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The impact of stellar activity on planets

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Abstract. The results of the *Sun in Time* program indicate that the X ray, far ultraviolet and ultraviolet fluxes of the young Sun were significantly higher than today. Similarly, the solar wind may have been much stronger in the past. Such environment of intense energy and particle emissions could have influenced the paleo-atmospheres of Solar System planets and, by extension, the habitability and stability of exoplanets.

Keywords. Sun: evolution, Sun: activity, Sun: rotation, Sun: UV radiation, Sun: solar wind, planets and satellites: general, stars: activity, stars: rotation

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It has long been established that young late-type stars rotate faster than their older counterparts (Skumanich 1972; Soderblom 1982). As a consequence, the interplay between the high rotation rate and the convective motions in the stellar envelope gives rise to high levels of dynamo-generated magnetic activity. From our privileged view of the active Sun and the observation of stars it is found that such activity is manifested through strong high-energy fluxes and particle emissions. The decrease in rotation rate between the 'young' and 'old' stellar populations does not appear to be abrupt but rather a gradual one that follows a power-law relationship of exponent ~ -0.6 as a function of age. Following the correlation between rotation rate and activity, Zahnle & Walker (1982) concluded using *IUE* observations that the UV emissions of late-type stars strongly decrease with increasing stellar age.

Inspired by these findings, the *Sun in Time* program was established to investigate the magnetic evolution of the Sun and associated high-energy emissions across its main sequence lifetime. To do so, a sample of stars within a narrow spectral range (G0 - G5) and well-determined properties (including age) were selected as stellar proxies for the Sun at different stages of its evolution. The five studied stars have ages covering from 130 Myr to 6.7 Gyr. Data obtained with the *ASCA, ROSAT, EUVE, FUSE* and *IUE* satellites, covering the wavelength range between 1 and 170 nm, indicate that the Sun had emissions in X rays, far ultraviolet and ultraviolet that were stronger than today's by factors of 1000 - 100, 60 - 20, and 20 - 0, respectively. Ribas *et al.* (2005) also propose a time-evolution relationship for emissions in the interval 1 - 120 nm. Such relationship indicates that the Sun had high-energy emissions some 2.5 times stronger 2.5 Gyr ago and 6 times stronger 3.5 Gyr ago. Near the ZAMS (age 0.1 Gyr), the Sun could have had fluxes up to 100 times larger than today (albeit during a short period of time).

Besides high-energy radiation, particle emissions are also an integral component of the active Sun. From simple arguments, it is reasonable to assume that the strong X-ray emissions and hot coronal temperatures of young solar analogs are also correlated with more massive stellar winds. Direct detection of such winds has been very elusive but Wood *et al.* (2002) succeeded in estimating indirectly the mass loss rate (i.e., stellar wind) of a number of main sequence stars. The results in that study indicated that the Solar wind may have decreased with time following a power law relationship with an exponent of roughly -2, which would seem to predict a mass loss rate some 1000 times higher than today for the young ZAMS Sun. More recent results (Wood *et al.* 2005), however, question the suitability of an extrapolation back in time to very young ages and suggest a change in regime for an age of about 0.7 Gyr. In any case, it is now clear that the wind of the young Sun could have been some two or three orders of magnitude stronger than today.

These high-energy and particle emissions of the young Sun could have played an important role in the evolution of the atmospheres (and even the surfaces) of the Solar System planets. The evolution of the Martian water inventory is one example. Because of its low gravity and the lack of a protecting magnetic field, Mars is (and has been) subject to strong losses of light atmospheric constituents from thermal and non-thermal processes. Simulations indicate that Mars could have lost a global ocean with a depth of about 10 m from photolysis of the water molecule and subsequent escape of hydrogen to space. The remaining oxygen would have been incorporated into the ground giving its characteristic rusty appearance. A similar process may have occurred in Venus, which could have lost an amount of water comparable to a terrestrial ocean, although results are still inconclusive because of uncertainties with the history of the magnetic field of the planet. In the case of the Earth, its protecting magnetic field and strong gravity have prevented massive evaporation processes from taking place. But the strong UV emissions of the young Sun could have played a role in the development of life, for example, by influencing the abundance of greenhouse gases such as CH_4 and NH_3, both prone to photo-dissociation processes, and by triggering photochemical reactions.

The results of the *Sun in Time* program can also be applied to exoplanets detected around solar-type stars. The most obvious case is that of the so-called Hot Jupiters. In this case, the high-energy emissions of the parent star heat the exosphere of the planet and produce strong thermal loss processes (of hydrogen and other constituents) that could evaporate a significant fraction of the planet's mass (Lammer *et al.* 2003). Such loss processes have indeed been detected observationally (Vidal-Madjar *et al.* 2003).

A logical extension of the study is the investigation of the evolution of high-energy and particle emissions in stars of other spectral types. This is done by using the X-ray flux as an overall proxy for stellar activity. With such scaling and a normalization using the bolometric luminosity, preliminary results suggest that the integrated 1 - 120 nm emissions of early K-type stars are some 3 - 4 times stronger than the emissions of solar-type stars of the same age and in the case or early M-type stars the emissions are larger by factors of 10 - 100. Accounting for these high emissions is critical to understand both the evolution and even the stability of exoplanets orbiting such stars. Because of its immediate application to the design of missions such as *Darwin* and *TPF*, the question of habitability of planets around M-type stars is especially relevant (Segura *et al.* 2005).

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