UV Habitability of Possible Exomoons in Observed F-star Planetary Systems

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ABSTRACT

In the present study we explore the astrobiological significance of F-type stars of spectral type between F5 V and F9.5 V, which possess Jupiter-type planets within or close to their climatological habitable zones. These planets, or at least a subset of them, may also possess rocky exomoons, which potentially offer habitable environments. Our work considers eight selected systems. The Jupiter-type planets in these systems are in notably different orbits with eccentricities ranging from 0.08 to 0.72. Particularly, we consider the stellar UV environments provided by the photospheric stellar radiation in regard to the circumstellar habitability of the system. According to previous studies, DNA is taken as a proxy for carbon-based macromolecules following the paradigm that extraterrestrial biology might be based on hydrocarbons. Thus, the DNA action spectrum is utilized to represent the impact of the stellar UV radiation. Atmospheric attenuation is taken into account based on parameterized attenuation functions. We found that the damage inflicted on DNA is notably different for the range of systems studied, and also varies according to the orbit of the Jupiter-type planet, especially in systems of high ellipticity. For some systems large values of damage are attained compared to an Earth-type planet at Earth-like positions in the solar system. A highly protective exomoon atmosphere would be required in most systems to foster habitable environments, notwithstanding extremophiles or systems based on nonstandard exobiology, which are beyond the scope of the present study.

Subject headings: exomoon, exoplanet, extraterrestrial life, F-type stars, habitable zone and UV radiation
1. INTRODUCTION

The identification of habitable regions around main-sequence stars constitutes a vital topic of contemporaneous astrobiological research. However, previous efforts concern mostly late-type stars at the lower end of the effective temperature scale (e.g., Lammer et al. 2013), though notable exceptions include the work on F-type stars by Cockell (1999) and Buccino et al. (2006). Cockell (1999) studied UV radiation environments for various main-sequence stars for different types of planetary atmospheres with different concentrations of N\textsubscript{2} and CO\textsubscript{2}, including genuine efforts to resemble the Archean Earth. He concluded that life may be able to survive in the vicinity of most main-sequence stars of spectral type F, G and K. Moreover, Buccino et al. (2006) introduced the concept of a UV habitable zone for main-sequence stars, including applications to exosolar systems known at the time of study.

A more recent contribution has been made by Sato et al. (2014), henceforth called Paper I. They focused on F-type stars of masses between 1.2 and 1.5 M\textsubscript{\odot}, and considered numerous important aspects, including (1) the role of stellar main-sequence evolution, (2) the location of planets within or relative to the circumstellar habitable zones, and (3) the general influence of planetary atmospheric attenuation, which was described through parameterized attenuation functions. It was found that the damage inflicted on DNA for planets at Earth-equivalent positions is between a factor of 2.5 and 7.1 higher than for solar-like stars, and the amount of damage critically depends on the planetary position. Additionally, there are intricate astrobiological relations for the time-dependency of damage during stellar evolutionary patterns. If atmospheric attenuation is considered, lesser amounts of damage are obtained in response to the model-dependent attenuation parameters.

Although the work by Cockell (1999), Buccino et al. (2006) and Sato et al. (2014), as well as contributions from other authors, indicates that UV radiation has a momentous potential of inducing significant damage on (or loss of) hydrocarbon-based life forms, the fundamental question, i.e., “Is UV a friend or a foe?” still remains unanswered. Favorable assessments about the role of UV, particularly pertaining to the origin of life, stem from a broad range of studies, including the work by Bernstein et al. (2002), Muñoz Caro et al. (2002), and Mulkidjanian et al. (2003). Bernstein et al. (2002) described laboratory demonstrations that racemic amino acids are able to form from the UV photolysis ice analogues, which is consistent with that at least some meteoritic amino acids resulted from interstellar photochemistry. Similar findings have been reported by Muñoz Caro et al. (2002). Moreover, as discussed by, e.g., Mulkidjanian et al. (2003), UV light may also have played a key role in the accumulation of the first polynucleotides through their abiogenic selection as the most UV-resistant biopolymers, a crucial step for the origin of self-replicating RNA-type molecules showing sufficient complexity for undergoing Darwinian evolution.
Setting those fundamental topics aside, noting that they are outside the main scope of our study, we tend to our main theme, which is the assessment of the UV environments of F-type stars. Objects of interest in such environments include potentially habitable objects such as Earth-type planets located in the stellar climatological habitable zone (CLIHZ). Other possibilities for the facilitation of habitability include objects associated with Jupiter-type planets, located in the CLIHZ, such as exosolar Trojan planets (e.g., Dvorak et al. 2004) or massive exomoons (e.g., Williams et al. 1997). Systems with giant planets located inside or crossing into the CLIHZ during their orbital motion are typically unable of hosting habitable planets; see, e.g., Noble et al. (2002) and Yeager et al. (2011) for results from orbital stability simulations. Hence, the focus of the present work consists in the study of potential exomoons in the environments of F-type stars possessing observed Jupiter-type planets. The systems selected for our study include HD 8673, HD 169830, HD 33564, υ And, HD 86264, HD 25171, 30 Ari, and HD 153950 (see Fig. 1 and Table 1) based on data sets not considering additions due to the Kepler mission. Note that the Kepler mission has revealed many new systems of F-stars hosting Jupiter-type planets, constituting relevant targets of future research.

Exomoons, albeit the lack of detections, have been the topic of numerous studies given by, e.g., Williams et al. (1997), Kipping et al. (2009), Kaltenegger (2010), Barnes & O’Brien (2002), and Cuntz et al. (2013). They consider a large variety of aspects such as orbital stability considerations, deciphering spectral fingerprints, and the lower mass limit of exomoons required for retaining a substantial and long-lived atmosphere. Other studies have been devoted to search methodologies as discussed by, e.g., Kipping et al. (2013), Kipping (2014), and Noyola et al. (2014). The work by Kipping and collaborators mostly focused on their efforts of finding exomoons, especially moons located in the stellar CLIHZs, with the Kepler space mission based on photodynamics and sophisticated data analysis techniques. Noyola et al. (2014) suggested to identify exomoons through observations of radio emissions; this type of research is guided by the physical structure of the Jupiter–Io system.

Our summary of literature indicates that exomoons are a topic of great interest, and it is both timely and appropriate to investigate the possibility of habitable exomoons, associated with Jupiter-type planets, despite the lack of observational identifications. Our paper is structured as follows: In Sect. 2, we describe the theoretical approach, including the key equations and concepts. In Sect. 3, we comment on the selection of target star–planet systems. In Sect. 4, we present our results and discussion on UV habitability, the main focus of this study. Our summary and conclusions are given in Sect. 5.

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1 The definition of the CLIHZ follows the work by Kasting et al. (1993), which assumes an Earth-like planet with a CO$_2$/H$_2$O/N$_2$ atmosphere and that habitability requires the presence of liquid water on the object’s surface; see Sect. 2.1 for details, including updates by Kopparapu et al. (2013, 2014).
2. THEORETICAL APPROACH

2.1. Climatological Habitable Zones

A crucial aspect in the study of circumstellar habitability is the introduction of the CLIHZ, a concept, previously considered by Kasting et al. (1993) and others. Even though the centerpiece of our study is quantifying impact of UV (see Sect. 3.2), the CLIHZ is important for two reasons. First, it conveys reference distances regarding the orbits of the Jupiter-type planets, which is highly relevant as the exomoons, if existing, are thought to be in close proximity to their host planets. Second, the inner and outer limits of the CLIHZ can be used as markers for the assessment of UV habitability, particularly the quantity $E_{\text{eff}}$ (see Sect. 4.1), thus supporting the interpretation of our results.

Previously, Kasting et al. (1993) utilized 1-D climate models, which were state-of-the-art at the time, to estimate the position and width of the CLIHZ for a range of main-sequence stars, including the Sun. The basic premise was the assumption of an Earth-like planet with a CO$_2$/H$_2$O/N$_2$ atmosphere and, furthermore, that habitability requires the presence of liquid water on the object’s surface. This work was significantly updated via subsequent studies, including the recent work by Kopparapu et al. (2013, 2014). Their approach consists in numerous improvements, such as new H$_2$O and CO$_2$ absorption coefficients. Moreover, their results pertaining to the various limits of habitability are presented in parametric form with the stellar luminosity and effective temperatures as independent variables, thus allowing applications to actual stars in a straightforward manner.

For example, the work by Kopparapu et al. (2013, 2014) defines the recent Venus / early Mars (RVEM) limits of the CLIHZ, already previously considered by Kasting et al. (1993). For a solar-like star, the range given by the RVEM limits extends from 0.75 to 1.77 AU. In the view of that the studies by Kopparapu et al. (2013, 2014) are based on cloud-free climate models, albeit numerous improvements, we still consider the outer limit to be extended to 2.40 AU. This limit, in part following investigations by Forget & Pierrehumbert (1997), was previously introduced by Mischna et al. (2000) based on the assumption of extreme CO$_2$ cloud coverage and upwelling IR radiation from the object’s surface. Hence, this type of CLIHZ, which extends from 0.75 to 2.40 AU for a solar-like star (see Fig. 2), is subsequently referred to as extended habitable zone (EHZ).

Other important limits concerning the stellar CLIHZs are based on the runaway greenhouse effect (inner limit) and maximum greenhouse effect (outer limit); in the following, these limits are used to signify the extended habitable zone (GHZ). As described by, e.g., Underwood et al. (2003), at the inner limit, the greenhouse phenomenon is enhanced by water vapor, thus promoting surface warming, which increases the atmospheric water vapor
content, thus further raising the surface temperature. At sufficient stellar flux, this will trig-
ger the rapid evaporation of all surface water. Thus, all water will be lost from the surface, and the water will also be lost from the upper atmosphere by photodissociation and subsequen
t water escape to space. Concerning the outer limit, it is assumed that a cloud-free CO\textsubscript{2} atmosphere shall still be able to provide a surface temperature of 273 K.

For solar-like stars, and assuming an Earth-mass object, Kopparapu et al. (2013, 2014) identified those limits as approximately 0.95 and 1.68 AU, respectively. In contrast, Kasting et al. (1993) identified these values as 0.84 and 1.67 AU, respectively. Another important limit of habitability constitutes the moist greenhouse limit, which for solar-like stars has been updated to 0.99 AU. In the previous work by Kasting et al. (1993) another limit was identified given by the first CO\textsubscript{2} condensation obtained by the onset of formation of CO\textsubscript{2} clouds at a temperature of 273 K, which was however not revisited by Kopparapu et al. (2013, 2014). Nevertheless, in the present work, the moist greenhouse limit and the limit due to the first CO\textsubscript{2} condensation are used to define the conservative habitable zone (CHZ), as motivated by a large array of previous studies\textsuperscript{2}.

The extents of the CHZ, GHZ and EHZ for the target stars (see Table 1) are given in Table 2. The results following the established behavior that the more luminous the star, the larger the extents of the CLIHZ. Additionally, a higher stellar luminosity also means that the inner limits of the respective HZ is placed further outward. A more thorough assessment of both the widths and the limits of the various types of HZs requires the consideration of both the luminosities and the effective temperatures of the target stars, which is done as part of our approach. For example, it is found that CLIHZ of the largest width is obtained for HD 86264, where the EHZ extends from 1.60 to 5.06 AU. Somewhat smaller extents for the CLIHZ are found for HD 8673 and \upsilon\ And A; here the outer limits of the EHZs are given as 4.37 and 4.39 AU, respectively. Relatively small extents for the CLIHZ are found for HD 33564 and 30 Ari B. Here the inner limits are given as about 0.95 AU, whereas the outer limits extent to nearly 3.0 AU. These stars are late-type F-stars with luminosities of 1.66 and 1.64 $L_{\odot}$, respectively (see Table 1). Detailed observational results about the various target stars are the focus of Sect. 3.

\textsuperscript{2}In the work by Kopparapu et al. (2013, 2014) the CLIHZ given by the RVEM limits is referred to as GHZ, whereas the CLIHZ between 0.95 and 1.68, as identified for an Earth-mass planet, is referred to as CHZ. This notation is different from that of the present study, which follows previous convention.
2.2. UV Based Habitability Concepts

Following Paper I, we consider the DNA action spectrum as a proxy to simulate the impact of UV radiation regarding hydrocarbon-based biostructure. Generally, an action spectrum is the rate of physiological activity plotted against wavelength or frequency of light. Biological effectiveness spectra can be derived from spectral data by multiplication with an action spectrum $S_\lambda(\lambda)$ of a relevant photobiological reaction with the action spectrum typically given in relative units normalized to unity for, e.g., $\lambda = 300$ nm. The biological effectiveness for a distinct range of the electromagnetic spectrum such as UV radiation is determined by

$$E_{\text{eff}} = \int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda) S_\lambda(\lambda) \alpha(\lambda) d\lambda ,$$

(1)

where $E_\lambda(\lambda)$ denotes the stellar irradiance (ergs cm$^{-2}$ s$^{-1}$ nm$^{-1}$), $\lambda$ the wavelength (nm), and $\alpha(\lambda)$ the planetary atmospheric attenuation function; see Horneck (1995). Here $\lambda_1$ and $\lambda_2$ are the limits of integration which in our computations are set as 200 nm and 400 nm, respectively. Although a significant amount of stellar radiation exists beyond 400 nm, this portion of the spectrum is disregarded in the following owing to the minuscule values for the action spectrum $S_\lambda(\lambda)$ in this regime. Atmospheric attenuation, also referred to as extinction, results in a loss of intensity of the incident stellar radiation. In Eq. (1) $\alpha = 1$ indicates no loss and $\alpha = 0$ indicates a complete loss (see Sect. 2.3).

For the computation of the stellar irradiance for targets in circumstellar environments, typically positioned in the CLIHZ (see Table 2), the domain of interest in the present study, a further equation is needed, which is

$$E_\lambda(\lambda) \propto F_\lambda(R_*/d)^2 .$$

(2)

Here $F_\lambda$ denotes the stellar radiative flux, $R_*$ is the stellar radius and $d$ is the distance between the target and the star. Note that Eq. (2) describes the geometrical dilution of the stellar radiation field. Based on previous work, the UV region of the electromagnetic spectrum has been divided into three bands termed UV-A, UV-B, and UV-C. The subdivisions are somewhat arbitrary and differ slightly depending on the discipline involved. In Paper I, we used UV-A, 400-320 nm; UV-B, 320-290 nm; and UV-C, 290-200 nm. Due to the shape of the action spectrum, it was found that in the environments of F-type stars, most of the damage occurs with respect to UV-C. If the incident stellar radiation is largely blocked in the short wavelength regime of the DNA action spectrum, due to atmospheric attenuation (see below), the majority of damage may occur regarding UV-B. Detailed information for sets of F-type stars, also considering effects of stellar evolution, has been described in detail in Paper I. Previous information, by using an earlier version for the DNA action spectrum, was given by Cockell (1999).
Action spectra for DNA, also to be viewed as weighting functions, have previously been utilized to quantify and assess damage due to UV radiation (Setlow 1974). Besides DNA, action spectra have also been derived for other biomolecules, for biostructures such as cellular components as well as for distinct species, especially extremophiles (e.g., Horneck 1995, and references therein). As discussed in Paper I, the DNA action spectrum increases by almost four orders of magnitude between 400 and 300 nm (see Fig. 4). The reason for this behavior is the wavelength dependence of the absorption and ionization potential of UV radiation in this particular regime. A further significant increase in the DNA action spectrum occurs between 300 and 200 nm. Regarding Earth, it is found that the terrestrial Earth’s ozone layer is able to filter out this type of lethal radiation (e.g., Diffey 1991; Cockell 1998); the terrestrial ozone layer itself has been an important feature for allowing its oxygen level to rise, and thus paving the way for the development of more sophisticated life forms. There is a large array of studies about the impact of UV, among other forcings, on different types of life forms. For example, Rettberg et al. (2010) describes the impact of solar UV on three highly resistant microorganisms as studied in the space experiment ADAPT on the European International Space Station (ISS) module Columbus.

2.3. Stellar Irradiance

The treatment of the stellar irradiance follows closely the concept of Paper I. The accurate account of stellar radiation is employed, including the adequate spectral energy distribution, by utilizing photospheric models computed by the PHOENIX code following; see Hauschildt (1992) and subsequent work. The adopted range of models for the F-type stars are in response to effective temperatures of 6440 K for spectral type F5, 6200 K for F8, and 6050 K for G0 ≡ F10. Contrary to Paper I, early-type F stars are not part of the sample, and their spectral information is thus not needed. For stars intermediate to that grid, spectral information is interpolated in accord to the stellar effective temperatures. The PHOENIX code solves the equation of state, including a very large number of atoms, ions, and molecules. With respect to radiation, the one-dimensional spherically symmetrical radiative transfer equation for expanding atmospheres is solved, including a treatment of special relativity. Opacities are sampled dynamically over about 80 million lines from atomic transitions and billions of molecular lines, in addition to background (i.e., continuous) opacities, to provide an emerging spectral flux as reliable and realistic as possible; see Paper I for further details and references.

A relevant ingredient to our study is the consideration of atmospheric attenuation $\alpha(\lambda)$, which typically results in a notable reduction of the incident stellar radiation. Appropriate
values for $\alpha(\lambda)$ can be obtained through the analysis of theoretical exoatmospheric models (e.g., Seager & Deming 2010 and subsequent work) or the usage of model-dependent historic Earth data (e.g., Cockell 2002). Within the scope of the present work that is focused on the impact of photospheric radiation from different F-type stars, we consider $\alpha(\lambda)$ as described by a parameterized attenuation function ATT defined as

$$\text{ATT} (\lambda) = \frac{C}{2} \left[ 1 + \tanh(A(\lambda - B)) \right]. \quad (3)$$

Here $A$ denotes the start-of-slope parameter, $B$ (in nm) the center parameter, and $C$ the maximum (limited to unity) of the distribution (see Paper I for examples of ATT(\lambda)).

For example, Cockell (2002) provided information about the ultraviolet irradiance reaching the surface of Archean Earth for various assumptions about Earth’s atmospheric composition; the latter allow us to constrain the wavelength-dependent attenuation coefficients for Earth 3.5 Gyr ago. Results for planetary atmospheres focused on the build-up and destruction of ozone have been given by, e.g., Segura et al. (2003).

### 3. TARGET STARS AND PLANETS

In the following, we summarize relevant information on our selection of star–planet systems considered in the present study, which are: HD 8673, HD 169830, HD 33564, $\upsilon$ And A, HD 86264, HD 25171, 30 Ari B, and HD 153950 (see Table 1). The systems consist of an F-type star and at least one Jupiter-type planet (see Table 3); the latter are in considerably different orbits with eccentricities ranging from 0.08 to 0.72. We also comment on the relationships between the planetary orbits and the stellar CLIHZs, subdivided into the CHZs, GHZs, and EHZs (see Sect. 3.1 and Table 2). Important considerations include the different values of the planetary eccentricities, which are also relevant for gauging the outlook for the habitability of possible exomoons.

HD 8673 is an F5 V star of $T_{\text{eff}} = 6413$ K (Fuhrmann 2008). It has a massive planet or brown dwarf with a minimum mass of $14.2 \, M_J$ at $a_p = 3.02$ AU (Hartmann et al. 2010). HD 8673b was discovered in 2010 via radial velocity (RV) measurements through the Tautenburg Observatory Planet Search (TOPS) program. The stellar mass is about $1.3 \, M_{\odot}$. The system’s age is estimated as 2.52 Gyr (Takeda et al. 2007). Since HD 8673b has an eccentricity of 0.723, the star–planet distance varies between 0.84 AU and 5.20 AU. Hence,

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3The spectral types as given have been determined based on the stellar effective temperatures. They may thus be modestly different from those conveyed by the references for the other stellar properties.
the planet moves across both the inner and outer limits of the EHZ. Note that it takes about 1634 days for the planet to complete one orbit.

HD 169830, an F7 V star of $T_{\text{eff}} = 6266$ K (Nordström et al. 2004) with a mass of 1.4 $M_\odot$ (Fischer & Valenti 2005), is host to two planets with $a_p = 0.81$ AU and 3.6 AU, respectively (Mayor et al. 2004). These planets, which are HD 169830b and c, were discovered in 2000 as part of the CORALIE planet search program aimed at the southern hemisphere. The planetary minimum masses are 2.88 and 4.04 $M_J$, respectively. The orbit of HD 169830c lies completely within the highly extended EHZ, whereas HD 169830b is positioned much closer to the star; it will thus be ignored in the following. The eccentricity of HD 169830c is 0.33; therefore, the star–planet distance varies between 2.41 AU, the periapsis, located inside the CHZ and 4.79 AU, the apoapsis, which is at a distance situated between the outer limits of the GHZ and EHZ. The orbital period of HD 169830c is 2102 days. The stellar age is estimated as 2.3 Gyr (Nordström et al. 2004).

HD 33564 is an F7 V star of $T_{\text{eff}} = 6250$ K (Acke & Waelkens 2004). It is a relatively inactive star with an age of 3.0 Gyr (Nordström et al. 2004; Galland et al. 2005). The stellar mass is given as 1.25 $M_\odot$ (Nordström et al. 2004). The star is host to a planet with a minimum mass of 9.1 $M_J$ and a semi-major axis of 1.1 AU; this determination was made based on the RV measurements with ELODIE spectrograph (Galland et al. 2005). The planet, HD 33564b, orbits the star with a period of 388 days; note that the orbital eccentricity is given as $e_p = 0.34$. Thus, the star–planet distance varies between 0.73 and 1.47 AU, corresponding to a distance closer to the host star than the inner limit of the EHZ, on the one hand, and a distance within the CHZ, on the other hand. HD 33564 also has two stellar companions (Dommanget & Nys 2002). However, they are probably unbound to the main star as revealed by the high differences between the proper motions of the components (Galland et al. 2005; Roell et al. 2012).

$\upsilon$ And is a binary system, consisting of an F8 V star of $T_{\text{eff}} = 6210$ K, $\upsilon$ And A (HD 9826), and of an M4.5 V star, $\upsilon$ And B (Lowrance et al. 2002; Santos et al. 2004). The separation between the stars is 750 AU (Lowrance et al. 2002), which implies that any habitable environment of $\upsilon$ And A would remain unaffected by $\upsilon$ And B (Cuntz 2014, 2015). RV measurements led to the detection of four planets around $\upsilon$ And A, and one of the planets, i.e., $\upsilon$ And Ad, is found to be located within $\upsilon$ And A’s CLIHZ. The semi-major axes of the planets $\upsilon$ And Aa, b, c, and d are given as 0.0592, 0.828, 2.51, and 5.25 AU, and their minimum masses are given as 0.69, 1.98, 4.13, and 1.06 $M_J$, respectively (Curiel et al. 2011). The eccentricity of $\upsilon$ And Ad is identified as 0.299 (Curiel et al. 2011), and its true mass has been estimated as 10.19 $M_J$ (Barnes et al. 2011). Its periapsis is given as 1.76 AU, a distance close to the inner limit of the GHZ. The planet stays inside the EHZ at its apoapsis at
3.26 AU. This system is known for the mutual inclination between the planets c and d, which is large as 30° (Barnes et al. 2011). The age of the star is about 3 Gyr (McArthur et al. 2010; Lachaume et al. 1999; Lambert & Reddy 2004; Nordström et al. 2004; Takeda et al. 2007).

HD 86264 is an F8 V star with the properties of $T_{\text{eff}} = 6210$ K and $M_\star = 1.42 M_\odot$ (Fischer et al. 2009). The star possesses a planet with a minimum mass of 7.0 $M_J$ at $a_p = 2.86$ AU, i.e., slightly beyond the outer limit of the CHZ. The planet was discovered in 2009 by the RV measurements at Lick Observatory. Since the planet has an eccentricity of $e_p = 0.7$, it approaches the star at about half the distance of the inner limit of the EHZ at its periapsis, and approaches the outer limit of the EHZ at its apoapsis; the corresponding distance range is between 0.86 AU and 4.86 AU. The orbital period is given as 1475 days. HD 86264 has an age of 2.24 Gyr, and it is moderately active (Fischer et al. 2009).

HD 25171 is an F9 V star of $T_{\text{eff}} = 6160$ K. It has a mass of 1.09 $M_\odot$ (Moutou et al. 2011). It is a non-active star with an age of 4.0 Gyr. Moreover, it possesses a Jupiter-type planet with a minimum mass of 0.95 $M_J$ in a nearly circular orbit with an eccentricity of $e_p = 0.8$. The planet orbits the star close to the outer edge of the EHZ. The planet was detected in 2011 via RV measurements with HARPS. The planet’s semi-major axis is 3.02 AU. Hence, its periapsis and apoapsis are given as 2.78 AU and 3.26 AU, respectively. The outer limit of the EHZ is given as 3.13 AU, thus nearly coinciding with the planet’s apoapsis. The planetary orbital period is 1845 days.

30 Ari is a triple star, consisting of the single line spectroscopic binary, 30 Ari A (HD 16246), and the single star, 30 Ari B (HD 16232). 30 Ari A (main component) is an F3 V star of $T_{\text{eff}} = 6668$ K, and 30 Ari B is an F9 V star of $T_{\text{eff}} = 6152$ K (Nordström et al. 2004). The separation between 30 Ari A and B is about 1520 AU (Perryman 1997; Zombeck 2007; Guenther et al. 2009), which ensures that any habitable environment of 30 Ari A and B would not interfere (Cuntz 2014, 2015). 30 Ari B has a planet at $a_p = 0.995$ AU, which was discovered by the RV measurements obtained at Thüringer Landessternwarte Tautenburg in 2009 (Guenther et al. 2009). The distance is slightly farther from the star than the inner limit of the EHZ at 0.947 AU. The periapsis is at 0.71 AU, but a large part of the orbit is in the CLIHZ. The apoapsis is at 1.28 AU, located in the CHZ. The eccentricity is 0.289, and the orbital period is 335.1 days (Guenther et al. 2009). The stellar mass and the minimum mass of the planet are 1.11 $M_\odot$ (Nordström et al. 2004) and 9.88 $M_J$ (Guenther et al. 2009), respectively. The stellar age is estimated as 0.91 Gyr.

HD 153950 is an F9.5 V star with an effective temperature of $T_{\text{eff}} = 6076$ K (Moutou et al. 2009), i.e., the low temperature limit of our sample. HD 153950 has a planet with a minimum mass of 2.73 $M_J$ and a semi-major axis of $a_p = 1.28$ AU. The planet’s semi-major axis corresponds to a distance about halfway between the inner limit of the EHZ and the inner
limit of the GHZ. At its apoapsis, the planet is located in the CHZ, but at the periapsis, it approaches the star as close as 0.84 AU. The eccentricity is $e_p = 0.34$ \cite{Moutou2009}. The orbital period is 499.4 days. The host star has a mass of 1.12 $M_\odot$. The stellar age has been estimated as 4.3 Gyr. The planet was detected in 2009 via RV measurements by the HARPS instrument.

4. RESULTS AND DISCUSSION

4.1. Comparative studies of $E_{\text{eff}}$

As main focus of our study, we explore the impact of the UV levels that possible exomoons in the eight systems would experience by computing $E_{\text{eff}}$ for the CLIHZs and for the various exoplanetary orbits. $E_{\text{eff}}$ describes the ratio of UV infliction on DNA for a particular set of conditions to the case without any atmospheric interference for an object at 1 AU from the Sun. Hence, $E_{\text{eff}} = 1$ implies that the set of conditions creates a similar level of UV-based damage as it would be found immediately above the Earth’s atmosphere. Here we simulate the case of no atmosphere as well as four cases of different atmospheric attenuations for each planetary system.

The results of the case without atmospheric attenuation, i.e., ATT= 1, are given in Figure 5. The ranges of $E_{\text{eff}}$ corresponding to the CLIHZs and to the orbits of possible exomoons (represented by their hosts, the Jupiter-type planets) are shown by different colors. As expected, the UV levels in the CLIHZs of the F-type stars are generally more severe than for the solar environment, except for regions beyond the outer limits of the GHZs. In the most severe case, found at the inner limit of the EHZ for HD 8673, $E_{\text{eff}}$ is 5.2. For this star, $E_{\text{eff}}$ at the outer limits of the GHZ and EHZ are 1.1 and 0.53, respectively. At the inner limit of the EHZ of HD 153950, which has the lowest $T_{\text{eff}}$ of our target stars, $E_{\text{eff}}$ is given as 3.2. For HD 153950, $E_{\text{eff}}$ at the outer limits of the CHZ, GHZ, and EHZ are identified as 1.0, 0.63 and 0.32, respectively. The distances between the host stars and the various limits of CLIHZs are strongly correlated with the stellar luminosities rather than the stellar effective temperatures. However, $E_{\text{eff}}$ at the limits of the CLIHZs is mostly correlated with the star’s effective temperature. For example, $E_{\text{eff}}$ at the inner limit of the EHZ for a relatively hot star is higher than that for a relatively cool star. Moreover, the differences between $E_{\text{eff}}$ at the various outer and inner limits of a CLIHZ are correlated with the stellar effective temperatures as well, whereas the widths of CLIHZs mostly depend on the stellar luminosities. Thus, $E_{\text{eff}}$ shows a steep rate of change with location within the CLIHZ for a hot, but less luminous star.
In the case of HD 33564, the EHZ extends from 0.95 to 2.99 AU (see Table 2), and the values for the $E_{\text{eff}}$ at the limits are given as 4.7 and 0.47, respectively. In contrast, HD 86264, which is cooler but more luminous than HD 33564, has a wider EHZ extending from 1.60 to 5.06 AU; thus, the change in $E_{\text{eff}}$ with distance in the CLIHZ is more gradual. For HD 86264, $E_{\text{eff}}$ at the inner and outer limit of the EHZ is identified as 4.5 and 0.45, respectively. However, a wider CLIHZ does not necessarily imply that there is a wider area of a relatively mild UV environment. For example, the EHZ of HD 8673 extends from 1.39 to 4.37 AU, but the region in the EHZ with $E_{\text{eff}} \leq 1$ only extends from 3.17 to 4.37 AU. HD 15395 has a narrower EHZ, extending from 1.10 to 3.48 AU, but has a slightly wider region within the EHZ with $E_{\text{eff}} \leq 1$; this latter region extends from 1.96 to 3.48 AU. Also note that for any star considered in our study, the $E_{\text{eff}}$ values obtained at the outer limits of the EHZs are fairly similar.

The UV environments along the orbits of possible exomoons, hosted by exoplanets of very high eccentricities, i.e., HD 8673b and HD 86264b (see Table 3), are most severe, as expected. Hypothetical exomoons of HD 8673b and HD 86264b would experience $E_{\text{eff}}$ values as high as 14.3 and 15.7, respectively, at the periapsis; however, these values would decrease to 0.37 and 0.49, respectively, at the exoplanets’ apoapsis positions. Fortunately, following Kepler’s second law, excursions of these exoplanets, and by implication, any possible exomoon, close to the host stars would be only of relatively short durations considering the relatively high orbital speeds at those positions. In contrast, HD 25171b’s orbit has a relatively low eccentricity, entailing that any possible exomoon would face an environment even milder than that of today’s Earth. Furthermore, any possible exomoon would be subjected to small fluctuations regarding possible DNA damage along its orbit, ranging from $E_{\text{eff}} = 0.38$ to 0.52. The UV environments for HD 196830c and $\nu$ And Ad are relatively moderate as well. The values of $E_{\text{eff}}$ at the periapsis and apoapsis of HD 196830c are identified as 2.1 and 0.52, whereas for $\nu$ And Ad, they are given as 2.8 and 0.82, respectively.

We also studied the impact of atmospheric attenuation regarding UV habitability of possible exomoons. Figure 6 shows that $E_{\text{eff}}$ is greatly reduced for the four cases of atmospheric attenuation taken into account, with the combinations of attenuation parameters given as (i) $(A, B, C) = (0.02, 250, 0.5)$, (ii) $(0.05, 250, 0.5)$, (iii) $(0.02, 300, 0.5)$, and (iv) $(0.05, 300, 0.5)$ (see also Paper I). Case (iv) attenuates UV radiation most effectively. Case (ii) is the least effective of the four cases. In Case (iv), $E_{\text{eff}}$ in the CLIHZs is almost at the same level for all systems taken into account.

Regarding HD 8673, $E_{\text{eff}}$ is given as 0.17 and 0.018 at the inner and outer limits of the EHZ, respectively. Similarly, the values for the $E_{\text{eff}}$ at the inner and outer limits of the EHZ of HD 153950 are given as 0.13 and 0.013, respectively. Even Case (ii) shows a
drastic reduction in $E_{\text{eff}}$ compared to the case without atmospheric attenuation. In this case, $E_{\text{eff}}$ is given as 1.5 and 0.15 at the inner and outer limits of the EHZ of HD 8673, respectively. Moreover, $E_{\text{eff}}$ is found as 1.0 and 0.10 at the inner and outer limit of the EHZ of HD 153950, respectively. The effect of atmospheric attenuation is highly significant in extreme situations for possible exomoons, as, e.g., at the periapsis position of HD 86264b. $E_{\text{eff}}$ in that case is reduced to (i) 4.5, (ii) 4.9, (iii) 1.6, and (iv) 0.6. On the other hand, $E_{\text{eff}}$ at the apoapsis position of HD 86264b is given as (i) 0.14, (ii) 0.15, (iii) 0.049, and (iv) 0.019. Concerning possible exomoons of HD 25171b, atmospheric attenuation as assumed results in even gentler UV environments. At the periapsis and apoapsis positions of HD 257171b, $E_{\text{eff}}$ is given as (i) 0.15 and 0.10, (ii) 0.16 and 0.12, (iii) 0.052 and 0.038, and (iv) 0.020 and 0.015, respectively.

### 4.2. The Case of HD 86264

We augmented our study of atmospheric attenuation in the case of HD 86264, as a tutorial example for a system with an extreme elliptical orbit for the exoplanet; i.e., $e_b \simeq 0.7$ (see Table 3). We studied the variation in DNA damage with the attenuation parameters by applying the atmospheric attenuation with various combinations of $A$ and $B$ to HD 86264b at the periapsis, i.e., the closest star–planet distance. We considered 10 values for $A$ (see Eq. 3), from 0.01 to 0.1 with intervals of 0.01 and 6 values of $B$ from 250 to 300 with intervals of 10. The results are depicted in Figure 7. As conveyed in the previous section, $E_{\text{eff}}$ at the periapsis of HD 86264b is 15.7 in case of no atmosphere. Note that small values of $A$ and $B$ describe prominent amounts of attenuation, which in case of today’s Earth are devised by its ozone layer.

Among the combinations of parameters, the one that produces the minimum $E_{\text{eff}}$ is $(A, B, C) = (0.1, 300, 0.5)$. $E_{\text{eff}}$ is reduced to 0.23 for these parameters. On the other hand, $(A, B, C) = (0.1, 250, 0.5)$ results in the maximum value, i.e., $E_{\text{eff}} = 5.1$, among the combinations. Generally, the amount of UV radiation able to reach the object’s surface decreases as $B$ increases, since $B$ determines the center of the ATT function. For a greater value of $A$, $E_{\text{eff}}$ shows a steeper change with $B$. For example, if $A$ is 0.01, $E_{\text{eff}}$ decreases from 4.2 to 2.4 as $B$ increases from 250 to 300, whereas if $A$ is 0.1, $E_{\text{eff}}$ decreases from 5.1 to 0.23 as $B$ increases from 250 to 300. The behavior of $E_{\text{eff}}$ with variable $A$ and constant $B$ depends on the value of $B$. For $B = 250$ and 260, $E_{\text{eff}}$ decreases with increasing $A$. For $B = 270$, $E_{\text{eff}}$ decreases from 3.47 to 3.07 as $A$ increases from 0.01 to 0.04, and then slightly increases to 3.10 as $A$ increases to 0.1. For $B = 280, 290$, and 300, $E_{\text{eff}}$ increases with increasing $A$. 
5. SUMMARY AND CONCLUSIONS

The aim of this study is to provide a tentative exploration of the astrobiological significance of selected F-type stars based on their UV environments, which host Jupiter-type planets within or close to their CLIHZs; it is assumed that these planets may also be hosts to exomoons. The planets have largely different orbital properties, noting that their semi-major axes range between 0.995 and 3.02 AU, and the eccentricities range between 0.08 (almost circular) and 0.72 (highly elliptical). Although exomoons have not yet been detected in these systems, possible existence of moons stems from inspecting the Solar System, noting that Jupiter and Saturn possess two to five planet-like moons combined, with the exact number depending on the adopted standard or definition, if available.

Our tentative assessments include the calculation of updated sizes for the CLIHZs following work by Kopparapu et al. (2013, 2014), and most importantly, the role of UV due to the stellar photospheric radiation based on the approach of Paper I. Following previous studies, including the work by Cockell (1999), DNA is taken as a proxy for carbon-based macromolecules according to the paradigm that extraterrestrial biology may be most likely based on hydrocarbons; see summary and elaborations by, e.g., Goldsmith & Owen (2002), and most recently by Kolb (2015). The DNA action spectrum is utilized to represent the impact of the stellar UV radiation; this allows us to assess different systems with or without consideration of atmospheric attenuation.

The exomoons, if existing, are considered to be in close proximity to the Jupiter-type planets; therefore, the orbits of these planets are decisive for assessing the general prospects of habitability. The UV exposures of the exomoons vary according to the changes in the star–planet distances given by the ellipticity of the planetary orbits. For example, it is found that the exoplanets HD 169830c and υ And Ad stay within the CLIHZ at all times, if the most extended limits are assumed. On the other hand, HD 8673b and HD 86264b make significant excursions beyond both the inner and outer limits of the CLIHZ even if the most extended limits are considered. This behavior may nullify the exomoon’s potential for habitability depending on its atmospheric and geological conditions, even though limited excursions from the CLIHZ may be permissible, especially for objects of thick atmospheres, as argued by Williams & Pollard (2002) and others. Moreover, Abe et al. (2011) explored habitability of water-limited objects, sometimes referred to as land-worlds (Franck et al. 2003, e.g.), and found that they could remain habitable much closer to the stars, a result relevant for the systems HD 8673, HD 33564, HD 86264, 30 Ari B, and HD 153950.

UV habitability in the context of this study has been measured by $E_{\text{eff}}$, defined as the ratio of damage for a given distance from the star for an object with or without atmospheric attenuation, as chosen by the model, relative to the damage for an object at 1 AU from
a solar-like star without atmospheric attenuation. Inspections of our results show that for the hypothetical exomoon environments of the stars HD 8673 and HD 86264, in the absence of atmospheric attenuation, the highest values for $E_{\text{eff}}$ are attained, given as about 14 and 15, respectively, which apply to the periapsis positions of the Jupiter-type planets. Relative decent values of 2.1 (maximum value) and 0.5 (persistent value) are found for the hypothetical exomoon environments of HD 169830 and HD 25171, respectively. All values of $E_{\text{eff}}$, including the exceptionally high values, are drastically reduced if atmospheric attenuation is applied, as identified for Earth, and as suggested for other objects beyond the Solar System (e.g., Segura et al. 2003).

Our study shows that the damage inflicted on DNA exhibit a large range of values compared to an Earth-type planet at Earth-type positions in the solar system. Typically, these values are relatively high, especially at periapsis position. However, appropriate protection due to atmospheric attenuation can dramatically increase the chances of providing habitable environments, which indicates another strong motivation for the continuation of exoplanet and exomoon focused atmospheric investigations. Current results have been given by Seager & Deming (2010), Rugheimer al. (2013), Madhusudhan al. (2014), and others. Obviously, the key challenge pertinent to the present study is the quest of discovering exomoons; see, e.g., Kipping et al. (2013), Kipping (2014), and Noyola et al. (2014) for proposed search programs and methodologies. Moreover, augmentations of the data base for F-stars with planets, including Jupiter-type planets in orbit within or close to the stellar CLIHZ, are expected in conjunction with the Kepler mission noting that large-scale data analyses are currently underway.
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Fig. 1.— Stellar evolutionary tracks for F-type stars of different masses (solid lines) with the main-sequence depicted by a dashed line. The positions of the eight target stars (see Table 1) considered in the present study are labeled accordingly. The evolutionary track for the Sun (G2 V) is depicted as a dotted line for comparison.
Fig. 2.— Types of CLIHZs; the EHZ, GHZ, and CHZ are color coded. Regarding the EHZ, the range defined by the RVEM limits is depicted in red, whereas the extension based on the work by Mischna et al. (2000) is depicted in green.
Fig. 3.— Domains of the stellar CLIHZs, subdivided into the respective CHZs (dark gray), GHZs (medium gray), and EHZs (light gray), for the various target stars (see Table 1) indicated by (1) to (8). The Earth-equivalent positions, roughly given by the square root of the stellar luminosities, are indicated as dashed lines. The positions of the giant planets are indicated by red dots. Moreover, the ranges of the star–planet distances due to the eccentricity of the planetary orbits are depicted as red lines.
Fig. 4.— DNA action spectrum, adopted from Paper I.
Fig. 5.— Top: $E_{\text{eff}}$ for possible exomoons in reference to the stellar CLIHZs. The CHZs, GHZs, and EHZs are indicated by dark gray, medium gray, and light gray colors. Earth-equivalent positions within the habitable zones are depicted by dashed lines. The target systems (see Table 1) indicated by (1) to (8). Additionally, we show the $E_{\text{eff}}$ values for different positions as defined by the Jupiter-type planets. The ranges in $E_{\text{eff}}$, indicated by the red lines, are due to the eccentric planetary orbits. The red dots are depicting $E_{\text{eff}}$, when the planetary distance is given by its semimajor axis. Bottom: Replication of the top panel, but using an enlarged $y$-scale to depict the extremes of the $E_{\text{eff}}$ values.
Fig. 6.— Values for $E_{\text{eff}}$ for different choices of ATTA, ATTB, and ATTC for possible exomoons in the eight target stars (see Table 1) indicated by (1) to (8).
Fig. 7.— $E_{\text{eff}}$ for a possible exomoon at the periapsis of HD86264b for different choices of ATTA and ATTB, assuming ATTC = 0.5. The color coding follows the value of ATTB. Note that ATTA, ATTB, and ATTC correspond to $A$, $B$, and $C$, respectively, of Eq. 3.
Table 1. Target Stars

| Star     | Type      | $T_{\text{eff}}$ | $L_*$  | $R_*$  | $M_*$  | Ref.          |
|----------|-----------|------------------|--------|--------|--------|--------------|
| HD 8673  | F5 V −27 K| 6413             | 3.60   | 1.54   | 1.312  | 1, 2 ($T_{\text{eff}}$), 3 ($R_*, M_*$) |
| HD 169830| F7 V −14 K| 6266             | 4.69   | 1.84   | 1.4    | 4 ($T_{\text{eff}}$), 5 ($R_*, M_*$) |
| HD 33564 | F7 V −30 K| 6250             | 1.66   | 1.1    | 1.25   | 6 ($T_{\text{eff}}$, $M_*$), 7 ($R_*$) |
| v And A  | F8 V +12 K| 6212             | 3.56   | 1.631  | 1.27   | 8 ($T_{\text{eff}}$), 9 ($R_*$), 10 ($M_*$) |
| HD 86264 | F8 V +10 K| 6210             | 4.72   | 1.88   | 1.42   | 11           |
| HD 25171 | F9 V +35 K| 6160             | 1.80   | 1.18   | 1.09   | 12           |
| 30 Ari B | F9 V +27 K| 6152             | 1.64   | 1.13   | 1.11   | 13, 4 ($T_{\text{eff}}$, $M_*$) |
| HD 153950| G0 V +26 K| 6076             | 2.20   | 1.34   | 1.12   | 14           |

Note. — For example, an expression such as F5 V −27 K means that the stellar effective temperature is 27 K lower than that of a standard F5 V star. The stellar parameters are chosen out of The Extrasolar Planet Encyclopaedia, with the original references given as: 1: [Hartmann et al. (2010)], 2: [Fuhrmann (2008)], 3: [Takeda et al. (2007)], 4: [Nordström et al. (2004)], 5: [Fischer & Valenti (2005)], 6: [Galland et al. (2005)], 7: [Pasinetti Fracassini et al. (2001)], 8: [Santos et al. (2004)], 9: [Baines et al. (2008)], 10: [Fuhrmann et al. (1998)], 11: [Fischer et al. (2009)], 12: [Moutou et al. (2011)], 13: [Guenther et al. (2009)], and 14: [Moutou et al. (2009)].
Table 2. Climatological Habitable Zones

| System     | HZ-iE (AU) | HZ-iG (AU) | HZ-iC (AU) | Earth eqv. (AU) | HZ-oC (AU) | HZ-oG (AU) | HZ-oE (AU) |
|------------|------------|------------|------------|-----------------|------------|------------|------------|
| (1) HD 8673 | 1.39       | 1.79       | 1.84       | 1.85            | 2.41       | 3.05       | 4.37       |
| (2) HD 169830 | 1.59       | 2.06       | 2.11       | 2.13            | 2.80       | 3.51       | 5.03       |
| (3) HD 33564 | 0.95       | 1.23       | 1.25       | 1.27            | 1.67       | 2.09       | 2.99       |
| (4) υ And A  | 1.39       | 1.80       | 1.84       | 1.86            | 2.45       | 3.07       | 4.39       |
| (5) HD 86264 | 1.60       | 2.08       | 2.12       | 2.14            | 2.82       | 3.54       | 5.06       |
| (6) HD 25171 | 0.99       | 1.29       | 1.31       | 1.32            | 1.75       | 2.20       | 3.13       |
| (7) 30 Ari B | 0.95       | 1.23       | 1.25       | 1.26            | 1.68       | 2.10       | 3.00       |
| (8) HD 153950 | 1.10       | 1.43       | 1.45       | 1.47            | 1.95       | 2.44       | 3.48       |

Note. — The inner limits of the EHZ, GHZ, and CHZ are indicated by HZ-iE, HZ-iG, and HZ-iC, respectively, whereas the corresponding outer limits are indicated by HZ-oE, HZ-oG, and HZ-oC, respectively. Additionally, we give the Earth-equivalent distances.
Table 3. Planetary Data

| Planet       | $M_p\sin i$ | $a_p$ (AU) | $e_p$ | $a_p(1-e_p)$ (AU) | $a_p(1+e_p)$ (AU) | Ref.                        |
|--------------|-------------|------------|-------|------------------|------------------|-----------------------------|
| (1) HD 8673b| 14.2        | 3.02       | 0.723 | 0.84             | 5.20             | Hartmann et al. (2010)      |
| (2) HD 169830c| 4.04       | 3.6        | 0.33  | 2.41             | 4.79             | Mayor et al. (2004)         |
| (3) HD 33564b| 9.1         | 1.1        | 0.34  | 0.73             | 1.47             | Galland et al. (2005)       |
| (4) $v$ And Ad| 10.19       | 2.51       | 0.299 | 1.76             | 3.26             | Curiel et al. (2011)        |
| (5) HD 86264b| 7.0         | 2.86       | 0.7   | 0.86             | 4.86             | Fischer et al. (2009)       |
| (6) HD 25171b| 0.95        | 3.02       | 0.08  | 2.78             | 3.26             | Moutou et al. (2011)        |
| (7) 30 Ari Bb| 9.88        | 0.995      | 0.289 | 0.71             | 1.28             | Guenther et al. (2009)      |
| (8) HD 153950b| 2.73        | 1.28       | 0.34  | 0.84             | 1.72             | Moutou et al. (2009)        |

Note. — The stellar parameters are chosen by reference to The Extrasolar Planet Encyclopedia. The original references of $M_p\sin i$, $a_p$, and $e_p$ are given here.