs lose a significant amount of mass. Pulsation enhanced by rapid rotation may be the driving mechanism of this mass loss. Mass loss models considering the evolution of a 2 solar mass Sun by Guzik et al. (1987) are not consistent with helioseismic observations (Graedel et al., 1991) and climate constraints for terrestrial planets discussed above. The good agreement between solar oscillation frequencies and the solar standard model may limit an enhanced mass loss from the young Sun to the first 0.2 Gyr of solar history (Graedel et al., 1991, Guzik & Cox, 1993). Alternative mass-loss models of solar evolution may also give an explanation of the anomalous depletion of lithium in the Sun and solar-like stars (Hobbs et al., 1989, Boothroyd et al., 1991). An enhanced mass loss of the young Sun as suggested in this paper may remove its outermost lithium rich layers. Former mass losing models, which were developed for the study of habitable zones around solar-like stars, used linear constant mass loss rates (Whitmire et al., 1995a, Whitmire et al., 1995b) since no reliable datasets of solar-like young stars were available. Future work will include our non-linear mass loss model for the study heating effects on planetary environments.

4. CONCLUSION

The observations obtained from solar proxies with different age indicate that the early Sun was much more active than predicted by the standard model. Non-linear mass-losing models according to recent available data should slightly modify the energy output, and may contribute to a solution of the faint young Sun paradox and related problems concerning evolution of atmospheres and climate of terrestrial planets.

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