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CALCULATING THE HABITABLE ZONE OF BINARY STAR SYSTEMS. I. S-TYPE BINARIES

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ABSTRACT

We have developed a comprehensive methodology for calculating the boundaries of the habitable zone (HZ) of planet-hosting S-type binary star systems. Our approach is general and takes into account the contribution of both stars to the location and extent of the binary HZ with different stellar spectral types. We have studied how the binary eccentricity and stellar energy distribution affect the extent of the HZ. Results indicate that in binaries where the combination of mass-ratio and orbital eccentricity allows planet formation around a star of the system to proceed successfully, the effect of a less luminous secondary on the location of the primary's HZ is generally negligible. However, when the secondary is more luminous, it can influence the extent of the HZ. We present the details of the derivations of our methodology and discuss its application to the binary HZ around the primary and secondary main-sequence stars of an FF, MM, and FM binary, as well as two known planet-hosting binaries α Cen AB and HD 196886.

Key words: astrobiology – planets and satellites: atmospheres – planets and satellites: dynamical evolution and stability – planets and satellites: terrestrial planets – planet–star interactions

Online-only material: color figures

1. INTRODUCTION

The discovery of circumstellar planets in close binary systems (i.e., binaries with stellar separations smaller than 50 AU) in the past two decades has lent strong support to the fact that planet formation around a star of a binary is robust, and these systems (known as S-type binaries, Figure 1) can host a variety of planets including small, terrestrial-class objects (see Haghighipour 2010; Haghighipour et al. 2010 for a review). At present, there are six close S-type systems that host planets: GL 86 (Queloz et al. 2000; Eggenberger et al. 2003), γ Cephei (Hatzes et al. 2003; Endl et al. 2011), HD 41004 (Zucker et al. 2004), HD 196885 (Correia et al. 2008; Chauvin et al. 2011), HD 176051 (Muterspaugh et al. 2010), and α Centauri (Dumusque et al. 2012, we note that the existence of the planet around the secondary star of this system has recently been challenged by Hatzes 2013). Although Earth-like planets are yet to be discovered in the habitable zone (HZ) of binary star systems, studies of the formation and long-term stability of these objects have shown that depending on the binary semimajor axis, eccentricity, and mass-ratio, Earth-sized planets can form around a star of a binary in a close S-type system and can have stable orbits in the star's HZ (Haghighipour 2006; Quintana et al. 2007; Haghighipour & Raymond 2007; Guedes et al. 2008; Thébault et al. 2008, 2009; Eggl et al. 2013a, 2013b).

In all these simulations, it has been generally assumed that the HZ of the binary is equivalent to the single-star HZ of its planet-hosting star. Although in binaries with separations smaller than 50 AU, the secondary star plays an important role in the formation, long-term stability, and water content of a planet in the HZ of the primary, the effect of the secondary on the range and extent of the HZ in these systems was ignored (in S-type systems, the motion of the binary around its center of mass is neglected and the secondary star is considered to orbit a stationary primary (bottom panel of Figure 1)). However, the fact that this star can affect planet formation around the primary, and can also perturb the orbit of a planet in the primary's HZ in binaries with moderate eccentricities implies that the secondary may play a non-negligible role in the habitability of the system as well. In this paper, we present a methodology for calculating the HZ of S-type binaries by taking the effect of both stars into account, as well as calculate the stability of a planet in the HZ.

Unlike around single stars where the HZ is a spherical shell with a distance determined by the host star alone, in binary star systems, the radiation from the stellar companion can influence the extent and location of the HZ of the system. Especially for planet-hosting binaries with small stellar separations and/or in binaries where the planet orbits the less luminous star, the amount of the flux received by the planet from the secondary star may become non-negligible.

In addition, effects such as the gravitational perturbation of the secondary star (see, e.g., Georgakarakos 2002; Eggl et al. 2012) can influence a planet's orbit in the binary HZ and lead to temperature fluctuations if the planetary atmosphere cannot buffer the change in the combined insolation. Since in an S-type system, the secondary orbits more slowly than the planet, during one period of the binary, the planet may experience the effects of the secondary several times. The latter, when combined with the atmospheric response of the planet, defines the binary HZ of the system. In this paper we concentrate on the extent of the binary HZ and not the dynamical effect of a binary on the orbit of individual planets, which depends on specific system parameters.

Despite the fact that, as a result of the orbital architecture and dynamics of the binary, at times the total radiation received by the planet exceeds the radiation that it receives from its parent star alone by a non-negligible amount, the boundaries of the actual HZ of the binary cannot be obtained by a simple extrapolation of the boundaries of the HZ of its planet-hosting star. Similar to the HZ around single stars, converting from insolation to equilibrium temperature of the planet depends strongly on the planet's atmospheric composition, cloud fraction, and

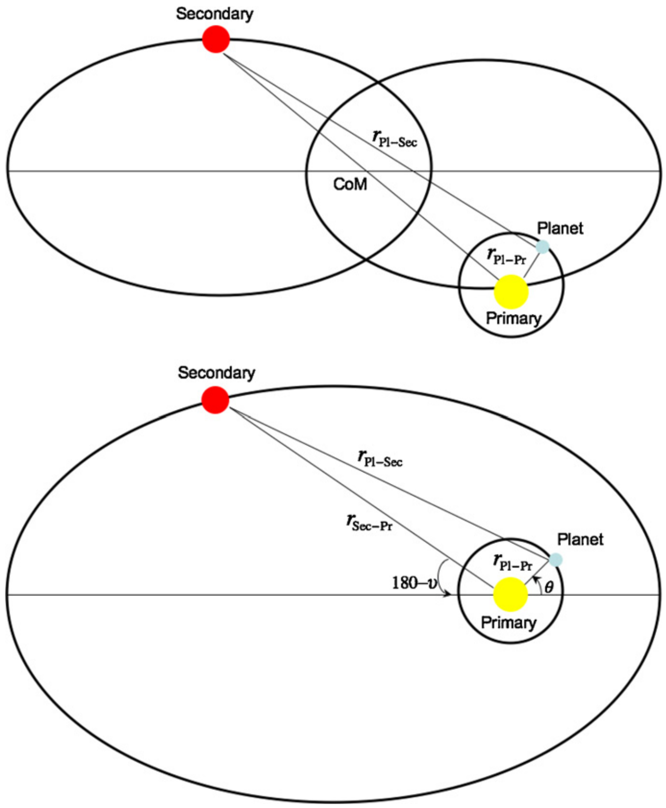

Figure 1. Schematic presentation of an S-type system. The two stars of the binary, primary and secondary, revolve around their center of mass (CoM) while the planet orbits only one of the stars (top panel). It is, however, customary to neglect the motion of the binary around its CoM and consider the motion of the secondary around a stationary primary (bottom panel).

(A color version of this figure is available in the online journal.)

star's spectral type. A planet's atmosphere responds differently to stars with different spectral distribution of incident energy. Different stellar types will therefore contribute differently to the total amount of energy absorbed by the planetary atmosphere (see, e.g., Kasting et al. 1993). A complete and realistic calculation of the HZ has to take into account the spectral energy distribution (SED) of the binary stars as well as the planet's atmospheric response. In this paper, we address these issues and present a coherent and self-consistent model for determining the boundaries of the HZ of S-type binary systems.

We describe our model and present the calculations of the HZ in Section 2. In Section 3.1, we calculate the maximum flux of the secondary on the single-star HZ of the primary in three general binary systems with F-F, M-M, and F-M stars as examples. In Sections 3.2 and 3.3, we demonstrate how to correctly estimate the binary HZ, taking into account the contribution of both components of the binary as well as the stability constraints. We then apply our methodology to two known exoplanetary systems, α Centauri and HD 196885. Among the currently known moderately close planet-hosting S-type binaries, these two systems are the only ones with main-sequence stars and known stellar characteristics (the primary star of the GL 86 system is a white dwarf, that of γ Cephei system is a K IV sub-giant, the HD 41004 system is a hierarchical quadruple system, and it is unclear which star in the binary HD 176051 hosts its planet). We do not take the known planets in these systems into account and instead consider them to host a fictitious Earth-like planet with a $CO_2/H_2O/N_2$ atmosphere (following Kasting et al. 1993; Selsis et al. 2007; Kaltenegger & Sasselov 2011; Kopparapu et al. 2013a). We calculate the HZ of the binary for the cases where the Earth-like planet orbits the primary or the secondary star and study the effect of the binary eccentricity on the width and location of the binary HZ. In Section 4, we discuss the effect of planet eccentricity and in Section 5, we conclude this study by summarizing the results and discussing their implications.

2. DESCRIPTION OF THE MODEL AND CALCULATION OF THE BINARY HABITABLE ZONE

Habitability and the location of the HZ depend on the stellar flux at the planet's location as well as the planet's atmospheric composition. The latter determines the albedo and the greenhouse effect in the planet's atmosphere and as such plays a strong role in determining the boundaries of the HZ. Examples of atmospheres with different chemical compositions include the original $CO_2/H_2O/N_2$ model (Kasting et al. 1993; Selsis et al. 2007; Kopparapu et al. 2013a) with a water reservoir like Earth's and model atmospheres with high H_2/He concentrations (Pierrehumbert & Gaidos 2011) or with limited water supply (Abe et al. 2011).

In this paper, we use the recent update to the Sun's HZ model (Kopparapu et al. 2013a, 2013b). According to this model, the HZ is an annulus around a star where a rocky planet with a $CO_2/H_2O/N_2$ atmosphere and sufficiently large water content (such as on Earth) can host liquid water permanently on its solid surface (which allows remote detectability of atmospheric biosignatures). This definition of the HZ assumes the abundance of CO_2 and H_2O in the atmosphere is regulated by a geophysical cycle similar to Earth's carbonate silicate cycle. The inner and outer boundaries of the HZ in this model are associated with an H_2O- and CO_2-dominated atmosphere, respectively. Between those limits on a geologically active planet, climate stability is provided by a feedback mechanism in which atmospheric CO_2 concentration varies inversely with planetary surface temperature.

The locations of the inner and outer boundaries of a single star's as well as a binary's HZ depend also on the cloud fraction in the planet's atmosphere. That is because the overall planetary albedo A is a function of the chemical composition of the clear atmosphere as well as the additional cooling or warming of the atmosphere due to clouds ($A = A_{\rm clear} + A_{\rm cloud}$). In this paper, we use the region between runaway and maximum greenhouse limits from the recent HZ model as the *narrow* HZ (Kopparapu et al. 2013a, 2013b). This model does not include cloud feedback. Therefore, we use the *empirical* HZ as a second limit that is derived using the fluxes received by Mars and Venus at 3.5 and 1.0 Gyr, respectively (the region between Recent Mars and Early Venus). At these times, the two planets do not show indications for liquid water on their surfaces (see Kasting et al. 1993). In this definition, the locations of the HZs are determined based on the flux received by the planet (see, e.g., Kasting et al. 1993; Selsis et al. 2007; Kaltenegger & Sasselov 2011; Kopparapu et al. 2013a).

2.1. *Effect of Star's Spectral Energy Distribution (SED)*

The locations of the boundaries of the HZ depend on the flux of the star at the orbit of the planet. In a binary star system where the planet is subject to radiation from two stars, the flux of the secondary star has to be added to that of the primary (planet-hosting star) and the total flux can then be used to calculate the

Table 1
Coefficients of Equation (4) (Kopparapu et al. 2013b) and Solar Flux at the Limits of the HZ

	Narrow HZ		Empirical HZ	
	Runaway Greenhouse	Maximum Greenhouse	Recent Venus	Early Mars
$l_{\mathrm{x-Sun}}$ (AU)	0.97	1.67	0.75	1.77
Flux (solar flux @ Earth)	1.06	0.36	1.78	0.32
a	1.2456×10^{-4}	5.9578×10^{-5}	1.4335×10^{-4}	5.4471×10^{-5}
b	1.4612×10^{-8}	1.6707×10^{-9}	3.3954×10^{-9}	1.5275×10^{-9}
c	-7.6345×10^{-12}	-3.0058×10^{-12}	-7.6364×10^{-12}	-2.1709×10^{-12}
d	-1.7511×10^{-15}	-5.1925×10^{-16}	-1.1950×10^{-15}	-3.8282×10^{-16}

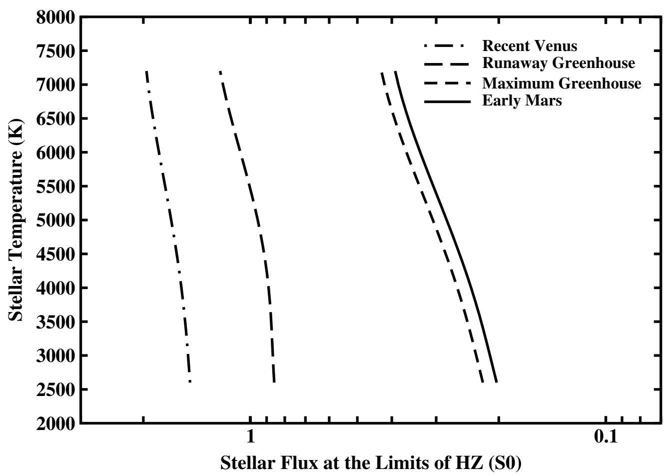

Figure 2. Stellar flux at the top of an Earth-like planet's atmosphere, based on atmospheric models (Kopparapu et al. 2013a, 2013b) when the planet is at the boundaries of the nominal and empirical HZs. The flux on the x axis is scaled to the flux of the Sun at Earth's orbit (S_0).

boundaries of the binary HZ. However, because the response of a planet's atmosphere to the radiation from a star depends strongly on the star's SED, a simple summation of fluxes is not applicable. The absorbed fraction of the absolute incident flux of each star at the top of the planet's atmosphere will differ for different SEDs. The planet's Bond albedo increases with the star's effective temperature (T_{Star}) because for stars with higher values of T_{Star}, more stellar photons are deposited at the top of planet's atmosphere in the short wavelengths where Rayleigh scattering in a planet's atmosphere is very efficient (see the definition of the spectral weight factor in Section 2.2). That increases the amount of reflected stellar light for hotter stars. As a result, the absolute incident stellar flux at the top of the planetary atmosphere that leads to a similar absorbed stellar flux and surface temperature for similar planetary atmospheres is larger for hotter stars (see Section 2.2 and Figure 2). Therefore in order to add the absorbed flux of two different stars and derive the limits of the binary HZ, one has to weight the flux of each star according to the star's SED. The relevant flux received by a planet in this case is the sum of the spectrally weighted stellar flux, separately received from each star of the binary, as given by

$$F_{\mathrm{Pl}}(f, T_{\mathrm{Pr}}, T_{\mathrm{Sec}}) = W_{\mathrm{Pr}}(f, T_{\mathrm{Pr}})\,\frac{L_{\mathrm{Pr}}(T_{\mathrm{Pr}})}{r^2_{\mathrm{Pl-Pr}}} + W_{\mathrm{Sec}}(f, T_{\mathrm{Sec}})\,\frac{L_{\mathrm{Sec}}(T_{\mathrm{Sec}})}{r^2_{\mathrm{Pl-Sec}}}\,. \quad (1)$$

In this equation, F_{Pl} is the total flux received by the planet, L_i and T_i (i = Pr, Sec) represent the luminosity and effective temperature of the primary and secondary stars, f is the cloud fraction of the planet's atmosphere, and $W_i(f, T_i)$ is the binary stars' spectral weight factor. The quantities $r_{\mathrm{Pl-Pr}}$ and $r_{\mathrm{Pl-Sec}}$ in Equation (1) represent the distances between the planet and the primary and secondary stars, respectively. In using Equation (1), we normalize the weighting factor to the flux of the Sun.

From Equation (1), the boundaries of the HZ of the binary can be defined as distances where the total flux received by the planet is equal to the flux that Earth receives from the Sun at the inner and outer edges of its HZ. Since the planet revolves around one star of the binary in an S-type system, we determine the inner and outer edges of the HZ with respect to the planet-hosting star. As mentioned before, it is customary to consider the primary of the system to be stationary, and calculate the orbital elements with respect to the stationary primary star (see bottom panel of Figure 1). In the rest of this paper, we will follow this convention and consider the planet-hosting star to be the primary star as well. In that case, the range of the HZ of the binary can be obtained from

$$W_{\mathrm{Pr}}(f, T_{\mathrm{Pr}})\,\frac{L_{\mathrm{Pr}}(T_{\mathrm{Pr}})}{l^2_{\mathrm{x-Bin}}} + W_{\mathrm{Sec}}(f, T_{\mathrm{Sec}})\,\frac{L_{\mathrm{Sec}}(T_{\mathrm{Sec}})}{r^2_{\mathrm{Pl-Sec}}} = \frac{L_{\mathrm{Sun}}}{l^2_{\mathrm{x-Sun}}}\,. \quad (2)$$

In Equation (2), the quantity l_{x} represents the inner and outer edges of the HZ with x = (in,out). As mentioned earlier, the values of l_{in} and l_{out} are model-dependent and change for different values of cloud fraction, f, and atmosphere composition.

2.2. Calculation of Spectral Weight Factors

To calculate the spectral weight factor $W(f,T)$ for each star of the binary depending on their SEDs, we calculate the stellar flux at the top of the atmosphere of an Earth-like planet at the limits of the HZ, in terms of the stellar effective temperature. To determine the locations of the inner and outer boundaries of the HZ of a main-sequence star with an effective temperature of $2600\ \mathrm{K} < T_{\mathrm{Star}} < 7200\ \mathrm{K}$, we use Equation (3) (see Kopparapu et al. 2013a)

$$l_{\mathrm{x-Star}} = l_{\mathrm{x-Sun}}\left[\frac{L/L_{\mathrm{Sun}}}{1 + \alpha_{\mathrm{x}}(T_i)\, l^2_{\mathrm{x-Sun}}}\right]^{1/2}. \quad (3)$$

In this equation, $l_{\mathrm{x}} = (l_{\mathrm{in}}, l_{\mathrm{out}})$ is in AU, $T_i(\mathrm{K}) = T_{\mathrm{Star}}(\mathrm{K}) - 5780$, and

$$\alpha_{\mathrm{x}}(T_i) = a_{\mathrm{x}} T_i + b_{\mathrm{x}} T_i^2 + c_{\mathrm{x}} T_i^3 + d_{\mathrm{x}} T_i^4\,, \quad (4)$$

where the values of coefficients $a_{\mathrm{x}}, b_{\mathrm{x}}, c_{\mathrm{x}}, d_{\mathrm{x}}$, and $l_{\mathrm{x-Sun}}$ are given in Table 1 (see Kopparapu et al. 2013b). From

Table 2
Samples of Spectral Weight Factors

Star	Eff. Temp	Narrow HZ		Empirical HZ	
		Inner	Outer	Inner	Outer
F0	7300	0.850	0.815	0.902	0.806
F8V (HD 196885 A)	6340	0.936	0.915	0.957	0.913
G0	5940	0.981	0.974	0.987	0.973
G2V (α Cen A)	5790	0.999	0.998	0.999	0.998
K1V (α Cen B)	5214	1.065	1.100	1.046	1.103
K3	4800	1.107	1.179	1.079	1.186
M1V (HD 196885 B)	3700	1.177	1.383	1.154	1.419
M5	3170	1.192	1.471	1.179	1.532
M2	3520	1.183	1.414	1.163	1.458

Equation (3), the flux received by the planet from its host star at the limits of the HZ can be calculated using Equation (5). The results are given in Table 1;

$$F_{\mathrm{x-Star}}(f, T_{\mathrm{Star}}) = F_{\mathrm{x-Sun}}(f, T_{\mathrm{Star}}) \left[1 + \alpha_{\mathrm{x}}(T_i)\, l^2_{\mathrm{x-Sun}}\right]. \quad (5)$$

From Equation (5), the spectral weight factor $W(f,T)$ can be written as

$$W_i(f, T_i) = \left[1 + \alpha_{\mathrm{x}}(T_i)\, l^2_{\mathrm{x-Sun}}\right]^{-1}. \quad (6)$$

Table 2 and Figure 3 show $W(f,T)$ as a function of the effective temperature of a main sequence planet-hosting star for the narrow (top panel) and empirical (bottom panel) boundaries of the HZ. As expected, hotter stars have weighting factors smaller than one whereas the weighting factors of cooler stars are larger than one.

2.3. *Effect of Binary Eccentricity*

To use Equation (2) to calculate the boundaries of the HZ, we assume here that the orbit of the (fictitious) Earth-like planet around its host star is circular. In a close binary system, the gravitational effect of the secondary may deviate the motion of the planet from a circle and cause its orbit to become eccentric. In a binary with a given semimajor axis and mass-ratio, the eccentricity has to stay within a small to moderate level to avoid strong interactions between the secondary star and the planet and to allow the planet to maintain a long-term stable orbit (with a low eccentricity) in the primary's HZ. The binary eccentricity itself is constrained by the fact that in highly eccentric systems, periodic close approaches of the two stars truncate their circumstellar disks depleting them from planet-forming material (Artymowicz & Lubow 1994) and restricting the delivery of water-carrying objects to an accreting terrestrial planets in the binary HZ (Haghighipour & Raymond 2007).

This all indicates that in order for the binary to be able to form a terrestrial planet in its HZ, its eccentricity cannot have large values. In a binary with a small eccentricity, the deviation of the planet's orbit from circular is also small and appears in the form of secular changes with long periods (see, e.g., Eggl et al. 2012). Therefore, to use Equation (2), one can approximate the orbit of the planet by a circle without the loss of generality.

The habitability of a planet in a binary system also requires long-term stability in the HZ. For a given semimajor axis a_{Bin}, eccentricity e_{Bin}, and mass-ratio μ of the binary, there is an upper limit for the semimajor axis of the planet beyond which the perturbing effect of the secondary star will make the orbit of the planet unstable. This maximum or *critical*

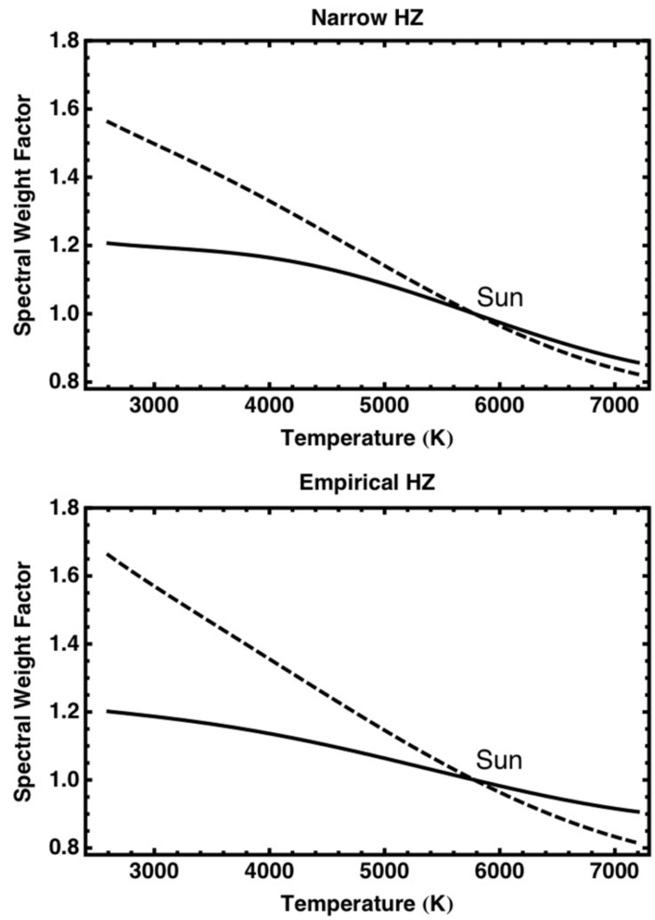

Figure 3. Spectral weight factor $W(f,T)$ as a function of stellar effective temperature for the narrow (top) and empirical (bottom) HZs. The solid line corresponds to the inner and the dashed line corresponds to the outer boundaries of HZ. We have normalized $W(f,T)$ to its solar value, indicated on the graphs (Sun).

semimajor axis (a_{Max}) is given by (Rabl & Dvorak 1988; Holman & Wiegert 1999)

$$a_{\mathrm{Max}} = a_{\mathrm{Bin}}\big(0.464 - 0.38\,\mu - 0.631\,e_{\mathrm{Bin}} + 0.586\,\mu\, e_{\mathrm{Bin}} + 0.15\,e^2_{\mathrm{Bin}} - 0.198\,\mu\, e^2_{\mathrm{Bin}}\big). \quad (7)$$

In Equation (7), $\mu = m_2/(m_1 + m_2)$ where m_1 and m_2 are the masses of the primary (planet-hosting) and secondary stars, respectively. One can use Equation (7) to determine the maximum binary eccentricity that would allow the planet to have a stable orbit in the HZ ($l_{\mathrm{out}} \leqslant a_{\mathrm{Max}}$). For any smaller value of the binary eccentricity, the entire HZ will be stable. We will present a detailed discussion of this topic in Sections 3.2 and 3.3, where we calculate the boundaries of the HZ of the α Centauri and HD 196885 systems, respectively.

3. THE HABITABLE ZONE OF MAIN SEQUENCE S-TYPE BINARIES

Without knowing the exact orbital configuration of the planet, one can only estimate the boundaries of the binary HZ by calculating the maximum and minimum additional flux from the secondary star at its closest and furthest distances from a fictitious Earth-like planet as a first order approximation. This brackets the limits of the binary HZ. Note that using the maximum flux of the secondary onto the planet for calculating the new binary HZ overestimates the shift of the HZ from the

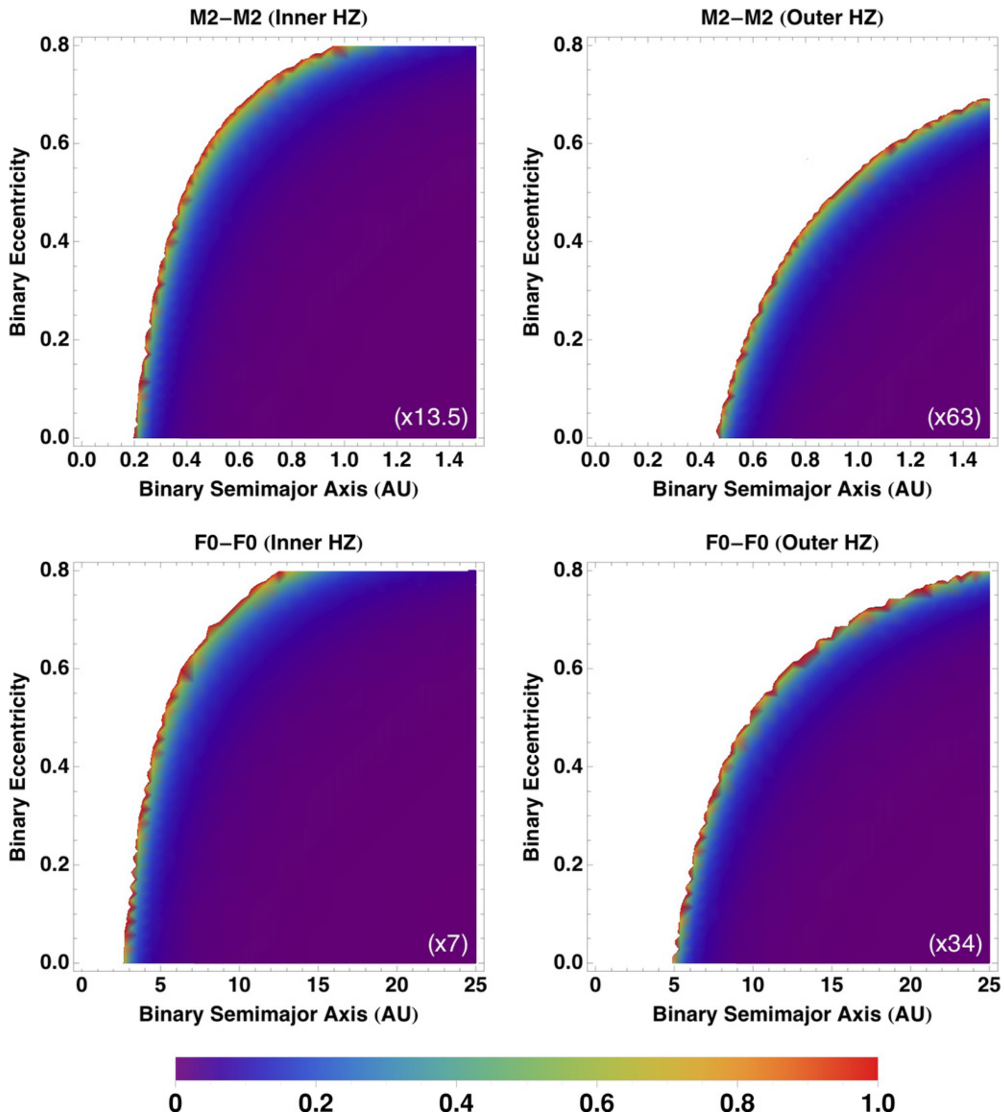

Figure 4. Maximum contribution of the secondary star to the total flux received at the boundary of the single-star HZ of the primary of an M2-M2 (top) and an F0-F0 (bottom) S-type binary. The color-coding, times the number on the lower right corner on each panel, represents the flux contributed by the secondary star at closest distance relative to the flux received from the primary. Note that we do not considering stability of a fictitious planet here. The left (right) column corresponds to the inner (outer) limit of the empirical HZ.

single star's HZ to the binary HZ due to the secondary because the planet's atmosphere can buffer an increase in radiation temporarily. This shift is underestimated when one uses the minimum flux received from the secondary star onto the planet. To improve on this estimation, one needs to know the orbital positions of the planet as well as the stars in the binary. That way one can determine the exact flux reaching the planet over time as well as the number of planetary orbits over which the secondary's flux can be averaged. This depends on the system's geometry (both stellar and planetary parameters) and needs to be calculated for each planet-hosting S-type system, individually. We assume here that the orbit of the planet around its host star is circular.

3.1. *Influence of the Secondary on the Single-star HZ of the Primary*

To explore the maximum effect of the binary semimajor axis and eccentricity on the contribution of one star to the extent of the HZ around the other component, we consider three extreme cases: an M2-M2 (Figure 4, top), an F0-F0 (Figure 4, bottom), and an F8-M1 (Figure 5) binary. We consider the M2 and F0 stars to have effective temperatures of 3520 (K) and 7300 (K), respectively, and their luminosities to be 0.035 and 6.56 of that of the Sun for our general examples here.

We first study the effect of a secondary on the single-star HZ around the primary star. Figures 4 and 5 show the maximum contribution of the secondary to the stellar flux at the limits of the single star's HZ of the primary, when the secondary star and a fictitious rocky planet are at their closest separation, and for different values of the binary eccentricity and semimajor axis. The color coding in these figures corresponds to the contribution of the flux received from the secondary relative to that of the primary star (note the multiplication factor on the lower right corner of each panel). Figure 4 shows secondary's flux at the inner (left) and outer (right) edge of the primary's single-star empirical HZ, for a M2-M2 binary (top) and for a F0-F0 binary (bottom). The contribution of the secondary can be several times larger than the primary's at closest approach. The contribution of the secondary is larger at the outer edge of the primary's HZ than at the inner edge and increases with decreasing periastron

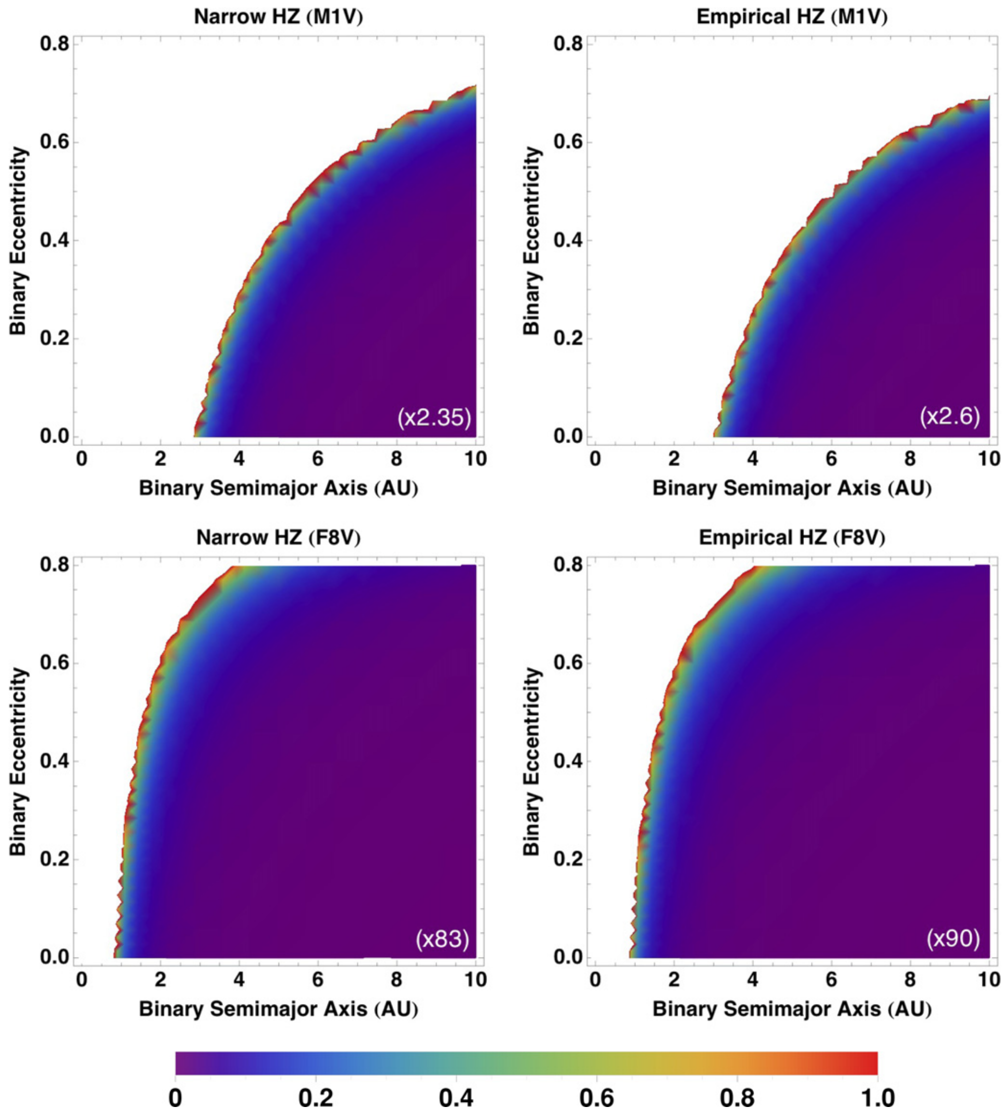

Figure 5. Maximum contribution of the secondary star (top: M1V, bottom: F8V) to the total flux received at the outer limit of the single-star HZ of the primary star (top: F8V, bottom: M1V) in a F8V-M1V S-type binary system—similar to HD 196885. The color-coding, times the number on the lower right corner on each panel, represents the flux contributed by the secondary star at closest distance relative to the flux received from the primary at the boundary of the primary's single-star HZ. Note that we do not consider the stability of a fictitious planet here. The left (right) column corresponds to the flux received at the outer limit of the narrow (empirical) HZ.

distance of the binary. Note that the actual flux contribution of the secondary that determines the binary HZ limits is the secondary's flux averaged over the planet's full orbit and as such it will be smaller than the secondary's flux at closest approach.

To explore the effect of the secondary for a binary with a hot and a cool star, we use an F-M system (see Figure 5). The top panels of Figure 5 show the maximum flux of the M1V secondary star at the outer edges of the F8V primary's single-star narrow (left) and empirical HZs (right) when the secondary is at its closest distance (i.e., during its periastron passage). The bottom panels show the maximum flux of the F8V at the outer edges of the single-star narrow and empirical HZ of the M1V star. As shown by these panels, the flux of the brighter star has a stronger contribution to the total flux at the outer edge of the primary's HZ (up to several times the primary's flux). Figures 4 and 5 do not consider the orbital (in)stability of the fictitious Earth-like planet. When in an individual case, the stability criterion as shown in Equation (7) is imposed, the closest distance between the secondary and planet, which ensures the orbital stability of the planet as well, will be larger than the closest distance shown in these figures, and as a result, the contribution of the secondary star to the total flux received by the planet is smaller.

As a second step, to demonstrate the effect of the secondary on the boundaries of the HZ, we calculate the binary HZ of the systems mentioned above, considering the minimum value of the binary semimajor axis for which the outer edge of the primary's empirical HZ will be on the stability limit. Figures 6 shows the results for the case of the three binaries described above, assuming circular orbits, (top) an M2-M2 (left), an F0-F0 (right) and (bottom) an F8-M1 S-type binary, with (left) the F8 star and (right) the M1 star being the planet-hosting star. The top panel of Figure 6 shows that the secondary does not have a noticeable effect on the extent of the HZ. The binary HZ around each star is equivalent to its single-star HZ for the M2-M2 and F0-F0 S-type systems when stability up to the outer region of the empirical HZ is maintained. Also as expected,

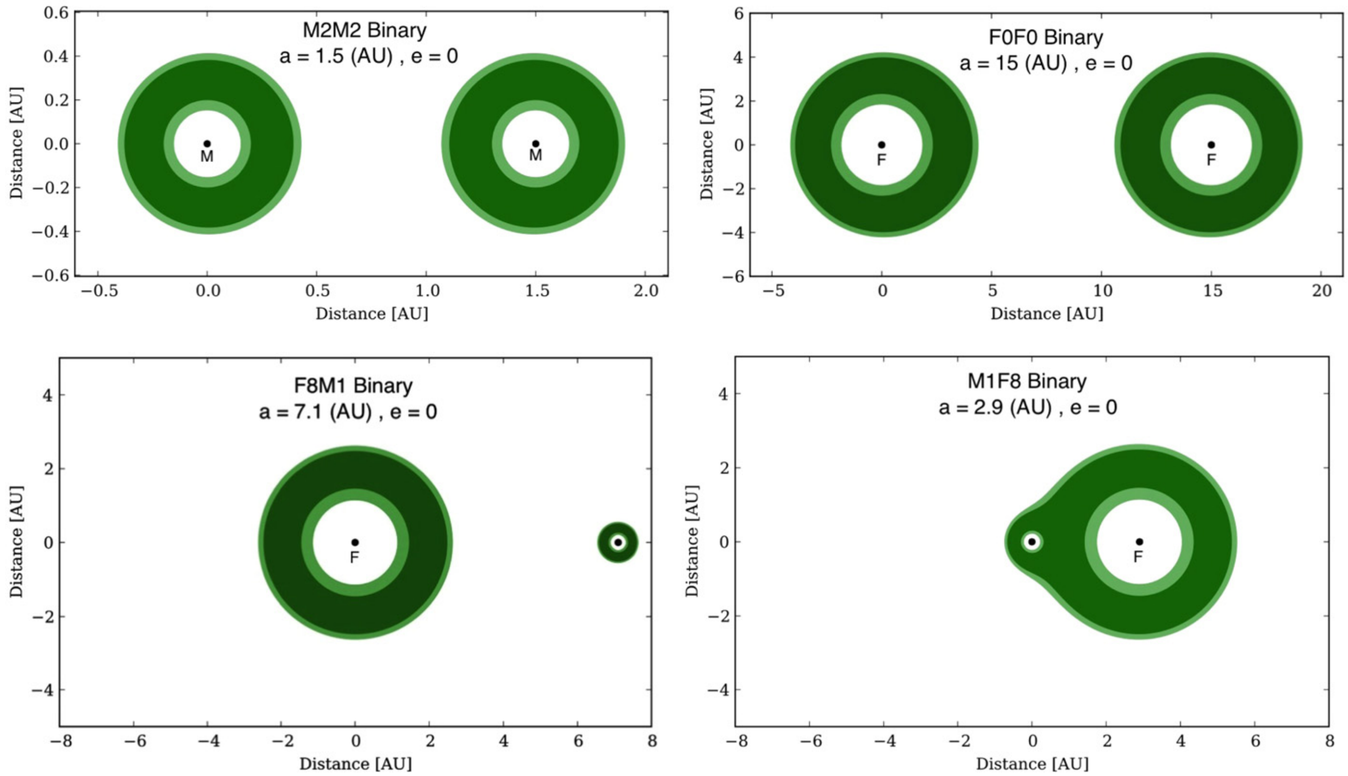

Figure 6. Boundaries of the narrow (dark green) and empirical (light green) HZs in an M2-M2 (top left), F0-F0 (top right), and M1-F8 S-type binary star system (bottom two panels). Note that the primary is the star at (0,0). The primary star in the bottom panels is the F8 star (left) and the M1 star (right). The semimajor axis of the binary has been chosen to be the minimum value that allows the region out to the outer edge of the primary's empirical HZ to be stabile in a circular binary.

(A color version of this figure is available in the online journal.)

the effect of the M1 star on the extension of the single-star HZ around the F8 star is negligible. However, at its closest distances, the F8 star can extent the limit of the single-star HZ around the M1 star so far out that at the binary periastron, the two HZs merge.

To further explore the effect of binary eccentricity in a system with a hot and cool star, we carried out similar calculations as those in Figure 6 for the F8-M1 binary, assuming the binary eccentricity to be 0.3. Figures 7 and 8 show the results for four different relative positions of the two stars to show the changing influence of the secondary over the binary's orbit. The primary and planet-hosting star is chosen to be the M star (Figure 7) and the F star (Figure 8). Figure 7 shows that a luminous secondary can have considerable effects on the shape and location of the HZ. However, a cool and less luminous secondary will not change the limits of the HZ (Figure 8). The figures also demonstrate why the exact boundaries of the binary HZ can only be calculated when the relative position of the planet to the stars is known—and the flux received by the planet over one full planetary orbit can be calculated.

3.2. Binary HZ—Example: α Centauri

The α Centauri system consists of the close binary α Cen AB and a farther M dwarf companion known as Proxima Centauri at approximately 15,000 AU. The semimajor axis of the binary is $\sim$23.5 AU and its eccentricity is $\sim$0.518. The component A of this system is a G2V star with a mass of 1.1 M_{Sun}, luminosity of 1.519 L_{Sun}, and an effective temperature of 5790 K. Its component B has a spectral type of K1V and its mass, luminosity and effective temperature are equal to 0.934 M_{Sun}, 0.5 L_{Sun}, and 5214 K, respectively.

The recent announcement of a probable super-Earth planet with a mass larger than 1.13 Earth-masses around α Cen B indicates that unlike the region around α Cen A where terrestrial planet formation encounters complications, planet formation is efficient around this star (Guedes et al. 2008; Thébault et al. 2009) and it could also host a terrestrial planet in its HZ. Here we assume that planet formation around both stars of this binary can proceed successfully and they both can host Earth-like planets. We calculate the spectral weight factors of both α Cen A and B (Table 2) and, using the minimum and maximum added flux of the secondary star, estimate the limits of their binary HZs using Equation (2).

Table 3 shows the estimates of the boundaries of the binary HZ around each star. The terms Max and Min in this table correspond to the planet–binary configurations of $(\theta, \nu) = (0, 0)$ and $(0, 180^\circ)$ (see Figure 1 for the definition of θ and ν) where the planet receives the maximum and minimum total flux from the secondary star, respectively. As shown here, each star of the α Centauri system contributes to increasing the limits of the binary HZ around the other star. Although these contributions are small, they extend the estimated limits of the binary HZ by a noticeable amount. This is primarily due to the high luminosity of α Cen A and the relatively large eccentricity of the binary which brings the two stars as close as $\sim$11.3 AU from one another (and as such making planet formation very difficult around α Cen A).

Generalizing our study, we examined the effect of increasing eccentricity in an α Cen-like system (with similar G2V and K1V stars) by calculating the critical distance around both stars

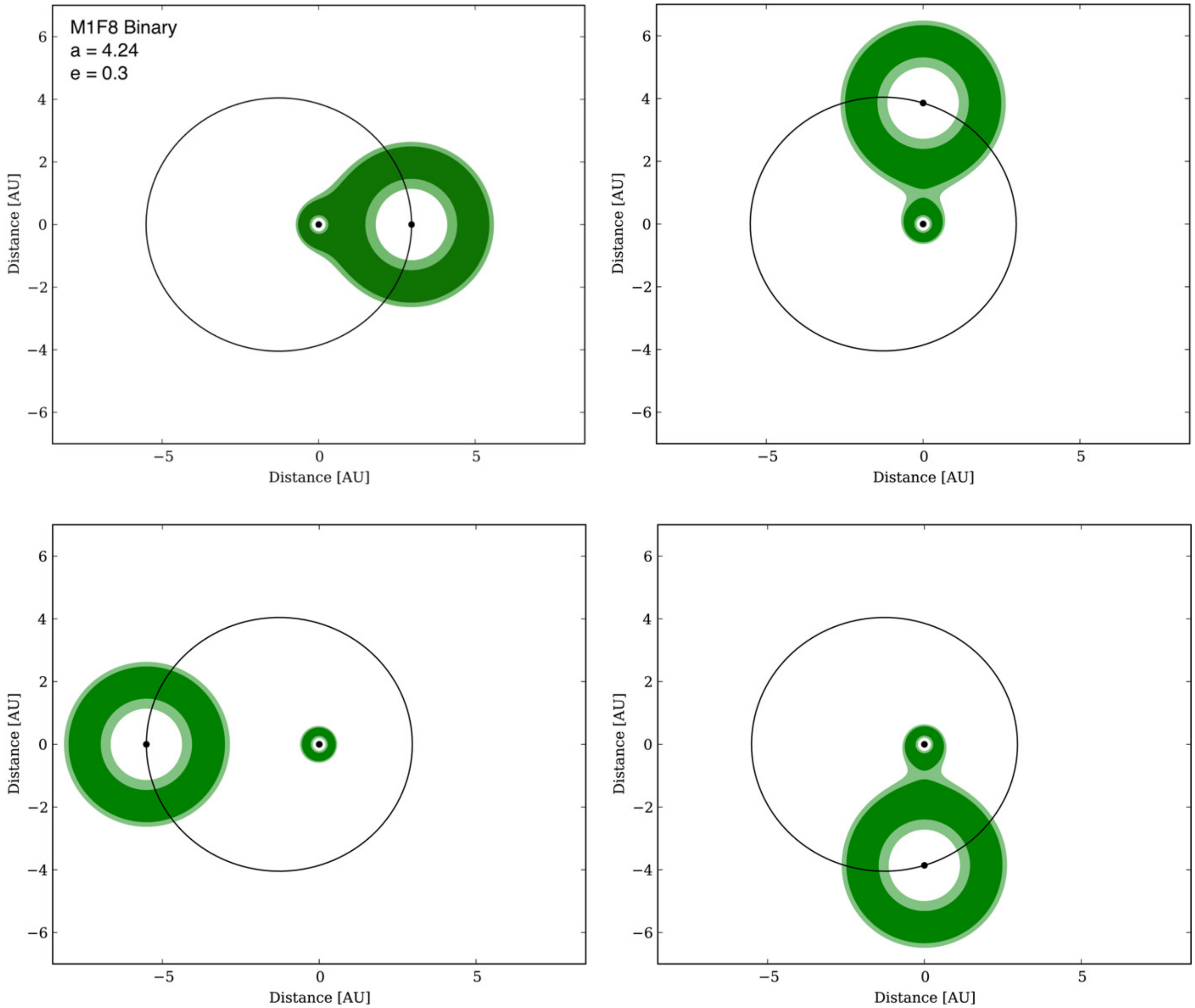

Figure 7. Boundaries of the narrow (dark green) and empirical (light green) HZs in an M1-F8 binary. Note that the primary is the M1 star at (0,0). The panels show the effect of the F8 star while orbiting the primary starting from the top left panel when the secondary is at the binary periastron. The semimajor axis of the binary has been chosen to be the minimum value that allows the region out to the outer edge of the primary's empirical single-star HZ to be stable for a binary eccentricity of 0.3.
(A color version of this figure is available in the online journal.)

Table 3
Estimates of the Boundaries of the Binary HZ for the Max. and Min. Flux from the Secondary at Closest and Farthest Approach between a Fictitious Planet and the Secondary Star

Host Star	Estimates of Narrow HZ (AU)				Estimates of Empirical HZ (AU)			
	With Secondary		Without Secondary		With Secondary		Without Secondary	
	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
α Cen A (max)	1.197	2.068	1.195	2.056	0.925	2.194	0.924	2.179
α Cen A (min)	1.195	2.057	1.195	2.056	0.924	2.181	0.924	2.179
α Cen B (max)	0.712	1.259	0.708	1.238	0.544	1.340	0.542	1.315
α Cen B (min)	0.708	1.241	0.708	1.238	0.543	1.317	0.542	1.315
HD 196885 A (max)	1.454	2.477	1.454	2.475	1.137	2.622	1.137	2.620
HD 196885 A (min)	1.454	2.475	1.454	2.475	1.137	2.620	1.137	2.620
HD 196885 B (max)	0.260	0.491	0.258	0.481	0.198	0.529	0.197	0.516
HD 196885 B (min)	0.258	0.483	0.258	0.481	0.197	0.518	0.197	0.516

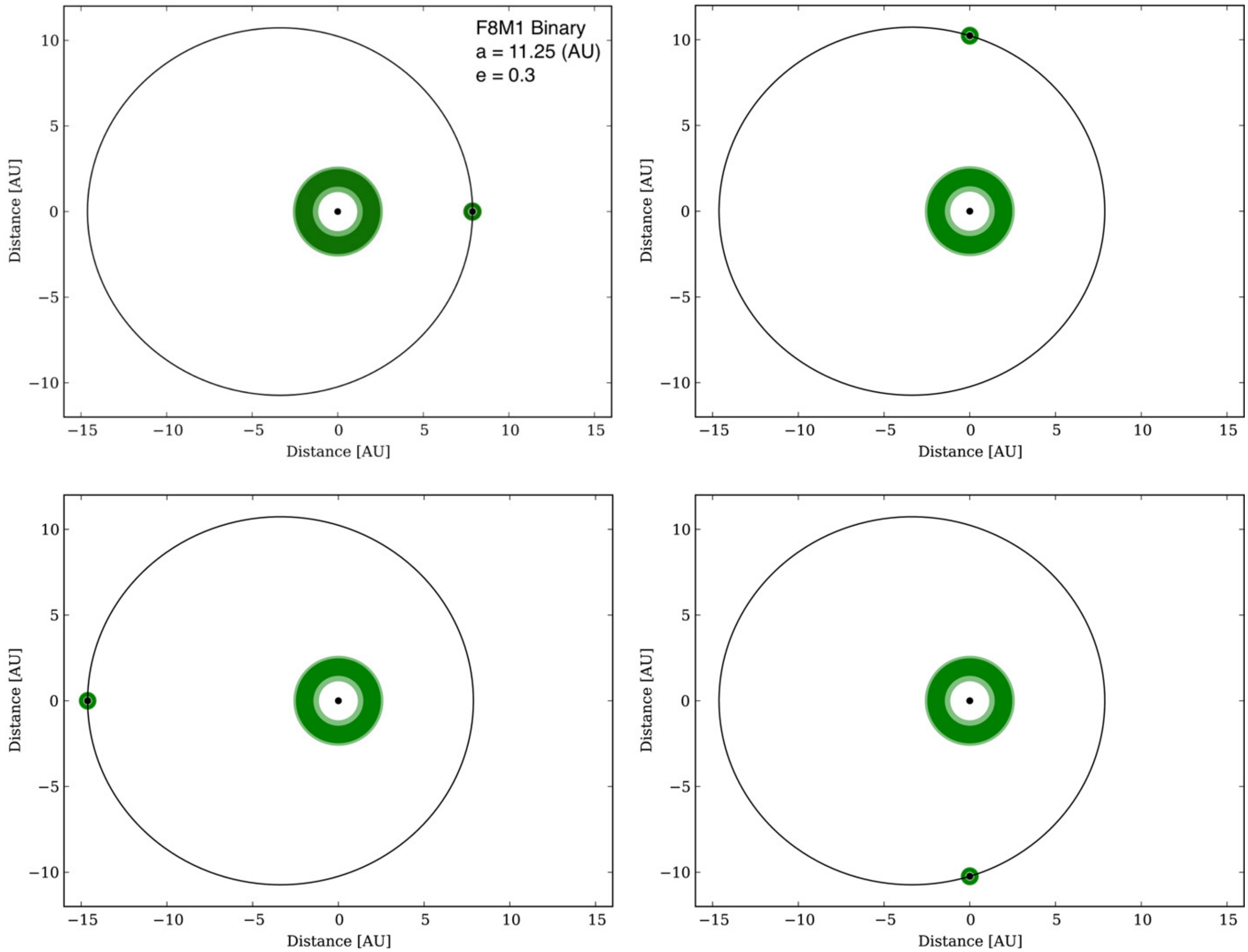

Figure 8. Same as Figure 7, with the F star as the primary.
(A color version of this figure is available in the online journal.)

of this binary for which the entire HZ will be dynamically stable (i.e., $l_{\rm out} \leqslant a_{\rm Max}$). For the G2V star, the stability limit is given by

$$a_{\rm Max} = 23.5\big(0.2892 - 0.361446\, e_{\rm Bin} + 0.05892\, e_{\rm Bin}^2\big), \quad (8)$$

and for the K1V star, it is equal to

$$a_{\rm Max} = 23.5\big(0.2584 - 0.313974\, e_{\rm Bin} + 0.042882\, e_{\rm Bin}^2\big). \quad (9)$$

The maximum value of the binary eccentricity for which an Earth-like planet around the G2V star can have a stable orbit at the outer boundary of the narrow HZ is 0.62. For the empirical HZ, this maximum eccentricity reduces to 0.59. For all values of the binary eccentricity smaller than 0.62 (0.59), the entire narrow (empirical) HZ around the G2V star will be stable. For the K1V star, the maximum binary eccentricity that allows the entire HZ to be stable is 0.73 for the narrow and 0.71 for the empirical binary HZs.

Given the eccentricity of the α Cen binary ($e_{\rm Bin} = 0.518$), both narrow and nominal HZs for α Cen A and B are stable. Figure 9 shows the maximum effective flux of a G2V star received by an Earth-like planet in the HZ of the K1V star during the secondary's (i.e., the G2V star) periastron passage. Note that this is a short-lived flux that can be buffered by the

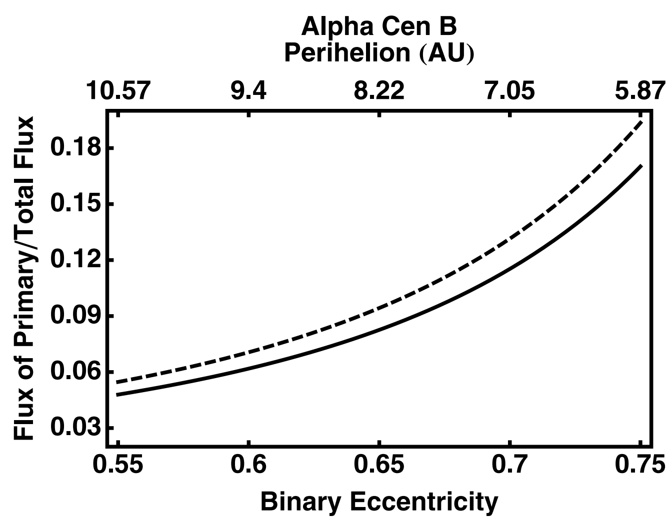

Figure 9. Maximum added flux at closest distance (periastron) from a secondary from a G2V secondary at the limits of the binary HZ of a K1V star in a generalized S-type binary similar to α Cen ($a_{\rm Bin} = 23.5$ AU) as a function of the binary eccentricity. The outer edge of the narrow (solid) and empirical (dashed) binary HZs are shown.

planet's atmosphere and reduces the secondary's heating effect in its closest approach. The maximum flux of the secondary is only used here to estimate the maximum shift from the single-star HZ to the binary HZ.

In the α Cen system, where the binary eccentricity is 0.518, the stability limit around the primary G2V star is at ∼2.768 AU. This limit is slightly exterior to the outer boundary of the star's narrow and empirical HZs. Although the latter suggests that the HZ of α Cen A is dynamically stable, the close proximity of this region to the stability limit may have strong consequences on the actual formation of an Earth-like planet in this region (see, e.g., Thébault et al. 2008; Eggl et al. 2012).

3.3. Binary HZ—Example: HD 196885

HD 196885 is a close main sequence S-type binary system with a semimajor axis of 21 AU and eccentricity of 0.42 (Chauvin et al. 2011). The primary of this system (HD 169885 A) is an F8V star with a $T_{\rm Star}$ of 6340 K, mass of 1.33 $M_{\rm Sun}$, and luminosity of 2.4 $L_{\rm Sun}$. The secondary star (HD 196885 B) is an M1V dwarf with a mass of 0.45 $M_{\rm Sun}$. Using the mass–luminosity relation $L \sim M^{3.5}$, where L and M are in solar units, the luminosity of this star is approximately 0.06 $L_{\rm Sun}$ and we consider its effective temperature to be $T_{\rm Star} = 3700$ K. The primary of HD 196885 hosts a Jovian-type planet suggesting that the mass-ratio and orbital elements of this binary allow planet formation to proceed successfully around its primary star. We assume that terrestrial planet formation can also successfully proceed around both stars of this binary and can result in the formation of Earth-sized objects.

To estimate the boundaries of the binary HZ of this eccentric system, we ignore its known giant planet and use Equation (2) considering a fictitious Earth-like planet in the HZ. We calculate the spectral weight factor $W(f,T)$ for both stars of this system (Table 2) and estimate the locations of the inner and outer boundaries of the binary's HZ (Table 3).

As expected (because of the large periastron distance of the binary and the secondary star being a cool M dwarf), even the maximum flux from the secondary star does not have a noticeable contribution to the location of the HZ around the F8V primary of HD 196886. However, being a luminous F star, the primary shows a small effect on the location of the HZ around the M1V secondary star (Table 3).

Generalizing our study, we examined the effect of increasing eccentricity in an HD 196885-like system (with similar F8V and M1V stars) by calculating the critical distance around both stars of this binary for which the entire HZ will be dynamically stable (i.e., $l_{\rm out} \leqslant a_{\rm Max}$). Around the F8V star, the stability limit is given by

$$a_{\rm Max} = 21\big(0.36786 - 0.482742\, e_{\rm Bin} + 0.1\, e_{\rm Bin}^2\big). \qquad (10)$$

Around the M1V secondary, the critical distance is at

$$a_{\rm Max} = 21\big(0.18014 - 0.193258\, e_{\rm Bin} + 0.002\, e_{\rm Bin}^2\big). \qquad (11)$$

Using Equation (7) for the case when the planet orbits the F8V star, the maximum value of $e_{\rm Bin}$ for which the binary HZ will be stable is 0.59 for the narrow and 0.57 for the empirical HZs. This suggests that for all values of $e_{\rm Bin} \leqslant 0.57$, the HZ of the F8V star will be stable. Similar calculations for the HZ around the M1V star indicate that the upper value of the binary eccentricity for which the narrow and empirical HZs of the M1V star will be stable are $e_{\rm Bin} \leqslant 0.82$ and $e_{\rm Bin} \leqslant 0.81$, respectively. Figure 10 shows the maximum effective flux of each star of the binary received by an Earth-like planet in the HZ of the other star during their periastron passages. Similar to the case of α Cen binary, this is a short-lived maximum flux that can be buffered by the planet's atmosphere and would reduce the secondary's heating effect at its closest distance. The maximum flux of the secondary is only used here to estimate the maximum shift of the HZ. In practice, the influence of a secondary in an S-type binary on the extent of the binary HZ around the other component has to be determined in a case by case basis for the specific geometry of the system.

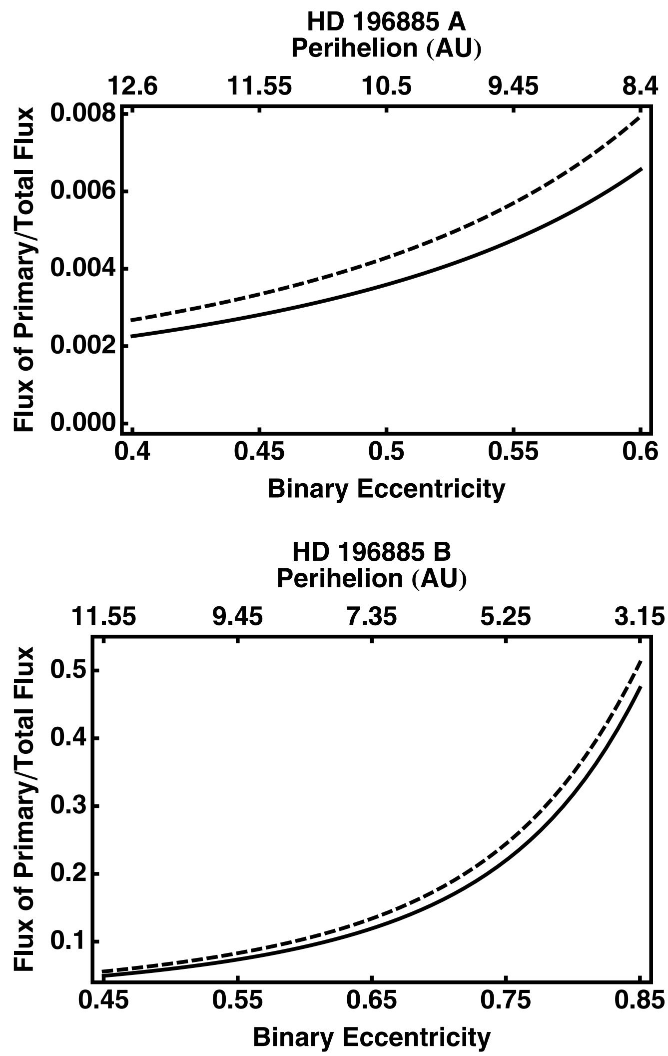

Figure 10. Maximum added flux at closest distance (periastron) from a secondary at the limits of the binary HZ of a F8V (top) and M1V (bottom) star in a generalized S-type binary similar to HD 196885, ($a_{\rm Bin} \sim 21$ AU) as a function of the binary eccentricity. The outer edge of the narrow (solid) and empirical (dashed) binary HZs are shown.

4. DISCUSSION: THE EFFECT OF THE PLANET ECCENTRICITY

We considered the (fictitious) Earth-like planet in the HZ to be in a circular orbit. In a close binary system, the gravitational effect of the secondary may deviate the motion of the planet from a circle and cause its orbit to become eccentric. Similar to the case of a planet orbiting a single star, a planet's eccentricity increases the annually averaged irradiation from the primary star by a factor of $(1 - e_{\rm Pl}^2)^{-1/2}$ (see Williams & Pollard

2002). In addition, for a planet in an eccentric S-type binary system, eccentricity can also increase the temporary maximum flux received from the secondary star due to the decrease in planet–secondary distance. This effect, however, depends on the planet's relative position to the secondary. We assume that one can average the secondary's flux on the planet over the orbital period of the planet as a very conservative estimate on the secondary's influence. This estimate can be used for close binaries, for which we assume that the planet's atmosphere can buffer the changing flux from the secondary, over the secondary's orbit. Detailed general circulation modeling is needed to determine the time, in terms of binary or planet orbital period, that the planet's atmosphere can efficiently buffer the changing flux of the secondary star.

5. CONCLUDING REMARKS

We have presented a methodology for calculating the spectral weight factors of the individual stars in a binary system, which can be used to determine the boundaries of the binary HZ. The foundation of our calculation is based on the fact that the response of the planet's atmosphere to the radiation from the star depends strongly on the star's SED as well as the planet's cloud fraction and atmospheric composition. For a given atmospheric composition, stars with different SEDs deposit different amounts of energy, implying that the flux of a star received at the top of the planet's atmosphere has to be weighted according to the star's SED. This is especially important in binary systems where the two stars are of different spectral types. We derived a formula for the spectral weight factor that takes into account the spectral type of the star as well as the models of the HZ around the Sun.

To demonstrate the maximum effect of a secondary, we calculated the single-star HZ around the primary and showed the contribution of the secondary in an F-F, M-M, and F-M binary for circular orbits as well as for eccentric binary orbits. We then demonstrated how to calculate the binary HZ and used two known planet-hosting binaries α Cen AB and HD 196886 as demonstrations. We chose these two systems because their stellar components are main-sequence stars and they present real examples of binaries in which stars have considerably different luminosities. We bracketed the binary HZ of these systems and studied the connection between their stability and the binary eccentricity. Our study indicates that the effect of the secondary star on the location and width of the binary HZ is generally small in an S-type system. In systems where the secondary is more luminous, its effect can influence the extent of the HZ, especially for close eccentric binaries (barring stability requirements).

Habitability of a system also requires the existence of a terrestrial-class planet in the HZ. In order for an S-type binary to form such a planet and maintain its long-term stability, its orbital elements have to satisfy stringent conditions. As can be seen from the currently known close, S-type systems, the semimajor axes of these binaries are within the range of 17–20 AU and their eccentricities are limited to low to moderate values. The perturbation of the secondary star in these systems may excite the dynamics of the Earth-like planet in the binary HZ and increase its orbital eccentricity slightly. However, such induced orbital eccentricities will not have drastic effects on the planet's habitability.

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