Ultraviolet Radiation Constraints around the Circumstellar Habitable Zones

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Abstract

Ultraviolet radiation is known to inhibit photosynthesis, induce DNA destruction and cause damage to a wide variety of proteins and lipids. In particular, UV radiation between 200-300 nm becomes energetically very damaging to most of the terrestrial biological systems. On the other hand, UV radiation is usually considered one of the most important energy source on the primitive Earth for the synthesis of many biochemical compounds and, therefore, essential for several biogenesis processes. In this work, we use these properties of the UV radiation to define the boundaries of an ultraviolet habitable zone. We also analyze the evolution of the UV habitable zone during the main sequence stage of the star.

We apply these criteria to study the UV habitable zone for those extrasolar planetary systems that were observed by the *International Ultraviolet Explorer (IUE)*. We analyze the possibility that extrasolar planets and moons could be suitable for life, according to the UV constrains presented in this work and other accepted criteria of habitability (liquid water, orbital stability, etc.).

Subject headings: Habitable zones, Extrasolar planets, UV radiation, Origin of life, Exobiology.

1.   Introduction

The so-called "Principle of Mediocrity" proposes that our planetary system, life on Earth and our technological civilization are about average and that life and intelligence will develop by the same rules of natural selection wherever the proper conditions and the needed time are given (von Hoerner 1961, 1973). In other words, the conditions that give place to the origin and evolution of life on Earth are average, in comparison to other worlds in the universe.

This hypothesis is in the "hard core" (Lakatos 1974) of all the research programs that search for life in the universe, which during the last fifty years were known within the scientific community as exobiology, bioastronomy, astrobiology, CETI, SETI, etc.

Using the "Principle of Mediocrity", we speculated about the existence of Earth-like planets, which must have liquid water on its surface, comparable surface inventories of CO_2, H_2O, N_2 and other biogenic elements, an early history allowing chemical evolution that leads to life, and subsequent climatic stability for at least 4.5 billion years (Lineweaver 2001; Owen 2000). We also speculated about the possible universal mechanisms for the origin of life, about universal mechanisms of Darwinian natural selection and for the appearance of intelligence and technological civilizations, and about how to detect primitive life and advanced technological civilizations beyond our home planet (Shklovskii and Sagan 1966; Lemarchand 1992).

Even though there are plans to do so (Fridlund 2000, 2002; Mennesson *et al.* 2005), State-of-the-Art technologies do not allow us yet to detect Earth-like extrasolar planets, and even less to analyze the composition of their atmospheres in detail. Recently, Vidal-Madjar *et al.* (2004) observed transits of the planet orbiting the star HD209458, and for the first time detected the existence of oxygen and carbon in an extrasolar planet's atmosphere, which is a step toward the confirmation that our home

planet may be "average".

Stars which are similar to the Sun in mass and evolutionary state, i. e. that have broadly a similar physical structure, are usually called *solar-like* stars. In practical terms, Soderblom and King (1998) defined *solar-like* as main sequence stars of spectral class F8V to K2V (or 0.50 to 1.00 in B−V). Several extrasolar planets have been found around this type of stars (Schneider 2005), and it is important to study whether they are suitable for life.

The original concept of Habitable Zone (HZ) was introduced by Huang (1959, 1960) and was later extended for the habitability by complex and intelligent life in a seminal study by Dole (1964). Later, Hart (1978, 1979) calculated the hypothetical evolution of the terrestrial atmosphere on geological time-scales for different orbital radius. He found that the HZ between runaway greenhouse and runaway glaciation processes is amazingly narrow for G2 stars like the Sun.

These early calculations omitted the negative feedback between atmospheric CO_2 partial pressure and mean global surface temperature via the carbonate-silicate cycle discovered by Walker *et al.* (1981). Taking into account this feedback, Kasting *et al.* (1988) found the interesting result of an almost constant inner boundary and a remarkable extension of the outer boundary.

In a comprehensive study, using a 1-D radiative-convective climate model, Kasting *et al.* (1993) presented a refined calculation of the HZ for the solar system and for other main sequence stars. They studied the effects of the loss of water via photolysis and of hydrogen escape, and the formation of CO_2 clouds, which cools the planet's surface by increasing its albedo and by lowering the convective lapse rate. They also showed how climatic stability is ensured by a feedback mechanism in which atmospheric CO_2 vary inversely with planetary surface temperature. For the internal

HZ boundary, they give three different estimations, ranging from 0.75 to 0.95 AU. The first case assumes the loss of planetary water by a moist greenhouse (Kasting 1988), the second one assumes loss of planetary water by a runaway greenhouse and the third one is based on the observation that there has been no liquid water on Venus' surface at least during the last Gyr. The external HZ boundary was also estimated in three different ways: the first criterion considers the characteristics of the evolution of the early martian atmosphere (Kasting 1991), the second one assumes a maximum possible CO_2 greenhouse heating, and the third one is related to the first condensation limit of CO_2 clouds that increase the planetary albedo. These criteria lead to an external boundary in a range from 1.37 to 1.77 AU.

Other more general criteria to understand the optimal position of the HZ was proposed by Franck *et al.* (2000a, 2000b). Based on the global carbon cycle as mediated by life and driven by increasing solar luminosity and plate tectonics, they estimated the biogeophysical domain supporting a photosynthesis-based ecosphere during planetary history and future. They corroborated the mediocrity assumption, since they found that the optimum position where the environment would accomplish the maximum life span and biological productivity[1] is at 1.08 AU, very close to the radius of Earth's orbit.

The evolution in time of stellar luminosity is another important factor to determine the location and the size of circumstellar habitable zones (Whitmire and Reynolds 1996). Habitable zones tend to migrate outward with time because main sequence stars become brighter as they age and convert hydrogen into helium and heavier elements. The continuously habitable zone (CHZ) is the region in space where

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[1]The biological productivity is the amount of biomass that is produced by photosynthesis per unit of time and per unit of continental area.

a planet remains habitable for some specified long time period (τ_{hab}). A common choice for this time is $\tau_{hab} \sim 4$ Gyr, the time that was needed on Earth for intelligent life to emerge and evolve into a technological civilization. Henry *et al.* (1995) and Turnbull and Tarter (2003a) considered $\tau_{hab} \sim 3$ Gyr, while Schopf (1993) used the time required for microbial life to emerge $\tau_{Mlife} \sim 1$ Gyr in his definition of the CHZ.

Recently, Turnbull and Tarter (2003a, 2003b) used the HZ definition, together with other variables like X-ray luminosity, Ca II H and K activity, rotation, spectral types, kinematics, metallicity and Strömgren photometry, to build a catalog of nearby stars suitable for the development of life and technological civilizations ("HabCat").

The ultraviolet radiation emitted by a star can also be important to determine the suitability of extrasolar planets for biological evolution and for the subsequent adaptation of life in exposed habitats (Cockell 1999). This factor will also determine the "average" environmental conditions that we think will help extraterrestrial life to develop on an Earth-like planet.

Ultraviolet radiation has also played a key role in the evolution of the terrestrial atmosphere. Guinan *et al* (2003) showed that the strong FUV and UV emissions of the young Sun could have played a major role in the early development and evolution of planetary atmospheres. X-ray and EUV emission fluxes of the early Sun could have also produced significant heating of the planetary exosphere and upper-atmosphere thus enhancing processes such as thermal escape (e.g. Luhmann and Bauer 1992) and could also played a role in the origin and development of life on Earth and possibly on Mars. The high levels of FUV radiation of the Sun could strongly influence the abundance of NH_3, CH_4 and O_3 in the prebiotic and Archean terrestrial atmosphere some 2-4 Gyr ago. Ozone is an efficient screening mechanism for the enhanced UV radiation, thus protecting the emerging and evolution of life on the surface planet.

In previous works (Buccino *et al.* 2002, 2004), we have shown that UVB and UVC radiation may have its own boundary conditions to fill the biological requirements of an habitable zone. This effect may be useful to define a new boundary condition for the UV-HZ inner limit.

On the other hand, besides the fact that ultraviolet radiation plays an important role destroying life, it was also one of the most important energy source on the primitive Earth for the synthesis of many biochemical compounds that may derivate from HCN (Toupance *et al.* 1977) and essential for some biogenesis processes (Sagan 1973). The need of a certain level of ultraviolet radiation to start several biogenic processes, naturally defines an outer border for an UV-HZ.

In this work, we use these concepts in a new definition of an ultraviolet habitable

zone, and apply it to all nearby stars harbouring exoplanets that have been observed in the UV by the *International Ultraviolet Explorer (IUE)*.

In section 2, we introduce two constrains for the origin and the development of life. The inner limit is determined by the levels of UV damaging radiation tolerable by DNA and the outer limit is characterized by the minimum UV radiation needed in the biogenic process.

In section 3, we apply these criteria to stars listed in the *Extrasolar Planets Catalog* (Schneider 2005) and we analyze the possible exoplanets and moons that may be suitable for life. Then, in section 4, we analyze the implication of the UV radiation on the HZ defined in Kasting *et al.* (1993) and we compare it with our results. We also discuss in that section the factors that can alter the UV constrains.

2. Biological boundaries for UV habitable zones

The destructive effect of the UV radiation on biochemicals processes is usually considered through a biological action spectrum (BAS) $B(\lambda)$, which represents a relative measure of damage as a function of wavelength. In this work, we define $B(\lambda)$ as the probability of a photon of energy $\frac{hc}{\lambda}$ to dissociate free DNA.

The first approximation of the action spectrum was obtained by Setlow and Doyle (1954, see also Setlow 1974). Cockell (1998) gave an estimation of the BAS based on studies by Green and Miller (1975) and Lindberg and Horneck (1991). We have semi-empirically adjusted the curve $B(\lambda)$ obtained from these previous studies with the following expression:

$$log\, B(\lambda) \sim \frac{6.113}{1 + \exp(\frac{\lambda[nm]-310.9}{8.8})} - 4.6\,. \tag{1}$$

Lindberg and Horneck (1991) showed that at wavelengths shorter than 230 nm, the action spectra and the absorption spectrum of DNA diverge. This can be explained by assuming that radiation of much less than 230 nm is absorbed by external layers of the spore cell wall surrounding the core in which the DNA is situated. Under these conditions only a very small fraction of shorter wavelengths reaches the DNA material.

A measure of the DNA-damage caused by UV photons radiated by a star of age t that reach the top of the atmosphere of a planet at a distance d (in AU) can therefore be expressed as

$$N_{DNA}^*(d) = \int_{200nm}^{315nm} B(\lambda)\frac{\lambda}{hc}\,\frac{F(\lambda,t)}{d^2}d\lambda\,, \tag{2}$$

where $F(\lambda, t)$ represents the UV flux of the star at 1 AU, h is the Planck constant and c is the speed of light.

If $N^*_{DNA}(d)$ is larger than a certain threshold, it would be difficult for life to develop on the planet's surface because of the damaging UV radiation. The maximum amount of DNA-damage that a planet could surmount can be larger than the one received by early Earth, where life has developed.

On the other hand, there might be several sources of natural attenuation of the UV radiation, in particular a planetary atmosphere. Each exoplanet might have different conditions that determine the exact amount of the UV attenuation over the planetary surface. We quantified this attenuation with a factor α, which is the ratio between the radiation received on the planetary surface and the incident radiation on top of the atmosphere.

Segura *et al.* (2003) performed a coupled radiative-convective/photochemical model for Earth-like planets orbiting G2V, F2V and K2V stars. They studied the levels of UV radiation received on the planetary surface considering different O_2 concentrations. For each atmospheric composition, therefore, we estimated the α-factor as the ratio between the UVB+UVC fluxes received on the planetary surface and those with zero O_2 concentration. For 10^{-5} times the present values of O_2 at Earth, which could have been the conditions of the Archean Earth, the attenuation is $\alpha=0.84$ for K and G stars and $\alpha=0.74$ for F stars.

For these reasons, and considering the complexity and self-regulating characteristics of life-systems, we apply the "Principle of Mediocrity" and assume that the maximum UV radiation tolerable, before DNA damaging prevents the appearance of life, is equal to twice the radiation that reached the outer space over the Earth's atmosphere 3.8 million years ago. We remark that the atmospheric corrections are contemplated within our mediocrity factor.

Therefore, we will define the inner limit of the UV habitable zone as the one given by

$$N^*_{DNA}(d) \leq 2 \times N^{\odot}_{DNA}(1\text{AU})|_{t=t^{\odot}_{Arc}}, \tag{3}$$

where $N^{\odot}_{DNA}(1\text{AU})|_{t=t^{\odot}_{Arc}}$ is calculated with Eq. 2, using the flux received by the Archean Earth (~ 3.8 Gyr ago), which we assumed equal to 75% the present radiation on top of the atmosphere, as was done by Kasting (1988) and Cockell (1998). Both authors followed the Solar Standard Model predictions.

On the other hand, UV radiation is thought to have also played a positive role in the origin of life. Toupance *et al.* (1977), using early models of terrestrial archean atmosphere, showed that UV radiation may have largely contributed to the synthesis of HCN in CH_4 - NH_3 and consequently to the synthesis of many biochemical compounds that derive from HCN. In the early Earth, methane-ammonia atmospheres

are no longer considered realistic. Ammonia, in particular, photolyzes rapidly and is unlikely to have been present in the early Earth (Pavlov *et al.* 2001).

Molecular Hydrogen can also be generated from near UV irradiation of aqueous ferrous hydroxide at pH 6-8 and the presence of banded iron formations in Archean rocks has been cited as evidence that Fe photo-oxidation occurred on the early Earth (Braterman and Cairns-Smith 1987).

Chyba and McDonald (1995) described a possible non-atmospheric mechanism by which ultraviolet photolysis could have acted as an energy source for prebiotic organic chemistry. Chyba and Sagan (1997) and Ehrenfreund *et al.* (2002) proposed that the greater rate of production of organics on Earth, 4 Gyr ago, was due to UV photolysis.

Recently, Tian *et al.* (2005) proposed a new model for the early terrestrial atmosphere that is CO_2-rich and not CH_4-rich, but contains as much as 30% H_2. In their model, the production of organic molecules through electrical discharges or ultraviolet light becomes increasingly important relative to the delivery of organic molecules by meteorites or comets. The organic soup in the oceans and ponds on early Earth would have been more favorable places for the origin of life than have been previously thought and, therefore, UV light would have been more important as an energy source for the formation of complex organic molecules.

Mulkidjanian *et al.* (2003) presented another evidence of the importance of UV radiation in biogenesis processes. They simulated the formation of first oligonucleotides under continuous UV illumination and confirmed that UV irradiation could have worked as a selective factor, leading to a relative enrichment of the system in longer sugar-phosphate polymers carrying nitrogenous bases as UV-protectors.

Consequently, we assume that there is a minimum number of UV photons needed as an energy source for the chemical synthesis of complex molecules. The *total* number of UV photons received by a planet at distance d can be computed as

$$N_{UV}^*(d) = \int_{200nm}^{315nm} \frac{\lambda}{hc} \frac{F(\lambda, t)}{d^2} d\lambda \,. \tag{4}$$

Based on the "Principle of Mediocrity," we request that the planet receives at least half the total number of UV photons received by the Archean Earth, $N_{UV}^{\odot}(1\text{AU})|_{t=t_{Arc}^{\odot}}$, and we set the outer limit of the UV habitable zone accordingly:

$$N_{UV}^*(d) \geq 0.5 \times N_{UV}^{\odot}(1\text{AU})|_{t=t_{Arc}^{\odot}} \,. \tag{5}$$

The mediocrity factor makes the UV habitable zone from 0.71 to 1.90 AU around the Sun, wider than the traditional one proposed by Kasting *et al.* (1993),

where the limits in the intermediate case, for the solar system, go from 0.84 to 1.67 AU in the solar system.

For life systems to evolve, the planet should be in the habitable zone continuously during a certain time. To analyze the evolution of the habitable zones, we first assume that the luminosities of F, G and K main sequence stars evolve in a similar way and that the UV radiation follows the same pattern.

According to Dorren and Guinan (1994) and Ribas *et al.* (2005), the early Sun emitted a proportionally higher flux at UV than at visible wavelengths. In particular, the UV continuum flux density of the early Sun exceeded the present one by a factor of 2 to 10 shortward of 200 nm. However, at longer UV wavelengths, where the photospheric emission dominates over that of the chromosphere, the UV flux of the young solar types would represent only 10-30% of that of the present Sun (Ribas *et al.* 2005). Taking into account the biological influence of UV radiation, in this work we focused our study only in those wavelengths between 200-315 nm, where the evolution of UV emission should scale with the bolometric solar luminosity.

For the evolution of the solar luminosity in the past Gough (1981) obtain the following relation:

$$L_{\odot}^{past}(t) = [1 + \frac{2}{5}(1 - \frac{t}{t_{\odot}})]^{-1} L_{\odot}^{pres}, \tag{6}$$

where $L_{\odot}^{pres}$ is the luminosity of the Sun at present time $t_{\odot}$ ($\sim$ 4.6 Gyr).

For the future evolution of the solar luminosity, we have interpolated the estimations given by Turck-Chieze *et al.* (1988), which we fit with the relation:

$$L_{\odot}^{fut}(t) = [5.59\,Gyr\frac{1}{t} - 1.39 + 0.26\,Gyr^{-1}t]L_{\odot}^{pres}. \tag{7}$$

In Fig. 1 we show the curve $L_{\odot}(t)$ obtained for both cases.

[Figure 1]

With Eq. 6 and 7, in the next section we calculate the evolution of the habitable zones from 1 to 10 Gyr for several stars.

3.   The UV radiation fluxes around the extrasolar planets

By August 2005, there have been discovered 157 extrasolar planets in 138 planetary systems, 14 of which are multiple planetary systems (Schneider 2005). From these, only 23 stars (harbouring 32 different planets) have been observed by IUE. We have excluded HD150706 and HD99492 from our consideration because their spectra are too noisy. The sample is listed in Table I.

[**Table I**]

The Hubble Space Telescope has also observed the UV spectra of Gliese 876, HD114762 and HD209458, but the observed bandwidth (115-320 nm) is incomplete to include these stars in our present analysis.

We use low dispersion (0.6 nm resolution) and high dispersion ($\lambda/\Delta\lambda \sim 10000$) spectra, taken by the long wavelength cameras (LWP and LWR) in the range 185-340 nm. The spectra are available from the IUE public library (at http://*ines.laeff.esa.es/cgi-ines/IUEdbsMY*), and have been calibrated using the NEWSIPS (New Spectral Image Processing System) algorithm. The internal accuracy of the high resolution calibration is around 4% (Cassatella *et al.* 2000) and the errors of the low dispersion spectra in the absolute calibration are around 10-15% (Massa and Fitzpatrick 1998).

In Fig. 2, we plot our sample of stars in an HR diagram, together with the criteria used by Turnbull and Tarter (2003a) to exclude stars that remain in the main sequence stage less than 3 Gyr.

[**Figure 2**]

The giants HD219449 and HIP75458, and the subgiants HD27442 and γ Cephei are above the curve M_V=-10[(B−V)-1.4]^2+6.5, one of the criteria used by Turnbull and Tarter.

Therefore, we exclude those stars from our analysis of habitability. It is worth noting that, although τ Boo, ρ Ind and 51 Peg are subgiants, their position in the HR diagram puts them within the Turnbull-Tarter habitability criteria.

Different estimations of the ages of the stars of our sample are given in Table I. In the column 3, the ages were estimated from the stellar luminosity (Lang 1992). From Henry *et al.* (1996) and Donahue (1993), we obtained the ages associated with the chromospheric activity (column 4). In column 5 and 6, the values were taken from Lachaume *et al.* (1999) and Nördstrom *et al.* (2004) respectively.

It can be seen that there are large discrepancies between the different estimated ages, that constitute an important source of uncertainty in the determination of the

environmental stability of each exoplanet during their τ_{Mlife} and τ_{hab} lifetimes.

In Fig. 3, we plot the evolution with time of the UV habitable zone, computed following the UV constrains found in Section 2 together with the traditional one, for each of the 17 stars of our sample and for our solar system. For the limits of the traditional HZ, we considered the intermediate criteria, which considers the *runaway greenhouse effect* for the inner edge and the *maximum greenhouse* for the outer one. For the solar case, these limits are 0.84 AU and 1.67 AU, respectively. The visible flux was computed from the visible magnitude m_v and the stellar parallax listed in Table I, and the limit was set as the distance to the star where the radiation is the same as that at 0.84 AU and 1.67 AU of the Sun.

[**Figure 3**]

In the figure, each exoplanet is represented by a triangular dot, indicating its orbital radius and the present stellar age.

4. Discussion

The traditional HZs plotted in Fig. 3 agree very well with those obtained by Underwood *et al.* (2003), who computed the evolution in time of luminosity and effective temperature for several main sequence stars, with masses between 0.5 and 1.5 $M_\odot$. This similarity supports our assumption that the stellar luminosity follows a pattern similar to the one predicted by the Solar Standard Model.

In Fig. 3 we see that, in most cases, the UV-HZ is placed much closer to the central star than the traditional one. In those cases, UV radiation inside the traditional HZ would not be an efficient source for photolysis, and therefore the formation of the macromolecules needed for life would be much more difficult, if not completely impossible.

To test the validity of our assumptions, in Fig. 3, we applied our definition of the UV habitable zone to our solar system. The results are consistent with previous analysis performed by Cockell (1998, 2000), Cockell *et al.* (2000) and Córdoba-Jabonero *et al.* (2003). For example, if the conditions of the atmospheric attenuation of ancient Venus were *similar* to Archean Earth, then the proximity to the Sun determines that the UV flux must have been 1.9 times higher than the Earth. The UV radiation environment would probably have been tolerable to any potential life (Cockell 2000), as it is shown in Fig. 3. For the case of Mars the UV flux is 0.43 times the terrestrial one. The lack of a significant ozone layer means that a significant portion of UV spectrum reaches the surface of the planet without attenuation (see Table II in the Appendix). Cockell *et al.* (2000) showed that the present Martian UV levels are about the same order of magnitude to the early terrestrial ones.

In near the 41% stars of the sample: HD19994, 70 Vir, 14 Her, 55 Cnc, 47 UMa, ϵ Eri and HD3651, there is no coincidence at all between the UV region and the HZ. In the cases of 51 Peg and HD160691, the outer limit of the UV habitable region nearly coincides with the inner limit of the HZ. Of course, the limits plotted in Fig. 3 are not strict, and taking into account the error in the flux, both HZ and HZ_{UV} could coincide in a tiny region. However, considering the evolution in time of both HZs, a planet orbiting in the habitable region would remain there for less than 1 Gyr. We, therefore, include 51 Peg and HD160691 in the set of stars where there is no overlap between the UV region and the HZ. Something similar happens to HD 186427 (16CygB). This means that there is no coincidence between the HZ_{UV} and the HZ in almost 59 % of the sample .

There are seven cases where the traditional and the UV HZs overlap at least partially and therefore can, in principle, host an habitable planet in it. However in three cases (H147513, HD143761 and HD217014) the location of the giant planet would make the orbit of the terrestrial planet unstable, according to Turnbull and Tarter (2003a) and Menou and Tabachnik (2003).

There are five extrasolar planetary systems (υ And, HD19994, HD143761, HD147513 and HD160691) that have giant planets detected inside the traditional HZ. Assuming that there is a rocky moon around these planets, we can check in Fig. 3 (see also Table II in the Appendix) if the UV radiation levels would be adequate for the origin and evolution of life. υ And c , HD160691c, HD147513b and HD19994b have low UV levels ($\lesssim$ 2 times the Earth value), and therefore in these cases a hypothetical moon will not be hostile for DNA-type life systems. However, UV radiation in HD147513b, HD19994b and HD160691c are too low to trigger the formation of life. In contrast, the UV radiation on HD143761b would have destroyed any possible life on a rocky moon around the planet, unless the atmosphere filters 99 % of the UV radiation (see Table II). Finally, a moon orbiting υ And c would be habitable according to both criteria.

The two F stars of our sample (HD114762 and τ Boo) also present an interesting case. Around both stars, there is a region in the HZ where complex life would be burnt by UV radiation. In both cases, an atmospheric protection much larger than that of early Earth would be needed to make the traditional HZ suitable for life. In general, the HZs around F stars are restricted by the damaging effect of UV radiation.

5. Conclusions

In this work we present a more restrictive criteria to habitability of an extrasolar Earth-like planet than the traditional liquid water one presented by Kasting *et al.* (1993), as we analyze the biological conditions to the origin and the development of

life once the liquid-water scenery is already satisfied.

Until an atmospheric protection would be built, a planetary surface would be exposed to larger amounts of UV radiation, which could act as one of the main source in the synthesis of bioproducts and, in a certain wavelength, could be damaging for DNA. Both concepts represent the UV boundaries for the UV-HZ. In this work, we also analyze the evolution of UV habitability during the main sequence life of the star. We recognize that an atmospheric correction should be present as star and a possible terrestrial planet age, but this point is beyond our scope. However, the mediocrity factor contemplates an attenuation from either the sea, the atmosphere, a rock, planetary obliquity, planetary rotation cycle, etc. of half the radiation. Applying all these criteria to those stellar systems whose central star has been observed by IUE, we obtained that an Earth-like planet orbiting the stars HD216437, HD114752, HD89744, τ Boo and Rho CrB could be habitable for at least 3 Gyr. A moon orbiting v And c would be also suitable for life. While, in the 59% of the sample (51 Peg, 16CygB, HD160691, HD ,HD19994, 70 Vir, 14 Her, 55 Cnc, 47 UMa, ϵ Eri and HD3651), the traditional HZ would not be habitable following the UV criteria exposed in this work.

A.   Appendix

The UV radiation is usually divided in three wavelength ranges, UVA (315-400 nm), UVB (280-315 nm) and UVC (190-280nm). In the Archean Earth, UVB and UVC would probably have reached the surface of the Earth without attenuation (Sagan 1973, Kasting 1993). UV radiation have played a major ecological role on the evolution and environmental distribution of cyanobacteria and their immediate ancestors during evolutionary history. García Pichel (1998) and Castenholz and García Pichel (2000) showed that the biologically effective exposure to UVB, and not so much UVC, must have been particularly important.

Besides our previous analysis, we may also estimate the UVB and UVC radiation values for the different extrasolar planets of our sample at the semi-major orbital axis (Buccino *et al.* 2004). In order to normalize the UVB and UVC radiation levels on the extrasolar planets, with the history of life on our planet, the fluxes are expressed in

Table II as multipliers of the Archean Sun UVB and UVC outer space levels at 1AU, as well as N^*_{DNA} values (without any consideration of the atmospheric or other natural attenuation, i.e. $\alpha \sim 1$). In Table II, we present the UVB, UVC and N^*_{DNA} fluxes at the semi-major axis (d_{s-p}) for a set of extrasolar planets in which IUE observations were available. We have also included Venus, Earth and Mars to compare our UV results within the Solar System habitable zone. Here the unit T.A.E. represents the number of times the Archean Solar radiation at 1 AU is available at each extrasolar planet.

The information provided in Table II is useful to compare the levels of N^*_{DNA} at different planets with the values of UVB and UVC radiation that are the most traditional way in which these analysis are presented in the literature.

In the last table column we indicate if the planet is inside Kasting *et al.* (1993) habitable zone at present (Y), or if it is outside (N), or if it will be inside it in the future (FY). If the central star is not suitable for life we leave an empty space.

Even though all these are giant planets, those with a (Y) sign, could have moons suitable for life as it was shown in the previous sections.

[**Table II**]

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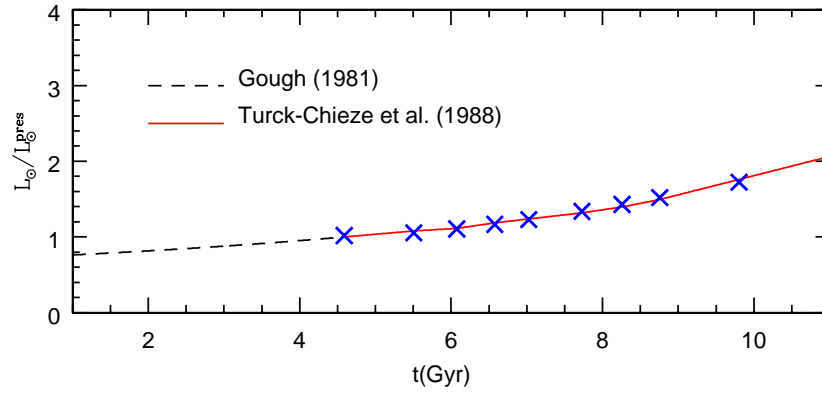This manuscript was prepared with the AAS LATEX macros v5.2.

Figures

Fig. 1.— Buccino *et al.* Evolution of solar luminosity.
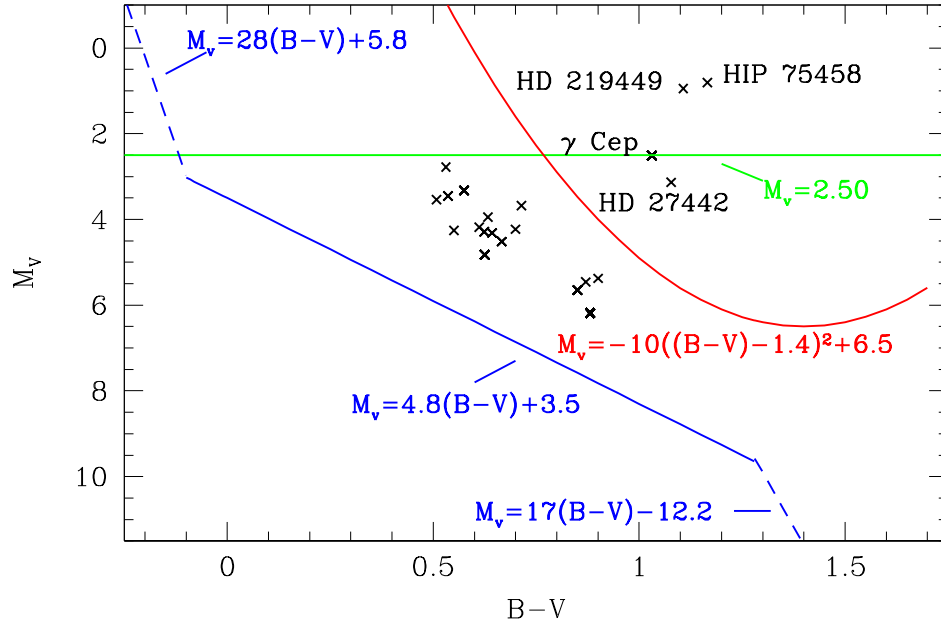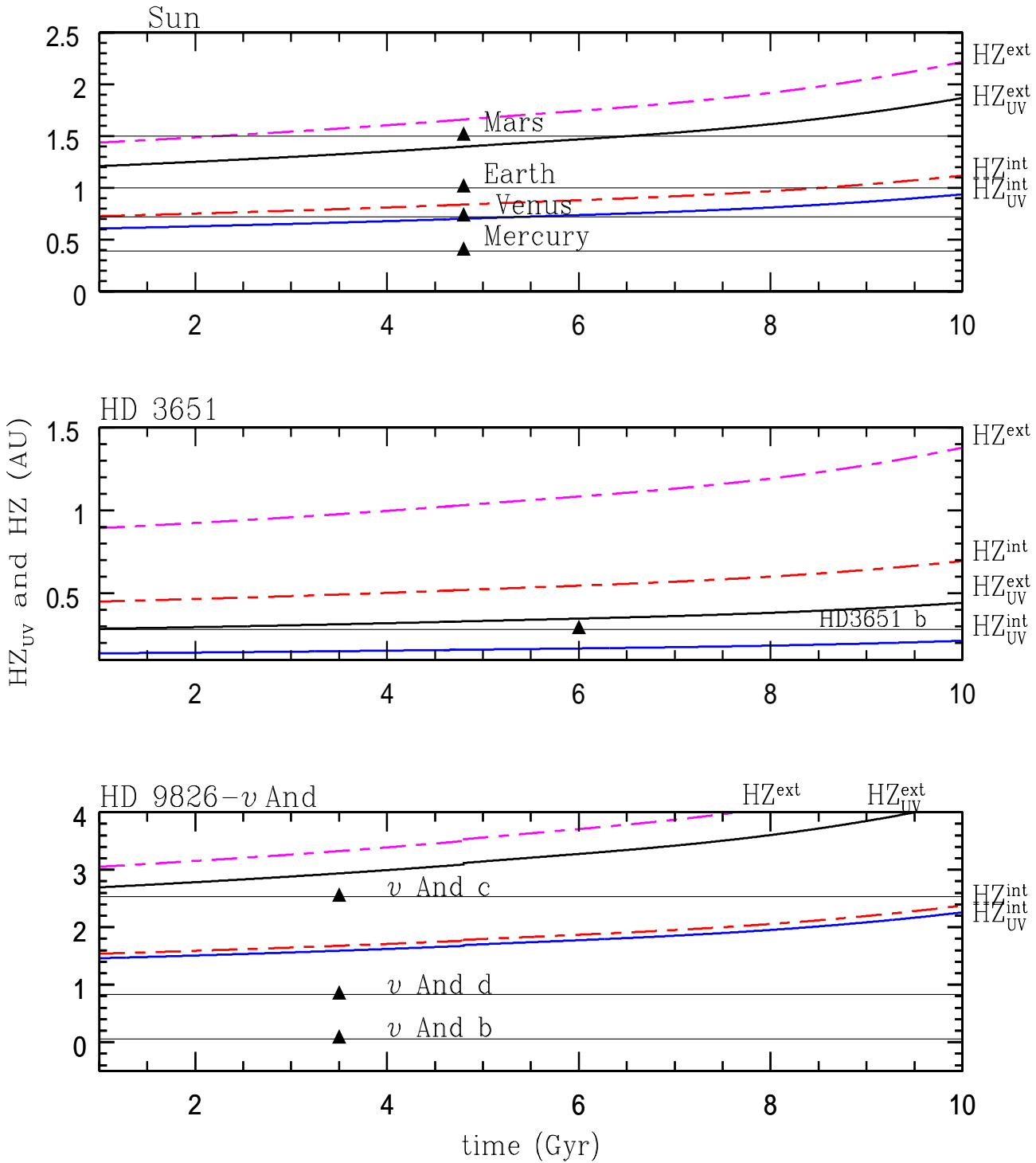
Fig. 2.— Buccino *et al.*. HR diagram.

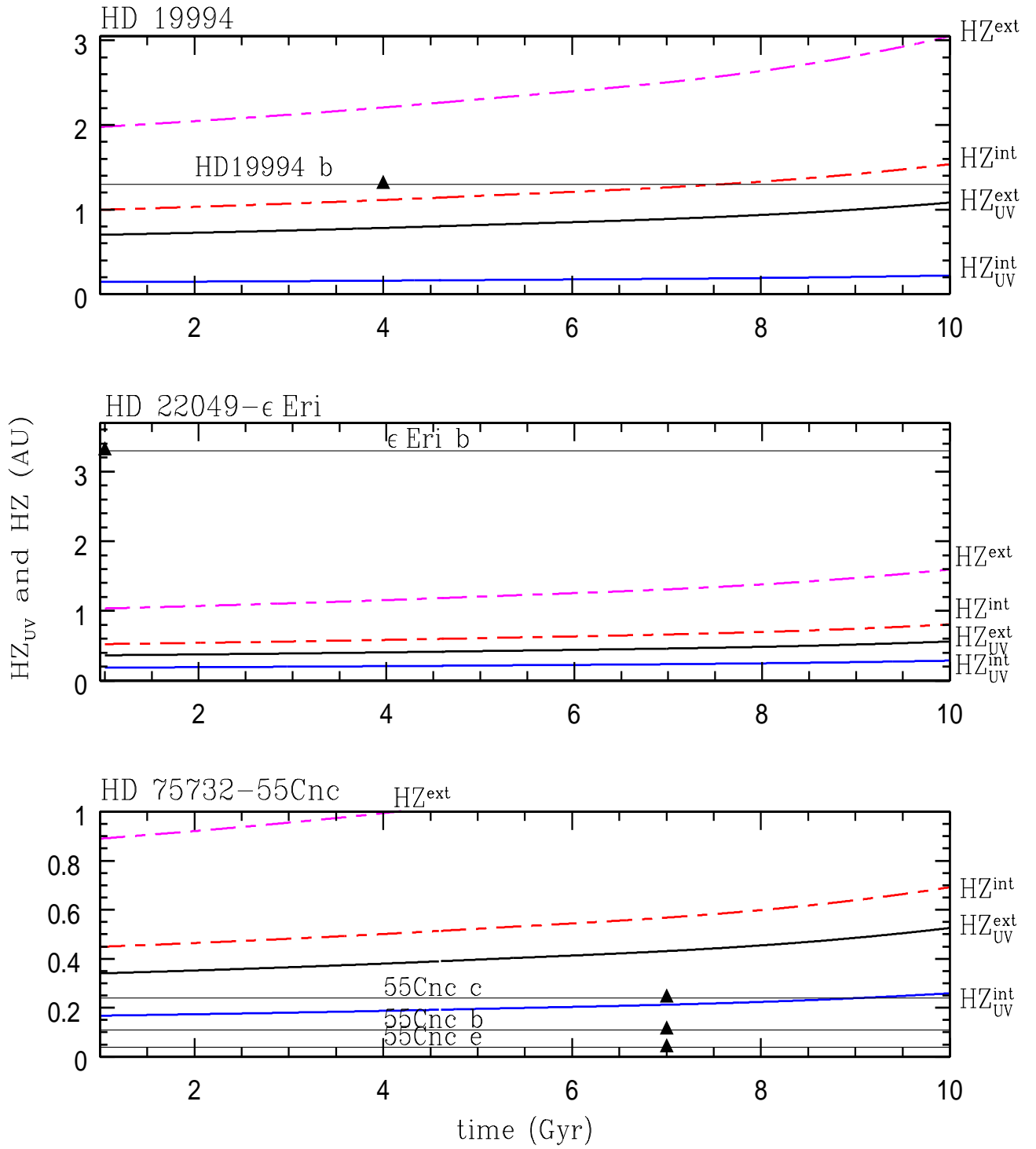Fig. 3.— Buccino *et al..* HZ and UV-HZ.

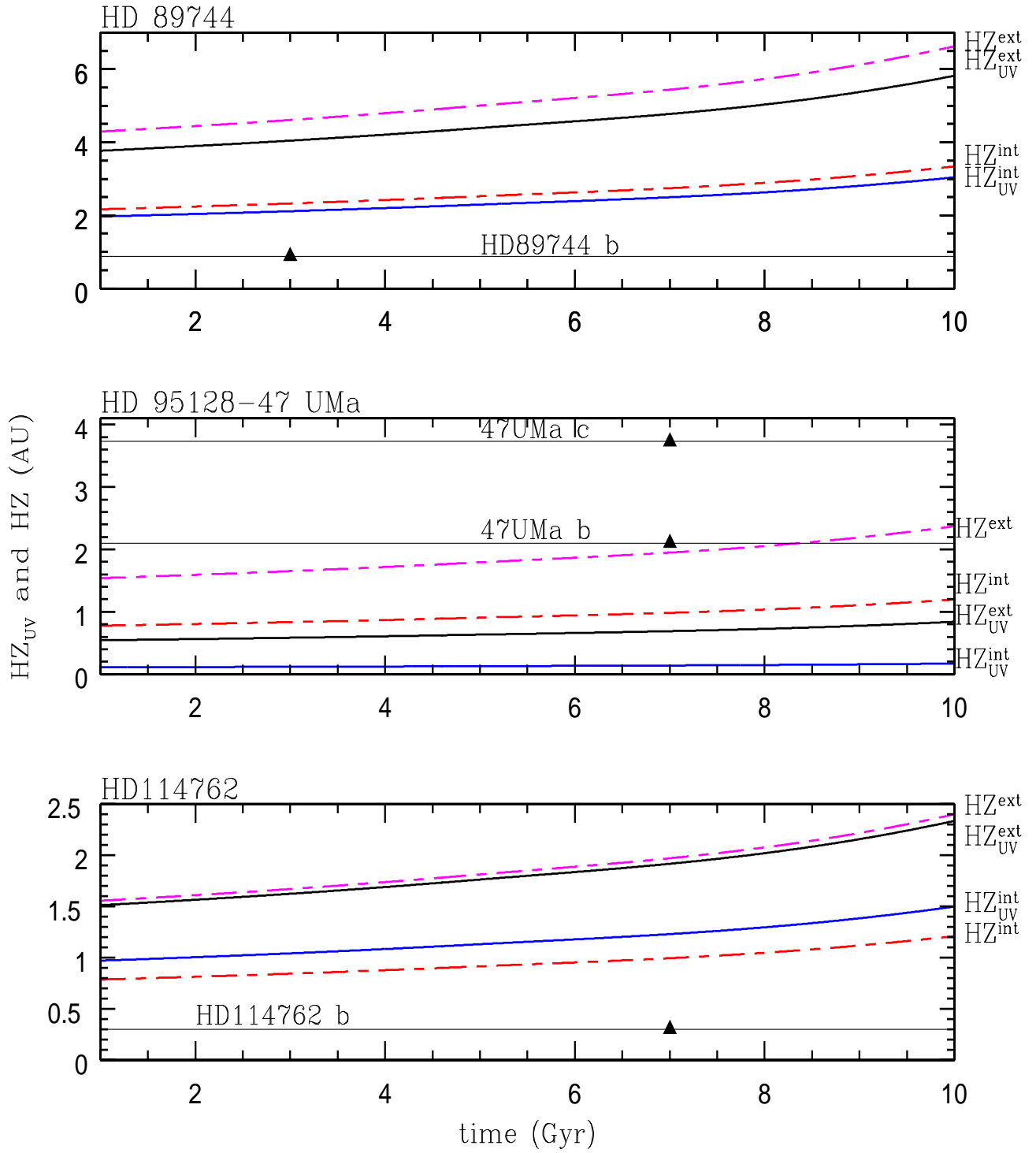Fig. 3.— Cont. Buccino *et al.*. HZ and UV-HZ.
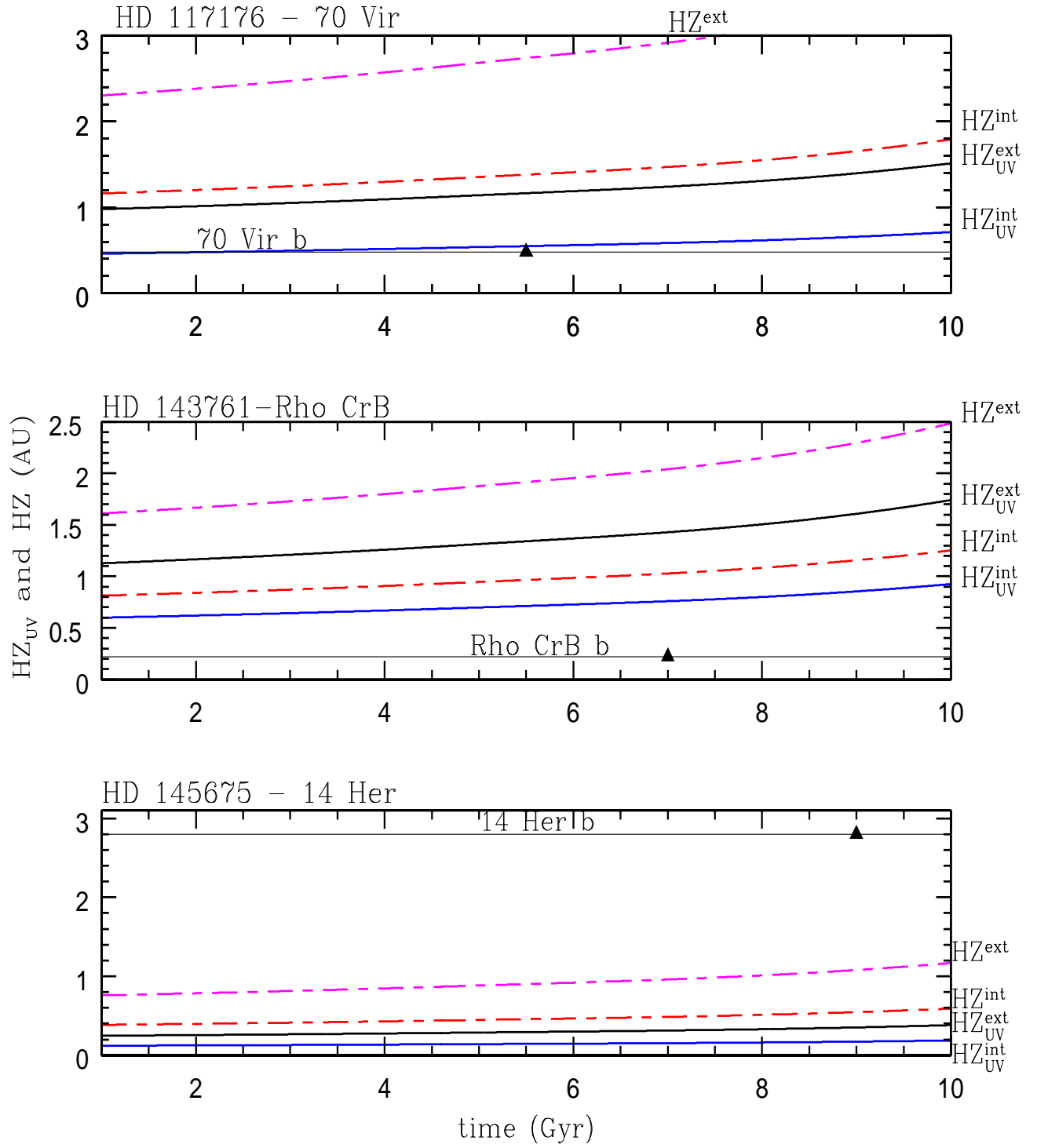
Fig. 3.— Cont. Buccino *et al.*. HZ and UV-HZ.
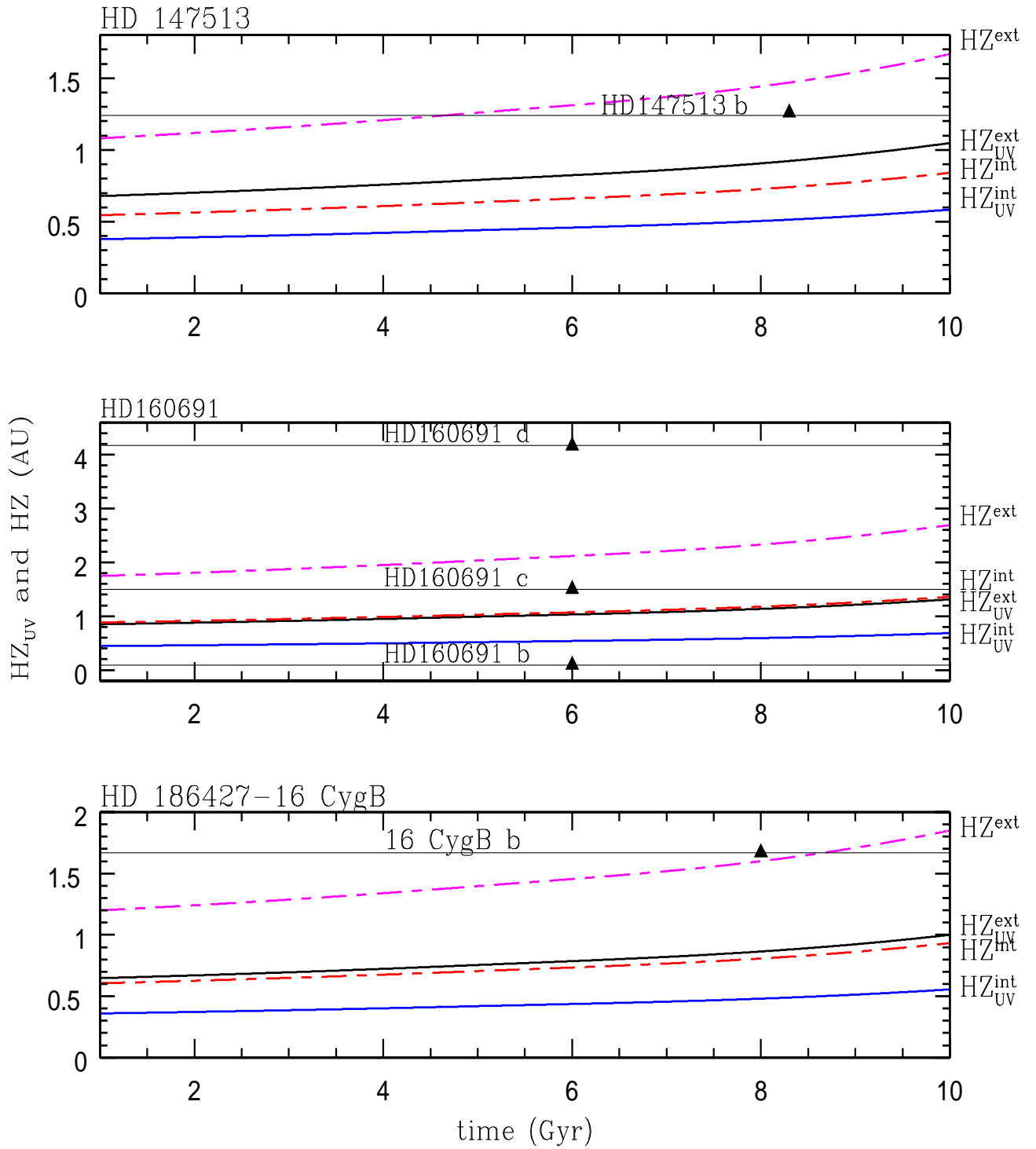
Fig. 3.— Cont. Buccino *et al.*. HZ and UV-HZ.

Fig. 3.— Cont.Buccino *et al.*. HZ and UV-HZ.

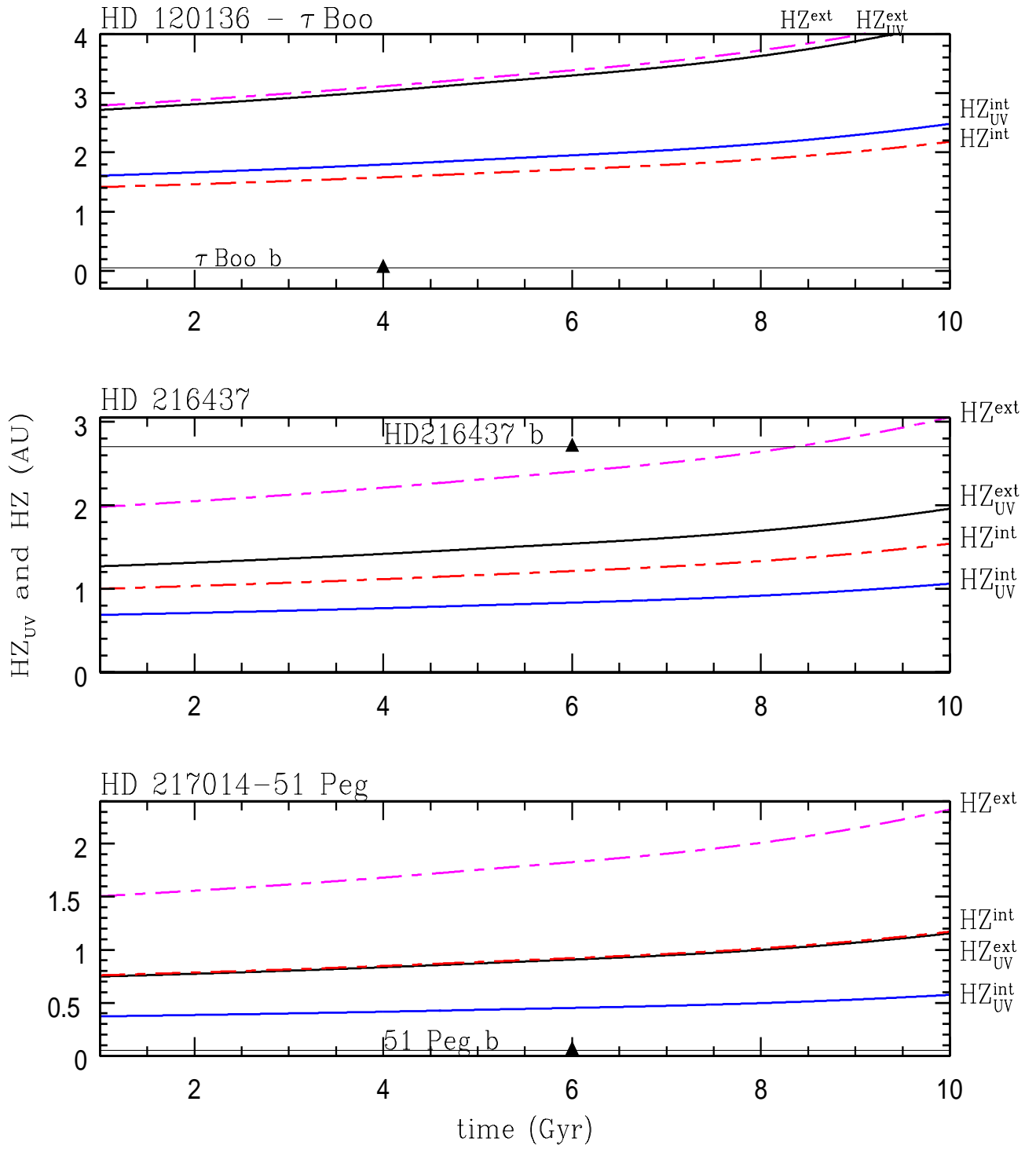Fig. 3.— Cont. Buccino *et al.*. HZ and UV-HZ.

Tables

Stars	Spectral type and class	m_v	Plx (mas)	Age[1] (Gyr)	Age[2] (Gyr)	Age[3] (Gyr)	Age[4] (Gyr)	HIP	HR	Other Names
Main sequence stars										
Archean Sun	G2V	-26.8	8749	1.0						
Present Sun	G2V	-26.8	8749	4.6						
HD 3651	K0V	5.9	90.0	15.1	5.9		17.0	3093	166	
HD 9826	F8V	4.1	74.3	4.3	6.3	2.88	3.3	7513	458	υ And
HD 19994	F8V	5.1	44.7	3.9	3.5		4.7	14954	962	
HD 22049	K2V	3.7	310.8		0.9			16537	1084	ϵ Eri
HD 75732	G8V	5.9	79.8	13.4	6.46			43587		55 CnC
HD 89744	F7V	5.7	25.7	2.8	4.5		2.2	50786	4067	
HD 95128	G1V	5.0	71.0	7.1	7.0	6.3	8.7	53721	4277	47 **UMa**
HD 114762	F9V	7.3	24.7	7.1			11.8	64426		
HD 117176	G5V	4.9	55.2	4.8	5.4	7.6	7.4	65721	5072	70 Vir
HD 143761	G0Va	5.4	57.4	6.6	7.2		12.1	78459	5968	ρ CrB
HD 145675	K0V	8.8	7.1	12.2	6.9			79248		14 Her
HD 147513	G5V	5.4	77.7	9.8			8.5	80337	6094	
HD 160691	G3IV-V	5.2	65.5	6.6		6.2		86796	6585	μ Ara
HD 186427	G3V	6.2	46.7	8.4	7.4		9.9	96901	7504	16 Cyg B
Subgiants										
HD 27442	K2IVa	4.4	54.8	2.8				19921	1355	ϵ Ret
HD 120136	F6IV	4.5	64.1	4.5	4.2		2.4	67275	5185	τ Boo
HD 216437	G2.5IV	6.0	37.7	5.6			8.7	113137	8701	ρ Ind
HD 217014	G2.5IVa	5.5	65.1	8.0	5.7	5.1	9.2	113357	8729	51 Peg
HD 222404	K1IV	3.2	72.5	2.0				116727	8974	γ Cep
Giants										
HD 137759	K2III	3.3	31.9					75458	5744	
HD 219449	K0III	4.2	21.9					114855	8841	91 Aqr

Table I: Planetary stars with IUE observation.

Planets	Star sp type and class	d_{s-p} (AU)	**UVB** (T.A.E)	**UVC** (T.A.E.)	$\mathbf{N^*_{DNA}}$ (T.A.E.)	Planet within HZ (Kasting *et al.* 1993)
Main sequence stars						
Present Earth	G2V	1.00	0.5	0.8	1.4	(Y)
Mercury	G2V	0.39	3.3	5.3	9.2	(N)
Venus	G2V	0.72	0.9	1.5	2.7	(N)
Mars	G2V	1.50	0.2	0.4	0.6	(Y)
HD 3651b	K0V	0.28	2.7	3.9	1.9	(N)
HD 9826b	F8V	0.06	1801.6	2591.3	1660.1	(N)
HD 9826c	F8V	2.53	1.0	1.4	0.9	(Y)
HD 9826d	F8V	0.83	9.1	13.1	8.4	(N)
HD 75732b	G8V	0.04	172.2	247.7	123.2	(N)
HD 75732c	G8V	0.11	20.6	29.6	14.6	(N)
HD 75732d	G8V	0.24	4.3	6.2	3.1	(N)
HD 75732e	G8 V	5.90	7E-3	1E-2	5E-2	(N)
HD 19994b	F8V	1.30	2.1	3.0	1.8	(Y)
HD 22049b	K2V	3.30	1E-02	1E-02	9E-2	(N)
HD 22049c	K2V	40.00	8E-06	1E-04	6E-5	(N)
HD 89744b	F7V	0.88	14.8	21.3	12.2	(N)
HD 95128b	G1V	2.10	0.4	0.6	0.3	(FY)
HD 95128c	G1V	3.73	0.1	0.2	9E-2	(N)
HD 114762b	F9V	0.30	41.4	59.6	66.1	(N)
HD 117176b	G5V	0.48	6.9	9.9	4.3	(N)
HD 143761b	G0Va	0.22	53.6	77.1	46.9	(N)
HD 145675b	K0V	2.80	3E-2	4E-2	2E-2	(N)
HD 147513b	G5V	1.26	0.8	1.2	0.8	(Y)
HD 160691b	G3IV/V	1.50	0.5	0.8	0.5	(N)
HD 160691c	G3IV/V	2.30	0.2	0.3	0.2	(Y)
HD 160691d	G3IV/V	4.17	0.1	0.1	5E-2	(N)
HD 186427b	F7V	1.67	0.4	0.6	0.4	(N)
Subgiants						
HD 27442b	K2IVa	1.18	0.5	0.8	0.3	
HD 120136b	F6IV	0.05	3182.5	4577.6	3720.1	(N)
HD 216437b	G2.5IV	2.70	0.3	0.5	0.3	(N)
HD 217014b	G2.5IVa	0.05	381.7	549.1	279.5	(N)
HD 222404b	K1IV	2.03	0.4	0.6	0.2	
Giants						
HD 137759b	K2III	1.34	2.2	3.2	0.6	
HD 219449b	K0III	0.30	51.0	73.4	28	

Table II: UVB and UVC fluxes.

Figures captions

Figure 1: Evolution of solar luminosity along main sequence stage (Turck-Chieze *et al.* 1988, and Gough 1981).

Figure 2: HR diagram representation of the IUE-observed planetary stars in Table I, the habitability restrictions defined by Turnbull and Tarter (2003a) are also included.

Figure 3: The dashed lines represent the HZ boundaries defined by Kasting *et al.* (1993) and the solid lines limit the region where UV is suitable for life, following the criteria in section 2. The triangles dot indicate the planets discovered in each system.

Table captions

Table I: Planetary stars with IUE observation. Stellar ages were determined according to (1) stellar luminosity (Lang 1992), or to (2) chromospheric activity (Henry *et al.* 1996, Donahue 1993), (3) taken from Lauchame (1999) or (4) from Nördstrom *et al.* (2004)

Table II: UVB and UVC fluxes at the semi-major orbital axis (d_{s-p}) of a set of extrasolar planets in which IUE observations were available. T.A.E: Times the solar radiation at 1 AU for the Archean Earth.

Footnote

Footnote 1: The biological productivity is the amount of biomass that is produced by photosynthesis per unit of time and per unit of continental area.