Evolution over Time of Magnetic Dynamo Driven UV & X-ray Emissions of dG-M Stars and Effects on Hosted Planets

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ABSTRACT

The evolution over time of the magnetic activity and the resulting X-ray and UV coronal and chromospheric emissions of main-sequence dG, dK, and dM stars with widely different ages are discussed. Young cool stars spin rapidly and have correspondingly very robust magnetic dynamos and strong coronal and chromospheric X-ray – UV (XUV) emissions. However, these stars spin-down with time as they lose angular momentum via magnetized winds and their magnetic generated activity and emissions significantly decrease. Studies of dK–dM stars over a wide range of ages and rotations show similar (but not identical) behavior. Particular emphasis is given to discussing the effects that XUV emissions have on the atmospheres and evolution of solar system planets as well as the increasing number of extrasolar planets found hosted by dG–dM stars. The results from modeling the early atmospheres of Venus, Earth and Mars using recently determined XUV irradiances and inferred winds of the young Sun are also briefly discussed. For example, the loss of water from juvenile Venus and Mars can be explained by action of the strong XUV emissions and robust winds of the young Sun. We also examine the effects of strong X-ray and UV coronal and chromospheric emissions (and frequent flares) that dM stars have on possible planets orbiting within their shrunken habitable zones (HZs) – located close to the low luminosity host stars (HZ $\leq$ 0.4 AU). Dwarf M stars make interesting targets for further study because of their deep outer convective zones (CZs), efficient dynamos, frequent flares and strong XUV emissions. Furthermore, a large fraction of dM stars are very old (>5 Gyr), which present intriguing possibilities for the development of highly advanced modes of intelligent life on planets that may orbit them.

Key words: UV astronomy; stars: late-type, activity, evolution, rotation

1. Introduction

Over the last 15 years, as part of the "Sun in Time" program, we have been carrying out an in-depth study of solar-type stars with different ages, rotation rates and correspondingly vastly different levels of magnetic activity. The main goals of this program are to investigate the solar dynamo, and to determine the dependence of coronal X-ray/EUV emissions and chromospheric/transition region (TR) FUV/UV emissions on stellar age and rotation. The latter goal was expanded to include the contruction of XUV spectral irradiance tables for the Sun over its main sequence lifetime (e.g. Guinan et al. 2003; Ribas et al. 2005). These spectral XUV irradiances are very important in studies of the effects of the young Sun's increased radiation on paleoplanetary atmospheres and environments. We use a homogeneous sample of ∼15 single, nearby dG0–5 stars as proxies for the Sun (and solar-type stars), covering ages from ∼100 Myr to 8.5 Gyr. The ages of the younger program stars are inferred from memberships in various clusters / moving groups, while the ages for the older stars are secured from isochronal fits. The rotation periods are obtained chiefly from ground-based photometry (star spot modulation) or from chromospheric Ca II rotationally induced variability. Excellent relationships are found among rotation, age and activity (see Guinan et al. 2003). The program stars have been observed from X-ray–UV using *ROSAT*, *ASCA*, *Chandra*, *XMM*, *EUVE*, *FUSE*, *IUE* and *HST*.

The strength of our sample is its homogeneity. In essence, we use a ∼1 $M_\odot$ star as a laboratory to study the effects of the stellar dynamo (with similar convective zone (CZ) depths) by varying the only free parameter, P_{rot}. Our studies have shown that the Sun's magnetic field has steadily declined as its rotation slowed due to magnetic breaking. Also, the study of the young Sun's (as well as other dG stars) XUV fluxes using solar proxies reveals unprecedented diagnostics for the state of the younger solar system and the physics of the much more active early Sun (Ayres et al. 1996; Guinan et al. 2003; Ribas et al. 2005). Fig. 1 shows a plot of rotation period vs. stellar age for most of our "Sun in Time" sample, with a power law fit, showing the spin-down of the Sun and other solar-type stars with age. Fig. 2 shows the related decrease in X-ray luminosity (L_x) with age for the "Sun in Time" sample. As shown in these figures, the young Sun was rotating over 10x faster than the present Sun and had correspondingly high (5–1000x) levels of XUV coronal and chromospheric emissions. Most of the observed ranges in L_x for the older, less active stars shown in Fig. 2 arise from solar-like activity cycles. Some results of the "Sun in Time" program have been summarized by Güdel et al. (1997), Guinan et al. (2003), Guinan & Ribas (2004) and Ribas et al. (2005).

The "Sun in Time" program also bears on the crucial question of the influence of the young Sun's strong XUV emissions on the developing planetary system – in particular on the photochemical and photoionization evolution of early planetary atmospheres. The constructed spectral irradiance tables are of interest to researchers in paleoplanetary atmospheres and for studies on the atmospheric evolution of the large number of extrasolar planets found orbiting other G-type stars. The irradiance

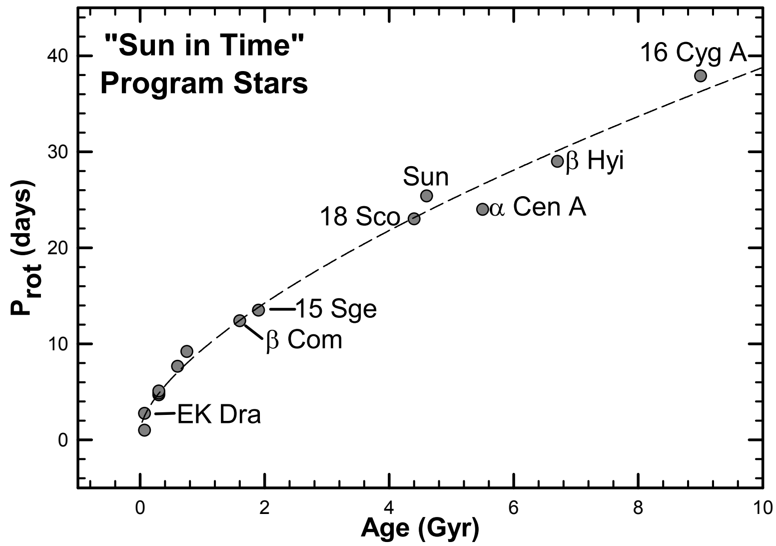

Figure 1: Plot showing the increase in P_{rot} for dG0–5 stars with increasing age. This spin-down with age arises from magnetic breaking from angular momentum loss via magnetized winds.

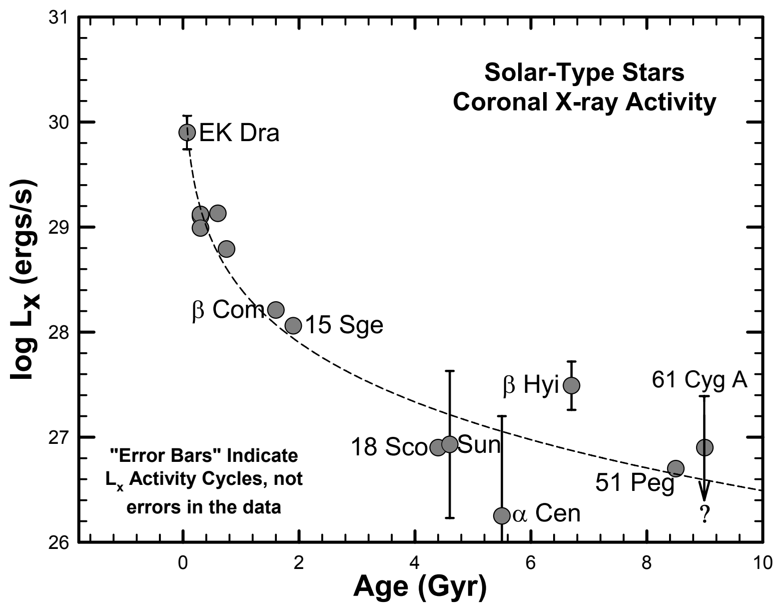

Figure 2: The variation of X-ray luminosity (L_x) for solar-type dG0–5 stars are shown and plotted against age. The ranges in L_x for the Sun and other older solar-type stars arise mainly from activity cycles.

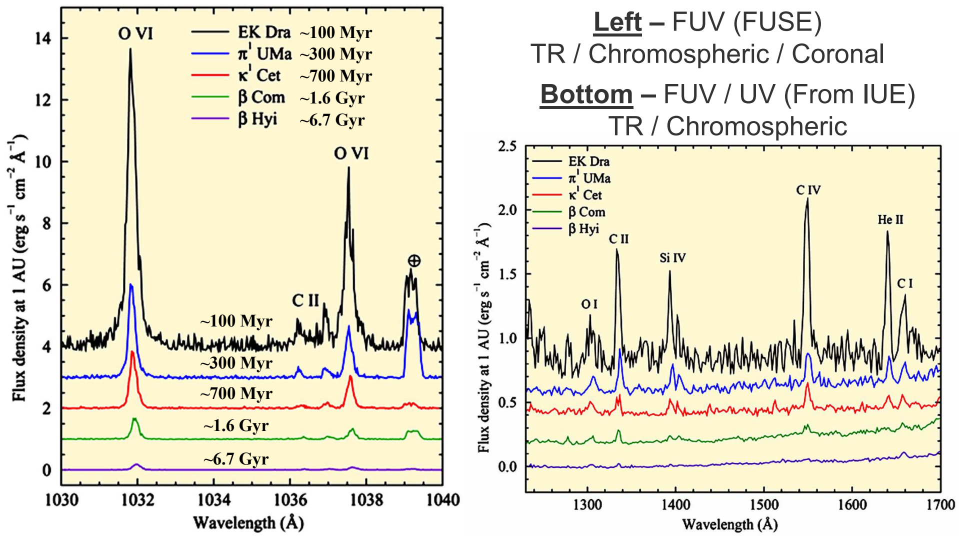

Figure 3: Plots of flux density at 1 AU for the *FUSE* O VI (1030–1040Å) region (left) and the FUV–UV 1200-1700Å region from *IUE* low dispersion *SWP* spectrophotometry (right). As shown in the figures the flux densities decrease rapidly with stellar age. The stars are plotted from top to bottom in order of increasing age and decreasing activity.

data have been published by Ribas et al. (2005) and examples in the FUV/UV region are given in Fig. 3. As shown, there are dramatic decreases in the FUV (*FUSE*) and FUV/UV (*IUE*) emission line strengths (and irradiances) as the star loses angular momentum and spins down with age. Fig. 4 shows the averaged XUV irradiance changes over time for the Sun and other solar-type (dG0–5) stars from solar proxies of different ages. The plot illustrates how emissions associated with hotter plasmas diminish more rapidly as the stars rotate slower with age. The coronal X-ray/EUV emissions of the young main sequence Sun were approximately 100–1000x stronger than the present Sun. Similarly, the TR and chromospheric FUV & UV emissions of the young Sun are 10–100x and 5–10x stronger, respectively, than at present. Also shown in Fig. 4 is the slow increase ($\sim$8%/Gyr) in the bolometric luminosity of the Sun over the past 4.6 Gyr. Over this time, the Sun's luminosity increased from $\sim$0.7 $L_\odot$ to 1.0 $L_\odot$. This change in solar luminosity arises from the acceleration of nuclear fusion in its core that causes its radius and surface temperature to slowly increase with time.

We have been collaborating with planetary scientists and astrobiology groups to study the effects of the young Sun's (and other dG0–5 stars) strong XUV irradiance on the loss of water from Mars and its implications for the oxidation of the Martian soil (Lammer et al. 2003). It has been assumed, from topographic and geological studies, that Mars was originally warmer and much wetter than at present, and likely possessed a $\sim$1 bar atmosphere. Lammer et al. considered ion pick-up sputtering, as

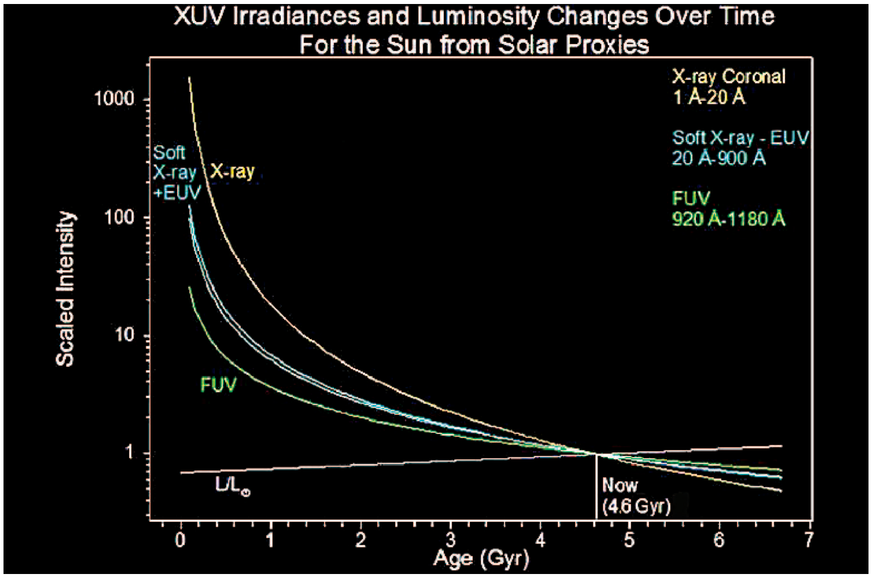

Figure 4: The smoothed XUV spectral irradiances of solar-type stars for three spectral intervals plotted against age. The flux scales were normalized to unity at the Sun's age. Also shown is the variation of bolometric solar luminosity ($L/L_\odot$) over time, where $L_\odot = 1$ is the luminosity of the present 4.6 Gyr Sun ($L_\odot$).

well as dissociative recombination processes. 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 $\geq$12 m. 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. For this study it has been assumed that, for the first billion years, Mars had a hot liquid iron core and, through rotation, possessed a significant magnetic field and resulting magnetosphere. This magnetosphere essentially protected the early Martian environment from the combination of high levels of XUV radiation and strong winds of the younger Sun that would have otherwise removed its atmosphere. However, Mars is a smaller, less massive planet than the Earth, and lost heat at a faster rate. Thus its iron core solidified $\sim$1 billion years after the planet's formation. Without the magnetic field, the outer Martian atmosphere was exposed to the ionizing effects and strong winds of the early Sun, and thus partially eroded. Photolysis of water ensued, with a preferential loss of the lighter Hydrogen over the heavier Oxygen. The loss of water and water vapor from the atmosphere resulted in a greatly diminished Greenhouse Effect and a rapid cooling of the lower Martian atmosphere. This rapid cooling (dropping below the freezing point of water) permitted some water to remain behind, possibly as permafrost trapped below the Martian soil. This scenario is illustrated in Fig. 5.

A recent study (Kulikov et al. 2006) has been published using solar-proxy data

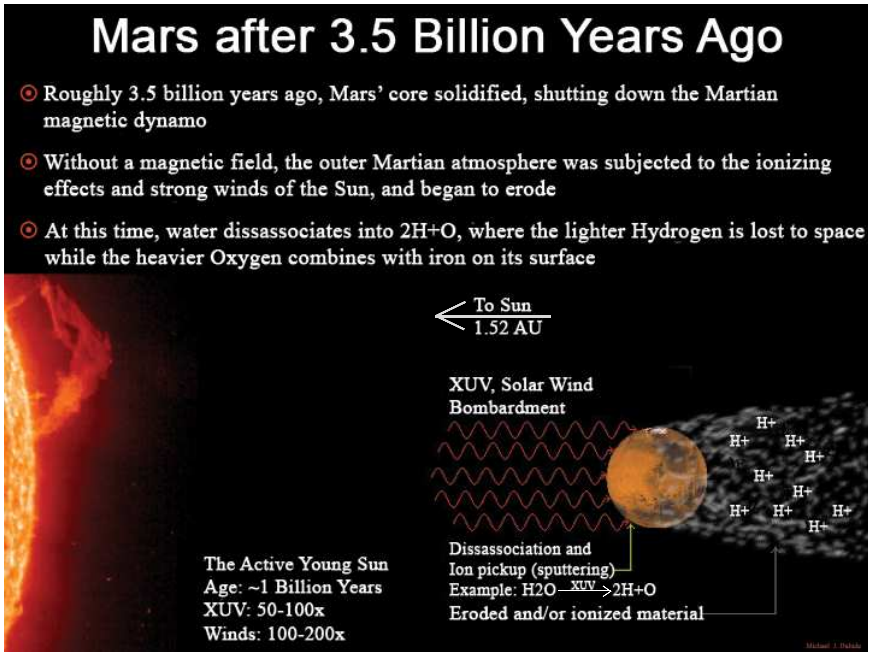

Figure 5: Cartoon depicting the early evolution and ensuing erosion/loss of the Martian atmosphere. (Based on Lammer et al. 2003)

(from Ribas et al. 2005 and Wood et al. 2002; 2005) to study the atmosphere and water loss from early Venus. This study shows that water on early Venus (only 0.71 AU from the Sun) was essentially all lost during the first $\sim$0.5 Gyr after its formation from the vigorous action of strong (massive) winds and high XUV fluxes from the young Sun. In another study, by Grießmeier et al. (2004), "Sun in Time" irradiance date were used to investigate the atmospheric loss of extrasolar planets resulting from XUV heating, which can lead to the evaporation of "Hot Jupiters."

2. Extension of the "Sun in Time" Program to dK–dM Stars

The discovery of extrasolar planets (now 200+ planets) orbiting mostly main-sequence dG, dK, and dM stars during the last decade has motivated the expansion of the "Sun in Time" program to include cooler, lower luminosity but very numerous dK and dM stars. Also, with the upcoming extrasolar planet search and study space missions such as *CoRot*, *Kepler*, *SIM* and, in a decade, *Darwin/TPF*, thousands of additional extrasolar planets are expected to be found. Also, with *CoRot* and *Kepler* it will even be possible to discover Earth-size planets orbiting within the circumstellar liquid water habitable zones (HZs) of the host stars.

The goals of this investigation are similar to the original "Sun in Time" program – *1)* Modeling of dK–dM stars to understand magnetic activity and dynamo energy generation in low mass stars with very deep CZs and *2)* Constructing XUV spectral irradiance tables covering dK–dM stars with a wide range of ages. The selected program stars (∼15 nearby dM0–5 stars) have well determined parallaxes, colors, spectral types and most have observations of age-sensitive measures such as UVW space motions, L_x, Mg II $h+k$ and Ca II $H+K$ emission fluxes.

This study, besides improving (and testing) our understanding of magnetic-related phenomena in cool stars, will help to identify and characterize dK & dM stars that have planets suitable for life. Because of their high space densities, dK stars, and especially dM stars, will be common targets of extrasolar planet search missions. Also, their low masses and small radii make them attractive targets for planet hunting using radial velocity, astrometric, and transit eclipse methods. dM stars in particular make interesting targets for exobiology. As shown in Fig. 6, the liquid water circumstellar HZs for Earth-like planets depend strongly on the luminosity of the host star (see Kasting & Catling 2003). The temperature of the planet depends on the luminosity of the host star, and the planet's distance ($1/r^2$) from the star. Also important are the planet's albedo and greenhouse gas heat trapping contributions. As shown in Fig. 6, because of the low luminosities of dM stars, their HZs are located quite close to the central star (≤0.4 AU). This makes the hypothetical HZ planet around a dM star more strongly influenced by stellar flares, winds, and plasma ejection events (Coronal Mass Ejections = CMEs) that are frequent in young dM stars (e.g. Kasting et al. 1993; Lammer et al. 2006). Also, because of the long lifetimes of dM stars (>50 Gyr), it might be possible for life on a planet in the HZ to be much more evolved (and advanced?) than ourselves. In the following section we focus on our new program to study the magnetic evolution and XUV fluxes of dM stars. This program is called "Living with a Red Dwarf."

3. "Living with a Red Dwarf" Program: Magnetic Dynamos, FUV & X-ray Emissions of dM stars

The major aims of the "Living with a Red Dwarf" program are to understand the magnetic activity, dynamo structure and plasma physics, as well as determining the X-ray/FUV spectral irradiances of dM stars with widely different rotations, ages and, therefore, greatly different corresponding levels of magnetic activity. The program stars are limited to spectral types of dM0–5 and cover a wide range of P_{rot} (<0.5 – 200d), ages (<0.1 – ∼13 Gyr), and activity levels (e.g. log L_x: ∼25.5 – 29.5 ergs/s). This work complements ongoing related programs being carried out on main sequence dG–dK stars (e.g. Guinan et al. 2005; Lakatos et al. 2005). Moreover, this program is a further important step in understanding the linkage between magnetic energy generation and propagation (from stellar dynamo activity) and emission losses in the stellar chromosphere, TR, and corona (e.g., Ulmschneider et al. 1999; Rammacher & Cuntz 2003) of stars with very deep convective envelopes. As part of this program we are carrying out high precision photometry to determine rotation periods and starspot coverages. Also, we are extensively utilizing NASA/ESA X-ray–UV archival data, and have several active programs/proposals to obtain further *FUSE* and *XMM* observations to fill in the parameter space of age/rotation/activity for our dM star sample.

For example, the *FUSE* FUV spectral region (920–1180Å) contains important diagnostic emission lines that can be used to characterize the energy transfer and atmospheric structure while the ratio of C III 977/1175Å fluxes provides valuable information about the TR electron pressure (see Guinan et al. 2003). These programs have also become important for gauging the FUV emissions of these stars (mostly contributed by the H I Lyman series, C III 977/1175Å, and O VI 1032/1038Å emissions) that are critical to assess the photochemical and photoionization evolution of planetary atmospheres and ionospheres and the possible development of life on extrasolar planets (Kasting 1997; Guinan & Ribas 2002; Kasting & Catling 2003; Guinan et al. 2003; Ribas et al. 2005).

The characterizations of the XUV irradiances of dM stars are important because dM stars comprise >70% of stars in the solar neighborhood (and probably in the Galaxy) and have extremely long (>50 Gyr) lifetimes. A fraction of these dM stars may host planets within their circumstellar HZs, located nearby (≤0.4 AU) the host star. On one hand, the frequent flaring of dM stars (e.g. see Güdel et al. 2003) and possible tidal locking of close-in planets (Joshi et al. 1997) could challenge the early development of life on a planet located in their shrunken, close-in circumstellar liquid water HZs. On the other hand, were life to form, the longevities of dM stars would be favorable to the development of advanced modes of intelligent life. Although dM stars have not been specifically targeted in major extrasolar planet searches, so far planets have been discovered orbiting 3 nearby dM stars (IL Aqr, GJ 581, and GJ 424). In fact, two of the three planets orbiting IL Aqr are located within the star's HZ – one of them is a "Super-Earth" (Rivera et al. 2005). Moreover, theoretical studies by Boss (2006) predict the rapid formation of "Super Earths" around dM stars indicating that Earth–like planets hosted by dM stars could be numerous. More recently, several additional dM stars in the direction of the galactic bulge have been found, from *HST/ACS* photometry, to show transit eclipses arising from Jupiter-size planets (Sahu et al. 2006). Interestingly, these extrasolar planets orbit with ultra-short periods ($P_{orb} < 1$ day).

Because of their deep outer CZs, dM stars have very efficient magnetic dynamos and, consequently, f_{XUV}/f_{bol} values of 10^2–10^4 higher than solar-type dG stars of comparable ages. Thus, possible Earth-like planets orbiting within the shrunken HZs near to the dM star host will receive enhanced XUV radiation relative to their incident bolometric irradiances. This could have interesting and significant photochemical and photoionization effects on the outer atmospheres of hosted HZ planets. On the other hand, as shown in Fig. 7, dM stars are cool and have no significant photospheric UV–NUV fluxes at wavelengths shorter than ∼2500Å. Thus, their NUV fluxes are far below those of dG and early dK stars. An excellent summary appraising the habitability of planets hosted by dM stars is given by Tarter et al. 2006.

4. Initial Results: Nuclear and Magnetic Evolution of dM Stars

Unlike more massive and luminous dG and early dK stars, the nuclear reaction rates in the cores of dM stars are very slow, resulting in their low luminosities ($L \leq 0.06\ L_\odot$) and extremely long main sequence lifetimes ($\tau > 50$ Gyr). As shown in Fig. 8, the luminosities of dM stars are essentially constant over tens of billions of years after their arrival on the main sequence. For this reason, their HZs remain fixed over eons of time, ensuring a stable energy source for a possible hosted planet. By contrast, stars like the Sun undergo significant changes in luminosity on timescales of billions of years, causing their HZs to move slowly outward over time. For example, in ∼1 billion years, our Earth will no longer lie within the then more luminous Sun's HZ, resulting in the commencement of the runaway Greenhouse Effect on Earth, in which the oceans begin to evaporate.

Given their low surface temperatures, dM stars radiate predominantly in the near IR, and they have essentially no photospheric continuum flux < ∼2500Å (see Fig. 7). However, because of their deep CZs and resulting efficient magnetic dynamos, dM stars have strong magnetic dynamo generated coronal/TR/chromospheric FUV/UV emissions with XUV surface fluxes exceeding those of dG stars with comparable ages. Similar to the results of the "Sun in Time" program, young dM stars rotate rapidly and have correspondingly strong dynamo-generated XUV emissions. For example, Fig. 9 shows the decrease in FUV O VI emission strengths between AD Leo (100 Myr) and Proxima Cen (5.8 Gyr). Young dM stars are also well known for strong and frequent high energy flares, which emit strong XUV radiation. Moreover, unlike dG stars, dM stars' magnetic related activity appears to persist for longer times (a few billion years). Even older dM stars are known to flare, examples being Proxima Cen (∼5.8 Gyr) and Barnard's Star (∼9 Gyr). A summary of some of the more important characteristics of dM stars are given below, as well as some implications for planets orbiting close to them.

Summary of Important dM Star Characteristics and Impacts on Earth-like planets within their Habitable Zones

- dM stars have long lifetimes (>50 Gyr) and nearly constant luminosities (see Fig. 8).
- dM stars are ubiquitous, comprising >70% of stars in the solar neighborhood and have low masses ($<0.5\ M_\odot$), temperatures (<3900 K) and luminosities ($\leq 0.06\ L_\odot$).
- Unlike solar-type stars, dM stars have essentially no photospheric continua in the UV (<2500Å), because of their low temperatures (see Fig. 7).
- dM stars have deep outer CZs, very efficient magnetic dynamos and, consequently, resulting strong coronal X-ray, transition region FUV & chromospheric FUV–UV emissions. For example, the ratio of L_x to total bolometric luminosity for dM stars is, on average, 10^3 times that of solar-type stars. (e.g. $[L_x/L_{bol}]_{dM} \approx 10^{-3}$ and $[L_x/L_{bol}]_\odot \approx 10^{-6}$)

- The only source of XUV radiation of dM stars is from dynamo-generated coronal/chromospheric emissions and related flares.
- dM stars have frequent flares even up to relatively old ages. For example, Proxima Cen ($\tau \approx 5.8$ Gyr) has about one large flare per day.
- Theoretical studies by Boss (2006) indicate that "Super Earths" can easily form in the proto-planetary disks of dM stars. Planets hosted by dM stars should be at least as common as those hosted by solar-type stars. Even without much effort, several dM stars have been found to host planets (see text).
- dM stars (dM0–5) have HZs located very close to the host star at $\sim$0.1AU $<$ HZ $\leq$ 0.4AU. (see Fig. 6)
- Although the bolometric irradiance levels within the shrunken HZs of dM stars would be comparable to those received on Earth from the present Sun, the dynamo-generated coronal-chromospheric XUV line emissions at wavelengths <1800Å could be 3–10x stronger. This occurs because dM stars have much higher values of L_x/L_{bol} and L_{FUV}/L_{bol} than the Sun and solar-type stars of comparable ages. Thus, because of the proximity of the planet to the dM star, the X–FUV irradiances are higher.
- dM stars flare frequently and thus emit impulsive XUV energies that could be a problem for life on a planet orbiting in the HZ. However, as shown by Cockell et al. (2000) and more recently by Cuntz et al. (2006), even a thin atmosphere, such as that of Mars, does not allow any incoming FUV/X-ray radiation with wavelengths <2000Å to reach the surface. On the other hand, these impulsive bursts of radiation (with >2000Å) could help, not hinder the development of life from mutations in the DNA of possible life forms.
- Although wind and coronal mass ejection events (CME) have yet to be directly measured for dM stars, scaling from the Sun and inferred wind properties of younger cool stars from astrosphere Ly-α studies (see Wood et al. 2002; 2005), it is assumed that young dM stars will have dense winds enhanced by frequent CME events that could have major effects on the heating of the exosphere of the planet and on the subsequent possible erosion and loss of its atmosphere if the planet does not possess a protective magnetosphere (see Grießmeier et al. 2004).
- The nearly constant luminosities of dM stars over time scales of tens of billions of years results in fixed HZs. This provides a stable environment for life to form and evolve on a possible dM star HZ planet.
- In our Galaxy, there are many old dM stars ($\tau > 5$ Gyr). This could mean that life (assuming that it formed in the first place) on a HZ planet around a dM star could be much more evolved and more advanced than us at 4.6 Gyr. However, for very old, metal poor, Pop II dM stars – like Barnard's Star, Kapteyn's Star and others, there could be a problem for terrestrial (rocky) planets to form because of the paucity of metals. Also, a low metal environment could be problematic for the development of life.

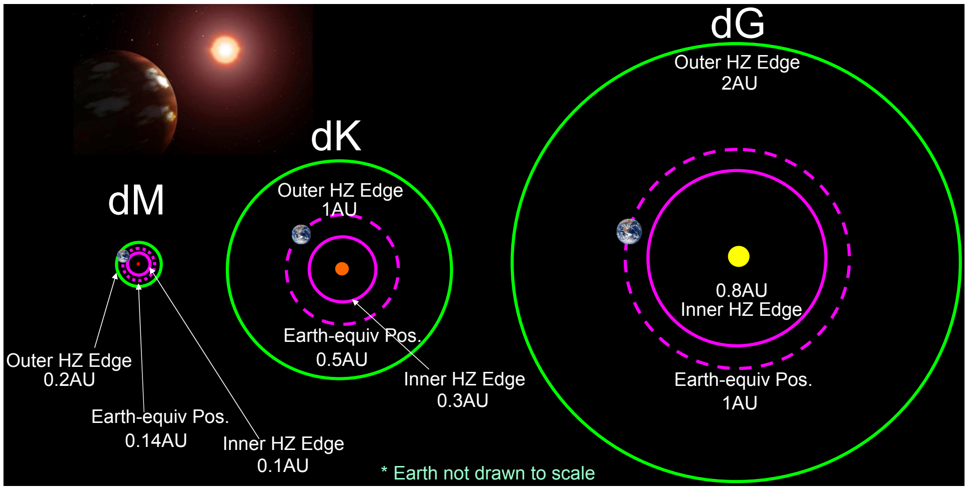

Figure 6: Approximate circumstellar liquid water habitable zones for Greenhouse-enhanced Earth-like planets around dM(dM0–5), dK(dK0–5) & dG(dG0–5) stars.

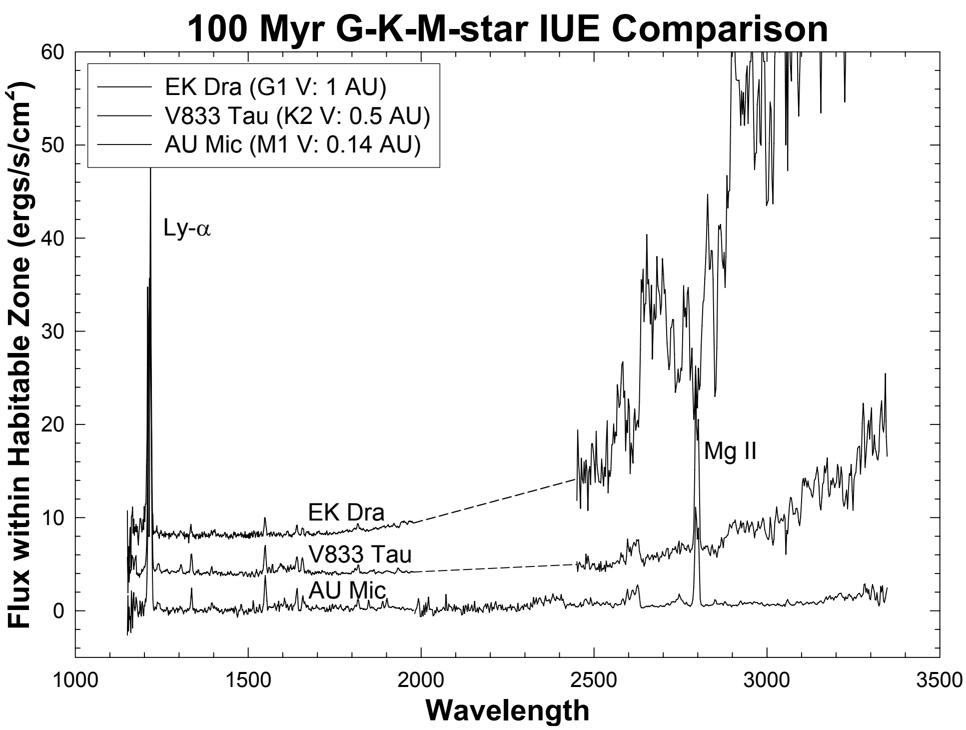

Figure 7: FUV–UV fluxes received from young (∼100 Myr) dG, dK and dM stars at the Earth-equivalent distances within their relative habitable zones. The data were secured from the *IUE* archives.

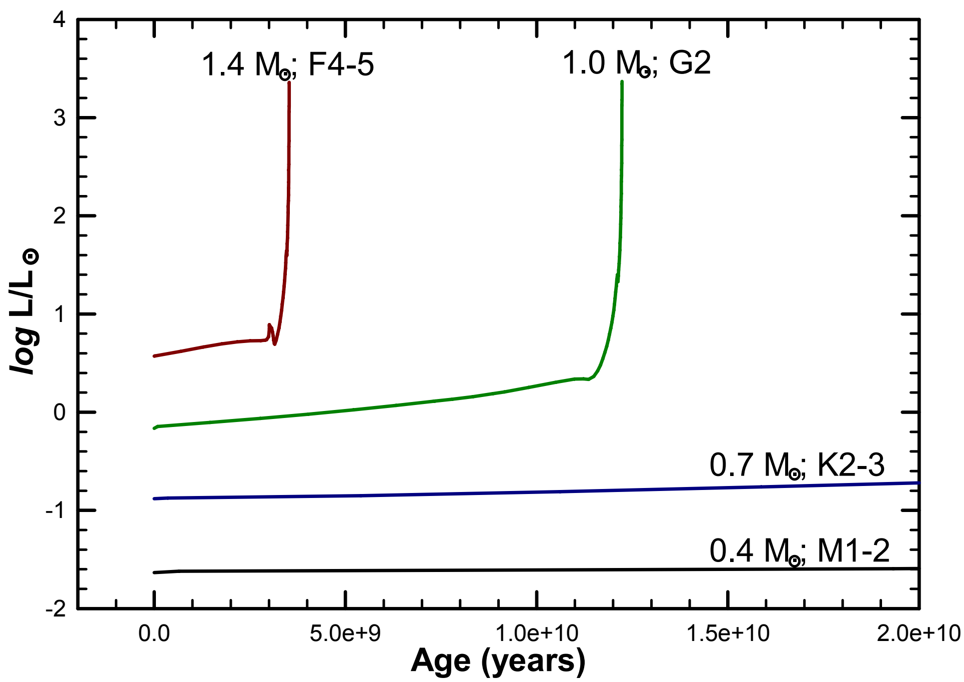

Figure 8: Stellar evolutionary tracks for $1.4M_\odot$, $1.0M_\odot$, $0.7M_\odot$ and $0.4M_\odot$ stars. These masses roughly correspond to dF4–5, dG2, dK2–3 and dM1–2 spectral types, respectively. Data taken from the Padova Database (http://pleiadi.pd.astro.it/).

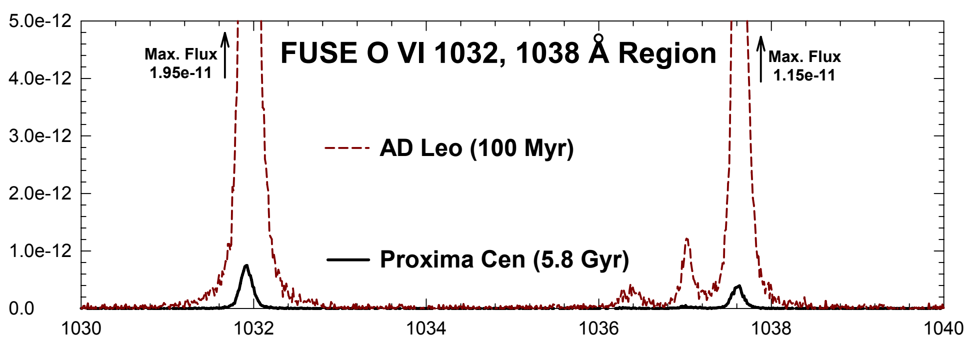

Figure 9: Plot of the *FUSE* O VI FUV region for a young (AD Leo; ∼100 Myr) and an old (Proxima Cen; ∼5.8 Gyr) dM star, indicating the large decrease in FUV emissions with age.

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