# Session VIII

# Impact of solar and stellar variability on planetary atmospheres and climate

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# Biological damage due to photospheric, chromospheric and flare radiation in the environments of main-sequence stars

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**Abstract.** We explore the biological damage initiated in the environments of F, G, K, and M-type main-sequence stars due to photospheric, chromospheric and flare radiation. The amount of chromospheric radiation is, in a statistical sense, directly coupled to the stellar age as well as the presence of significant stellar magnetic fields and dynamo activity. With respect to photospheric radiation, we also consider detailed synthetic models, taking into account millions or hundred of millions of lines for atoms and molecules. Chromospheric UV radiation is increased in young stars in regard to all stellar spectral types. Flare activity is most pronounced in K and M-type stars, which also has the potential of stripping the planetary atmospheres of close-in planets, including planets located in the stellar habitable zone. For our studies, we take DNA as a proxy for carbon-based macromolecules, guided by the paradigm that carbon might constitute the biochemical centerpiece of extraterrestrial life forms. Planetary atmospheric attenuation is considered in an approximate manner.

**Keywords.** astrobiology, planets and satellites: general, stars: activity, stars: chromospheres, stars: evolution, stars: flare, stars: late-type

## 1. Theoretical Approach

The centerpiece of all life on Earth is carbon-based biochemistry. It has repeatedly been surmised that biochemistry based on carbon may also play a pivotal role in extraterrestrial life forms, if existent. This is due to the pronounced advantages of carbon, especially compared to its closest competitor (i.e., silicon), which include: its relatively high abundance, its bonding properties, and its ability to form very large molecules as it can combine with hydrogen and other molecules as, e.g., nitrogen and oxygen in a very large number of ways (Goldsmith & Owen 2002).

In the following, we explore the relative damage to carbon-based macromolecules in the environments of late-type main-sequence stars using DNA as a proxy. We focus on the effects of both photospheric and chromospheric radiation and comment on the significance of flare activity. Previous studies indicating the importance of UV radiation concerning the suitability of extrasolar planets for the existence of life and biological evolution has been given by, e.g., Cockell (1999), Guinan & Ribas (2002), Guinan *et al.* (2003), Ribas *et al.* (2005), Buccino *et al.* (2006), and Guinan & Engle (2009). With respect to the Sun-Earth system, a detailed investigation about the UV effects on biological systems has been

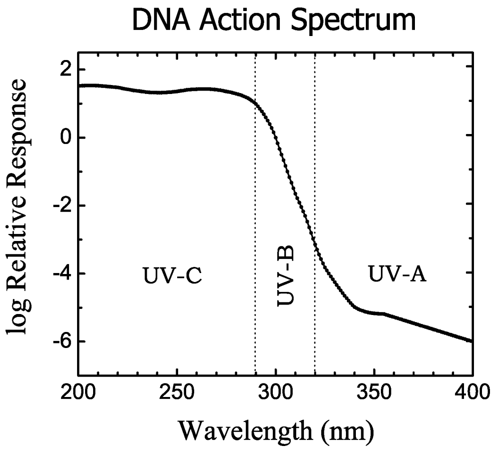

**Figure 1.** DNA action spectrum following Horneck (1995) and Cockell (1999).

**Table 1.** Stellar Data and Habitable Zones

| Sp. Type<br>... | $T_{\rm eff}$<br>(K) | $R_*$<br>($R_\odot$) | $L_*$<br>($L_\odot$) | HZ-i (gen.)<br>(AU) | HZ-i (con.)<br>(AU) | HZ (E.)<br>(AU) | HZ-o (con.)<br>(AU) | HZ-i (gen.)<br>(AU) |
|---|---|---|---|---|---|---|---|---|
| F0 V | 7200 | 1.62 | 6.33 | 1.826 | 2.251 | 2.516 | 3.222 | 3.710 |
| F5 V | 6440 | 1.40 | 3.03 | 1.370 | 1.614 | 1.740 | 2.316 | 2.741 |
| G0 V | 6030 | 1.12 | 1.49 | 1.002 | 1.152 | 1.220 | 1.657 | 1.991 |
| G5 V | 5770 | 0.95 | 0.90 | 0.799 | 0.904 | 0.948 | 1.302 | 1.580 |
| K0 V | 5250 | 0.83 | 0.47 | 0.604 | 0.665 | 0.685 | 0.961 | 1.188 |
| K5 V | 4350 | 0.64 | 0.13 | 0.342 | 0.359 | 0.363 | 0.525 | 0.670 |
| M0 V | 3850 | 0.48 | 0.05 | 0.207 | 0.213 | 0.213 | 0.313 | 0.407 |

Abbreviations: con. = conservative, gen. = general, E. = Earth-equivalent

pursued by Diffey (1991). This line of studies also includes the detailed modeling of the atmospheric attenuation of UV (especially due to an Earth-type ozone layer, e.g., Segura *et al.* 2003), photobiological effects and the effects of UV on biomolecules, particularly DNA, and microorganisms.

We consider the radiative effects on DNA by applying a DNA action spectrum (Horneck 1995) that shows that the damage is strongly wavelength-dependent, increasing by more than seven orders of magnitude between 400 and 200 nm (see Fig. 1). The different regimes are commonly referred to as UV-A (400–320 nm), UV-B (320–290 nm), and UV-C (290–200 nm). The test planets are assumed to be located in the stellar habitable zone (HZ). Following the analyses by Kasting *et al.* (1993) and Underwood *et al.* (2003), we distinguish between the conservative and generalized HZ (see Table 1). For stars of different spectral types, we also define planetary Earth-equivalent positions given as $R_{\rm E} = \sqrt{L/L_\odot}$. For the conservative HZ, the inner limit of habitability is given by the onset of water loss that occurs in an atmosphere warm enough to have a wet stratosphere, resulting in a gradual loss of water by photodissociation and subsequent hydrogen loss to space. Moreover, the outer limit of habitability is given by the first $CO_2$ condensation where for a surface temperature of 273 K, $CO_2$ begin to form. Concerning the general HZ, the inner limit of habitability is given by the runaway greenhouse effect.

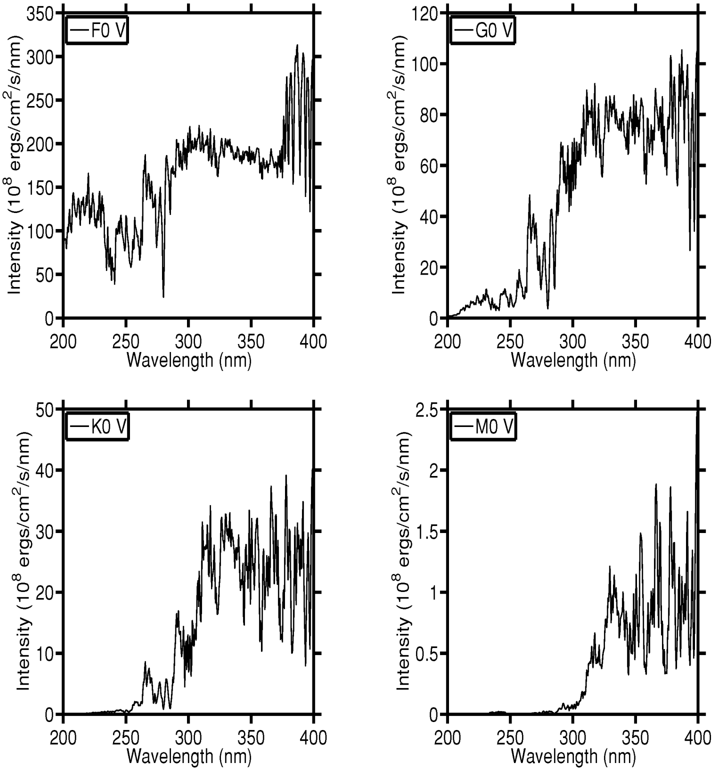

**Figure 2.** Kurucz models for the F0 V, G0 V, K0 V, and M0 V stars used in this study. For the sake of display, the spectral resolution has artificially been decreased to $\lambda/\Delta\lambda \simeq 300$, implemented by running means. Note the different scales of the $y$-axes.

In the following, we will present our results for different positions of Earth-type planets while considering both stellar photospheric and different levels of chromospheric radiation. We will also discuss the likely consequences of stellar flares.

## 2. Stellar Photospheric Radiation

For our study we employ a detailed consideration of stellar photospheric radiation for the UV-A, UV-B, and UV-C spectral regimes. The adopted target stars are: F0 V, F5 V, G0 V, G5 V, K0 V, K5 V, and M0 V with effective temperatures of 7200, 6440, 6030, 5770, 5250, 4350, and 3850 K, respectively (see Table 1). As stellar surface gravity, log g = 4.5 (cgs) is used, and the microturbulence broadening is considered. We make use of the spectral models by R. L. Kurucz which take into account millions or hundred of millions of lines for atoms and molecules; see Castelli & Kurucz (2004) and related publications for details.

Note that it is virtually impossible to display the complete photospheric spectra of our target stars owing to the richness in their spectra features, particularly the very large number of narrow lines due to the large number of elements and line levels taken into account. Thus, to provide a tutorial comparison between the different spectra in the 200 to 400 nm wavelengths regime, we created “fake spectra” obtained by installing a running mean. This has been done by smoothing the spectra for a length of 1 nm, corresponding to artificially decreasing the spectral resolution to $\lambda/\Delta\lambda \simeq 300$ (see Fig. 2).

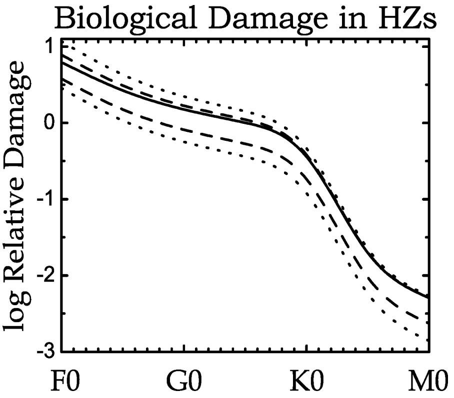

**Figure 3.** Biological damage to DNA for a planet (no atmosphere) at an Earth-equivalent position (solid line), and at the inner and outer limits of the conservative (dashed lines) and generalized HZ (dotted lines).

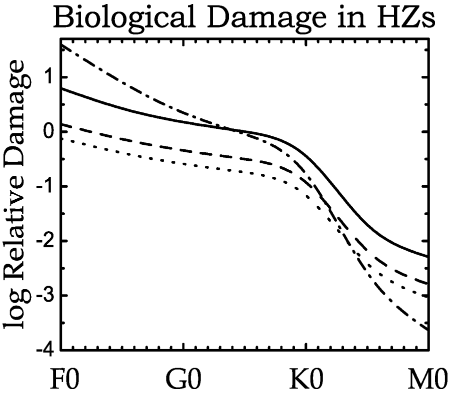

**Figure 4.** Biological damage to DNA for a planet at an Earth-equivalent position without an atmosphere (solid line), and an atmosphere akin to Earth 3.5 Gyr ago (dashed line) and today (dotted line). The dash-dotted line refers to a planet without an atmosphere at 1 AU from its host star, irrespectively of the position of the stellar HZ.

As part of our models, we also consider the effects of attenuation by an Earth-type planetary atmosphere, which allows us to estimate wavelength-dependent attenuation coefficients appropriate to the cases of Earth as today, Earth 3.5 Gyr ago, and no atmosphere at all (Cockell 2002). Improved simulations of the effects of planetary atmospheres must be based on the detailed treatment of atmospheric photochemistry, including the build-up and destruction of possible ozone layers.

Our results are presented in Figs. 3 and 4. They show the relative damage to DNA due to different types of main-sequence stars encompassing spectral spectral types between F0 and M0 normalized to today's Earth. We consider Earth-type planets at the inner and outer edge of either the conservative or generalized HZ as well as planets of different atmospheric attenuation. We obtained the following findings: (1) All main-sequence stars of spectral type F to M have the potential of damaging DNA due to UV radiation. The amount of damage strongly depends on the stellar spectral type, the type of the planetary atmosphere and the position of the planet in the HZ; see Cockell (1999) for previous work. (2) The damage to DNA for a planet in the HZ around an F-star (Earth-equivalent distance) due to photospheric radiation is significantly higher (factor 5) compared to

**Table 2.** Increase in Biological Damage due to Chromospheric Radiation

| Sp. Type | log $F_{\rm basal}$ | Inact. Chr. | Act. Chr. |
|---|---|---|---|
| F0 V | 5.890 | ... | ... |
| F5 V | 5.755 | ... | 1.08 |
| G0 V | 5.590 | ... | 1.12 |
| G5 V | 5.486 | ... | 1.16 |
| K0 V | 5.316 | ... | 1.4 |
| K5 V | 4.879 | 1.6 | 6.7 |
| M0 V | 4.498 | 2.6 | 17 |

Note: $F_{\rm basal}$ is given in ergs cm$^{-2}$ s$^{-1}$.

planet Earth around the Sun, which in turn is significantly higher than for an Earth-equivalent planet around an M-star (factor 180). (3) We also found that the damage is most severe in the case of no atmosphere at all, somewhat less severe for an atmosphere corresponding to Earth 3.5 Gyr ago, and least severe for an atmosphere like Earth today, as expected. Moreover, any damage due to photospheric stellar radiation is mostly due to UV-C. The relative importance due to UV-B is relatively small, and damage due to UV-A is virtually nonexistent (see Cuntz *et al.* 2010 for details).

## 3. Effects by Stellar Chromospheres and Flares

The study of chromospheric radiation and its effects on circumstellar environments, including hosted planets, has been the focus of a large array of research projects. In our study, we added chromospheric emission as exemplified by Mg II $h$+$k$ at 2803, 2796 Å to the photospheric emergent radiation. Previous studies including those associated with the “Sun in Time” project (see Sect. 4), have shown that for F and G-type stars, the photospheric UV continua are typically dominant relative to any chromospheric contributions implying that chromospherically induced biological damage for planets hosted by these stars will be insignificant.

The situation is, however, decisively different for K and M dwarfs. Any of these stars, including inactive stars, show noticeable chromospheric emission. Previous research (e.g., Cuntz *et al.* 1999, and references therein) point to the existence of two-component stellar chromospheres with the non-magnetic component (prevalent in case of old stars; see Sect. 4) heated by acoustic waves and the magnetic component heated by magnetic energy dissipation. The acoustically heated chromospheric component is usually also referred to as basal component $F_{\rm basal}$, noting that the radiative energy flux ranges from $3 \times 10^4$ (M dwarfs) to $8 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ (F dwarfs); see Rutten *et al.* (1991).

Table 2 depicts the enhancement of biological damage due to chromospheric radiation relative to photospheric radiation for stars between spectral type F0 V and M0 V. This study has been pursued for stars with both basal (inactive) and significantly increased (active) chromospheric emission. For the latter, we considered an increase in chromospheric emission by a factor of 10, which for solar-type stars amounts to the maximal chromospheric emission observed in regard to fast-rotating (i.e., young) stars (Vilhu & Walter 1987). Our results show that for stars with basal chromospheric emission, chromosphere-induced biological damage only occurs for stars of spectral type mid-K and later, whereas for stars with relatively high chromospheric emission, chromosphere-induced biological damage can also be found in the environments of very late G-type and early K-type stars.

Other important agents for the delivery of highly energetic radiation, especially UV-C, are flares (e.g., Pettersen 1989, Redfield *et al.* 2002, Hawley *et al.* 2003, Robinson *et al.* 2005). Note that flare activity is most pronounced in K and M-type stars. It has also the potential of (partially) stripping the planetary atmospheres (e.g., Kulikov *et al.* 2007, Lammer *et al.* 2008), which is especially relevant for close-in planets, particularly planets located in the HZs of K and M-type stars (see Table 1). The maximal near-UV and far-UV radiative energies of flares are akin or larger than those of an active stellar chromosphere, although flare energy is typically provided episodically rather than continuously. Therefore, the results given in Table 2 may also be applicable to flaring as a first approximation, except that the actual biological damage due to flares might be enhanced further by a factor of 5 to 10 due to the possible damage (i.e., evaporation) of the planetary atmosphere.

Nonetheless a more detailed analysis of flare-related effects is still required, which should also incorporate a detailed treatment of planetary atmospheric photochemistry, including the build-up and destruction of ozone as pointed out by Segura *et al.* (2003, 2005) and others.

## 4. Summary: The 'Sun in Time' Project and Its Biology Expansion

We attempted to quantify the biological damage expected to occur in the environments of late-type main-sequence stars due to photospheric, chromospheric and flare radiation. Stellar photospheric radiation has been considered by utilizing spectral models given by R. L. Kurucz and collaborators, which take into account millions or hundred of millions of lines for atoms and molecules; see, e.g., Castelli & Kurucz (2004). Concerning chromospheric radiation, we considered models exemplifying basal chromospheric emission (e.g., Schrijver 1987, Rutten *et al.* 1991) and significantly increased chromospheric emission (e.g., Vilhu & Walter 1987). Note that basal emission is usually attributed to acoustic heating in the limiting case of magnetic energy dissipation to be small or negligible. Detailed models of one-component and two-component chromospheric heating for late-type stars have been given by, e.g., Buchholz *et al.* (1998), Cuntz *et al.* (1998, 1999), Fawzy *et al.* (2002), and Rammacher & Cuntz (2003).

It is highly noteworthy that there is a deeper underlying connection between the level of chromospheric heating and emission, on one hand, and more fundamental stellar physics involving processes concerning the stellar interior and phenomena associated with stellar winds, on the other hand. In case of the Sun, this connection has been explored in detail by, e.g., Guinan & Ribas (2002), Guinan *et al.* (2003), Ribas *et al.* (2005), and Güdel (2007). A highly crucial question, as gauged by its implied planetary, biological and societal percussions, is whether the Sun has always been a relatively inactive star or, in contrast, has experienced some periods of stronger magnetic activity.

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 of different ages, Skumanich (1972), Simon *et al.* (1985), Charbonneau & MacGregor (1993), MacGregor & Charbonneau (1994) and others showed that the Sun loses angular momentum with time via magnetized winds (magnetic breaking), thus leading to a secular increase in its rotational period (e.g., Durney 1972, Keppens *et al.* 1995). This rotation slowdown is well fitted by a Skumanich-type power law roughly proportional to $t^{-1/2}$ (e.g., Skumanich 1972, Soderblom 1982, Ayres 1997). In response to slower rotation, the solar dynamo strength diminishes with time, causing the Sun's high energy emissions and mass loss also to undergo significant decreases.

A direct consequence of this behavior concerns the generation of photospheric and chromospheric magnetic flux, which constitute the physical reason for the varying level of chromospheric heating and associated generation of UV and EUV radiation with stellar age or rotation period (e.g., Mathioudakis *et al.* 1995). Consequently, it is thus also possible to relate the photospheric magnetic flux to the stellar rotation period (Noyes *et al.* 1984; Marcy & Basri 1989; Montesinos & Jordan 1993; Saar 1996a) as well as to the emergent chromospheric emission (Saar & Schrijver 1987; Schrijver *et al.* 1989; Montesinos & Jordan 1993; Saar 1996b; Jordan 1997).

The acquisition, interpretation and modeling of data for any of these phenomena is the main focus of the "Sun in Time" project (originally solely focused on G0–G5 V stars) pursued under the leadership of E. F. Guinan, which relates, in a statistical sense, the strength of the emergent UV, EUV and X-ray flux and the stellar mass loss rate to the stellar age. More recently, this project has been extended to K-type and M-type dwarfs with the latter element of study now referred to "Living with a Red Dwarf". The critical ultimate connection to be targeted in the future, see Guinan & Engle (2009) for the dissemination of various intermediate results, is to relate the type and strength of stellar activity for different types of stars to planetary climatology, particularly for planets in stellar HZs, and to exosolar planetary biology, if existing.

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