Nikolaos Georgakarakos
NYUAD, United Arab Emirates

Habitable zones in stellar binaries

Saclay, France, 21/11/2014

Star-Planet Interactions and the Habitable Zone

In collaboration with:

Siegfried Eggl

Elke Pilat-Lohinger

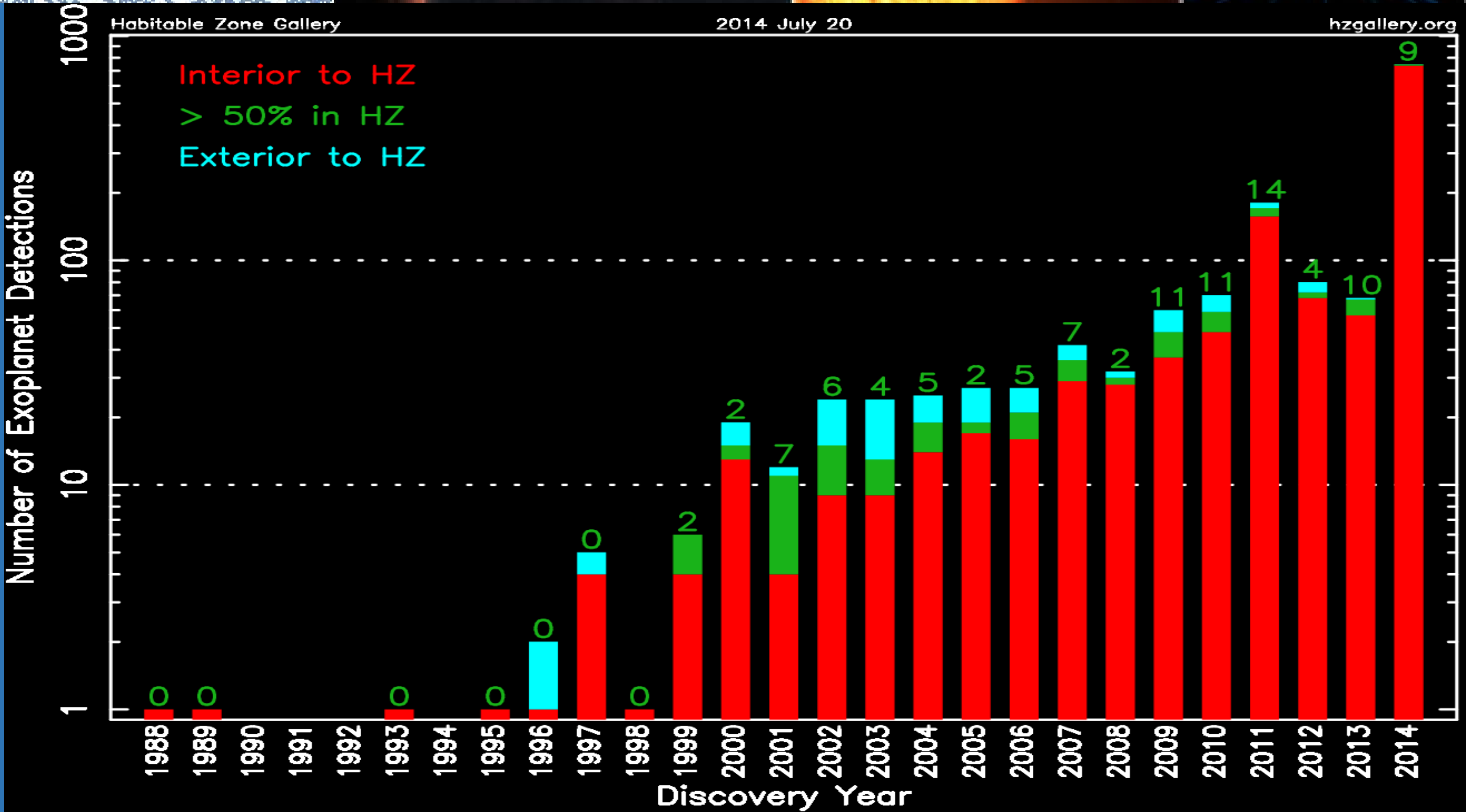
Markus Gyergyovits

Barbara Funk

Habitability condition: the capacity of water to stay in liquid form on the planet’s surface (Kasting et al. 1993)

Star-Planet Interactions and the Habitable Zone

www.hzgallery.org



Why stellar binaries?

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i) a significant number of stars may be members of binaries (e.g. Duquennoy & Mayor 1991, Raghavan et al. 2010)

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i) a significant number of stars may be members of binaries (e.g. Duquennoy & Mayor 1991, Raghavan et al. 2010)

ii) 85 circumstellar + 22 circumbinary (http://www.openexoplanetcatalogue.com)

Star-Planet Interactions and the Habitable Zone

1960 →

LIFE-SUPPORTING REGIONS IN THE VICINITY OF BINARY SYSTEMS

Su-Shu Huang
Goddard Space Flight Center
National Aeronautics and Space Administration

In two previous papers we have discussed the requirements that a star should fulfill in order to be able to support life of a high form in its neighborhood.[1] We have concluded that in general there should be a smaller chance of finding a life-supporting* planet in binary systems than near single stars. We have further stated, though qualitatively, that if a life-supporting planet does exist in a binary system at all, it must be an interior planet in the case of a distant binary and an exterior planet in the case of a close binary. In this paper we shall make a quantitative study of the previous statement.

STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

THE ASTROPHYSICAL JOURNAL, 752:74 (11pp), 2012 June 10 doi:10.1088/0004-637X/752/1/74

AN ANALYTIC METHOD TO DETERMINE HABITABLE ZONES FOR S-TYPE PLANETARY ORBITS IN BINARY STAR SYSTEMS

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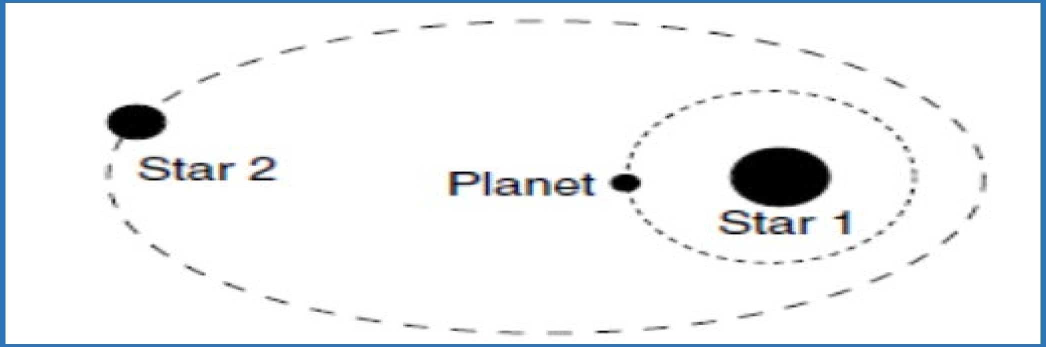
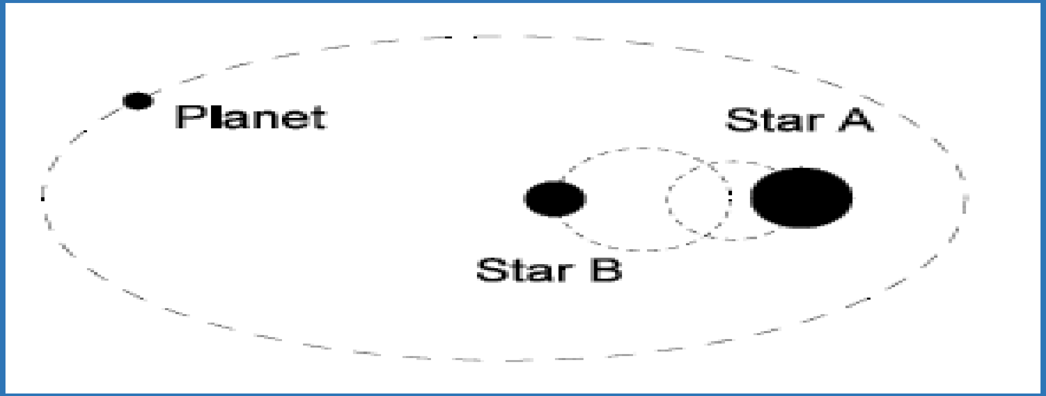
ABSTRACT

With more and more extrasolar planets discovered in and around binary star systems, questions concerning the determination of the classical habitable zone have arisen. Do the radiative and gravitational perturbations of the second star influence the extent of the habitable zone significantly, or is it sufficient to consider the host star only? In this article, we investigate the implications of stellar companions with different spectral types on the insolation a terrestrial planet receives orbiting a Sun-like primary. We present time-independent analytical estimates and compare them to insolation statistics gained via high precision numerical orbit calculations. Results suggest a strong dependence of permanent habitability on the binary's eccentricity, as well as a possible extension of habitable zones toward the secondary in close binary systems.

We shall focus on S-type planets (the planet orbits one of the stars),



although the basic principles also apply on P-type orbits (the planet orbits both stars)

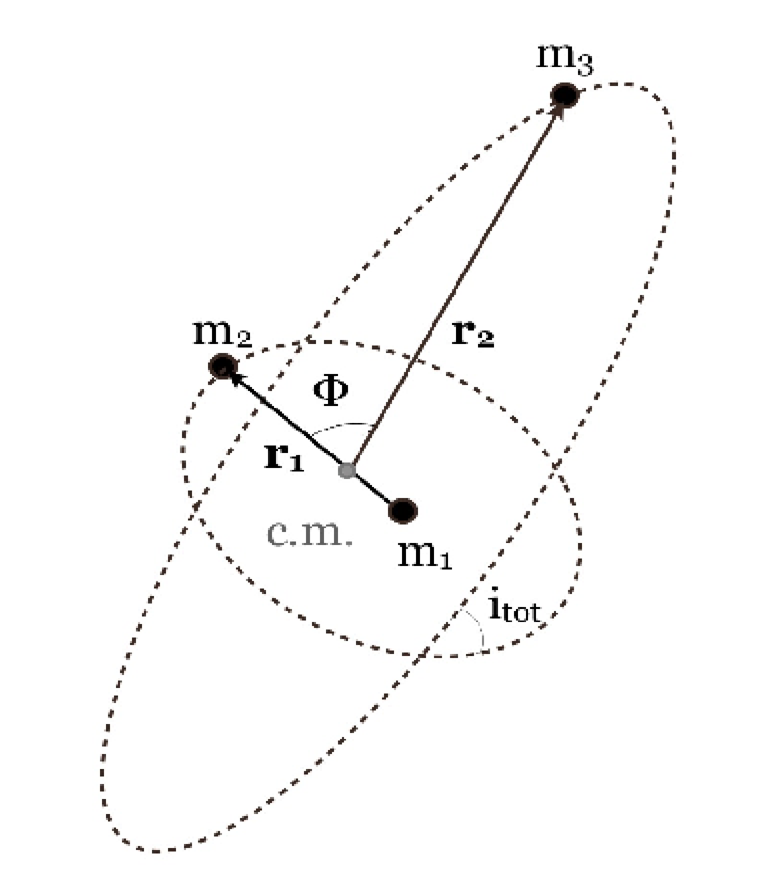


When we deal with a planet in a binary, we must take into consideration:

i) the extra source of radiation

ii) the gravitational perturbations to the planetary orbit (especially to the eccentricity)

Hierarchical triple system



Even when an orbit is initially circular, the perturber will inject eccentricity into it

(e.g. Mazeh & Shaham 1979, Georgakarakos 2002,2003,2004)

$da/dt=0$

(no secular changes in a, e.g. Harrington 1968)

Star-Planet Interactions and the Habitable Zone

Spiegel et al. (2010)

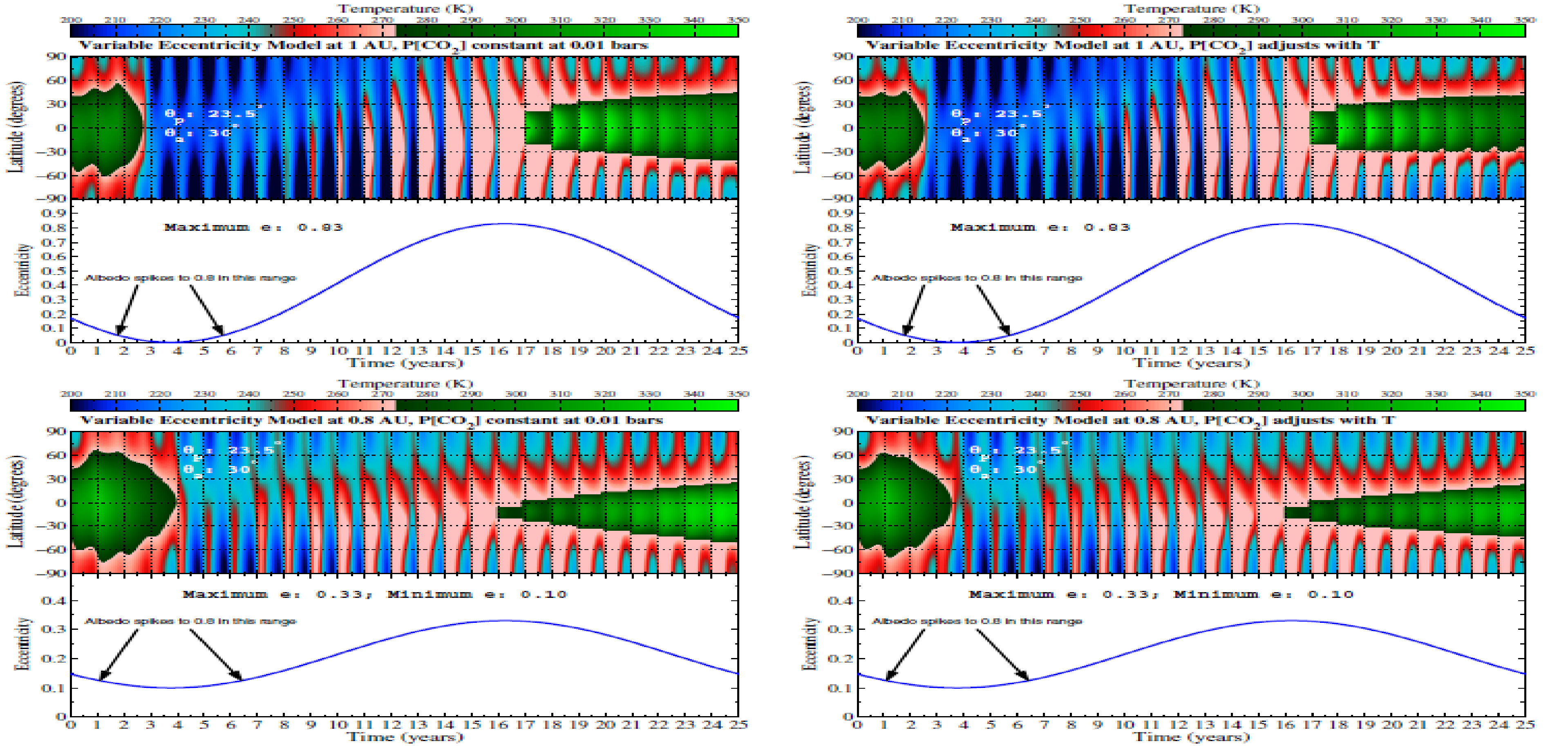
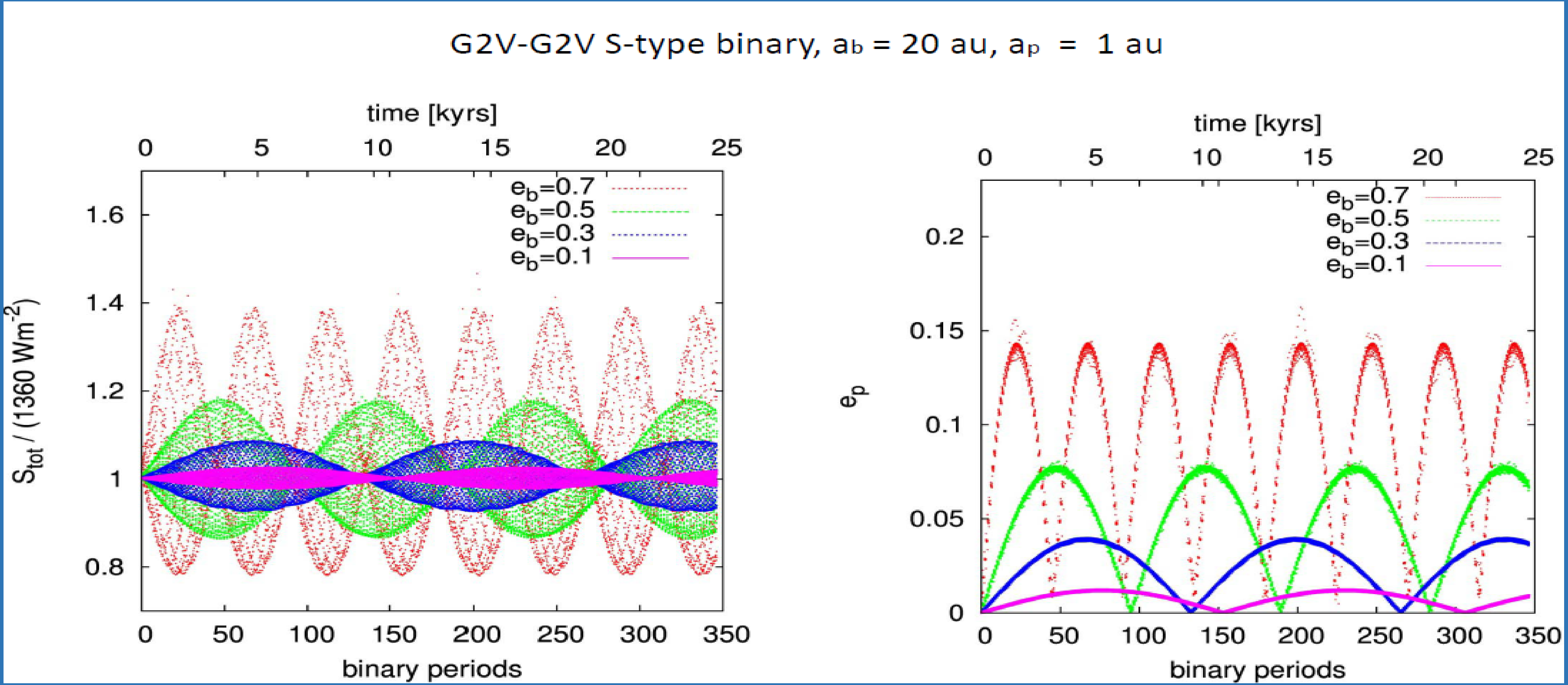
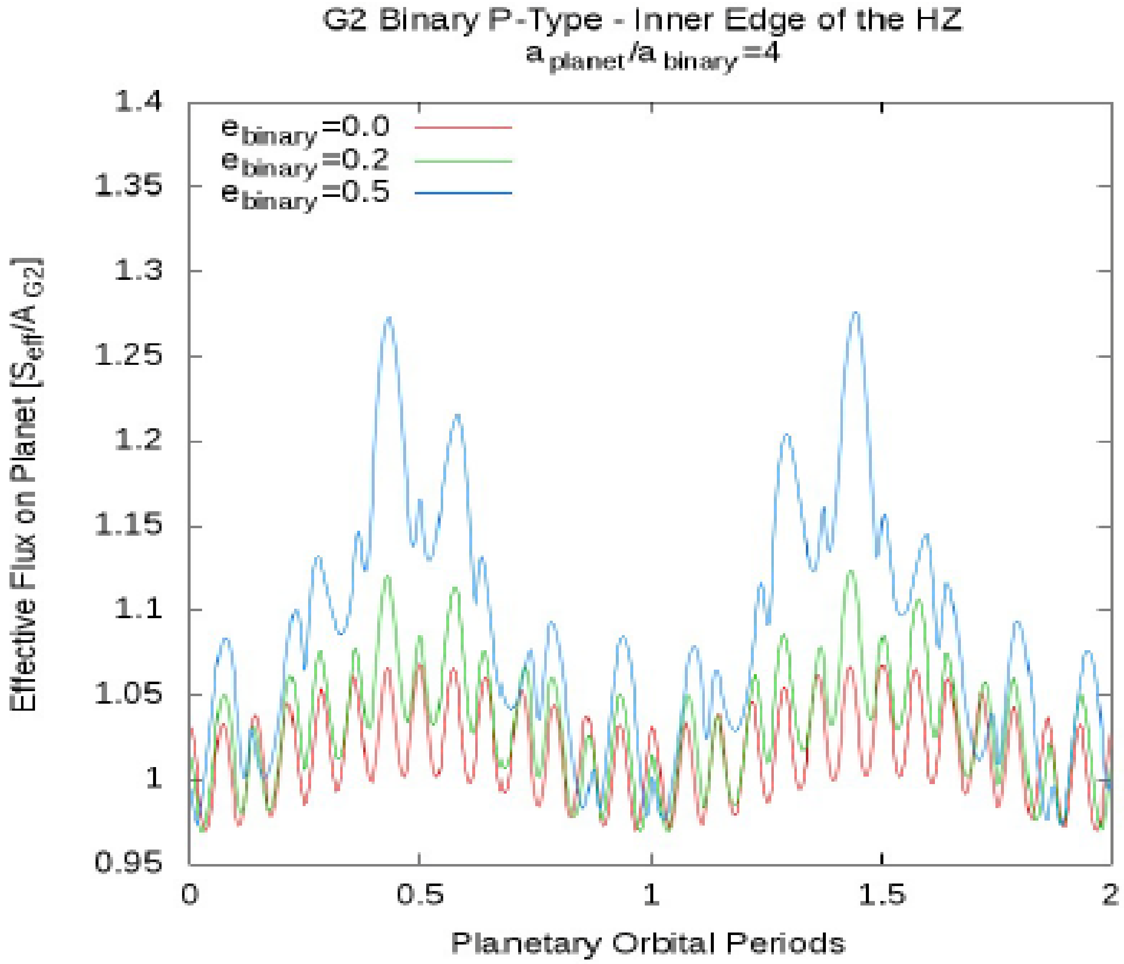
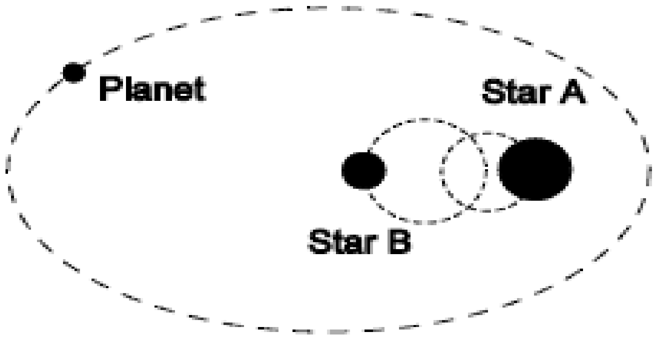


Figure 2. Compressed Milankovitch-like evolution of eccentricity and temperature at 1 AU and at 0.8 AU. Planets are initialized with warm equator and cold poles, similar to present-day Earth. In the top row (1 AU), the model planets are the same as in Figure 1, except the eccentricity varies sinusoidally between 0 and 0.83 with a 25 year period, to simulate a time acceleration (by a factor of $\sim 10^2$ to $\sim 10^4$) of a Milankovitch-like cycle. When the eccentricity falls below 0.05, the planet's albedo spikes to 0.8, simulating a catastrophic event that plunges the planet into a snowball state, with the latent heat prescription of Section 2.2. In the bottom row (0.8 AU), the eccentricity varies between 0.1 and 0.33, also with a 25 year period. Left: CO_2 partial pressure is held fixed at 0.01 bars. As in the left panel of Figure 1, these planets do not establish a temperate equilibrium. Right: CO_2 partial pressure varies with temperature. Here, increases in temperature are muted by reduced greenhouse effect once the ice-cover has melted somewhere.



Eggl et al. (2012)


G2 Binary P-Type - Inner Edge of the HZ
a planet/a binary=4
e binary=0.0
e binary=0.2
e binary=0.5
Effective Flux on Planet [Seff/A G2]
Planetary Orbital Periods
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0
0.5
1
1.5
2


Planet
Star A
Star B

We need:

1) An atmospheric model

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2) A sufficient description of the planetary orbit

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2) A sufficient description of the planetary orbit

orbital stability

evolution of the orbit

Assumptions made:

i) The planet is initially circular

ii) The binary-planet system is coplanar

iii) Stellar luminosities are constant on planetary secular motion timescales

iv) Stellar occultation effects are negligible

Atmospheric Model

Kasting et al. (1993)

Kopparapu et al. (2013, 2014)

I=Inner
O=Outer

$S_{eff} = F_{IR}/F_s$

$S_{eff,I} \equiv S_I$

$S_{eff,O} \equiv S_O$

Assuming a non-Keplerian orbit for the planet, offer us the ability to construct different types of habitable zones:

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1) **PHZ** (Permanently Habitable zone): planet is always within habitable insolation limits ($S_I \leq S_{tot} \leq S_O$)

Star-Planet Interactions and the Habitable Zone

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2) **AHZ** (Average Habitable Zone): planet is on average within habitable insolation limits $(S_I \le \langle S_{tot} \rangle_t \le S_O)$

STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

Assuming a non-Keplerian orbit for the planet, offer us the ability to construct different types of habitable zones:

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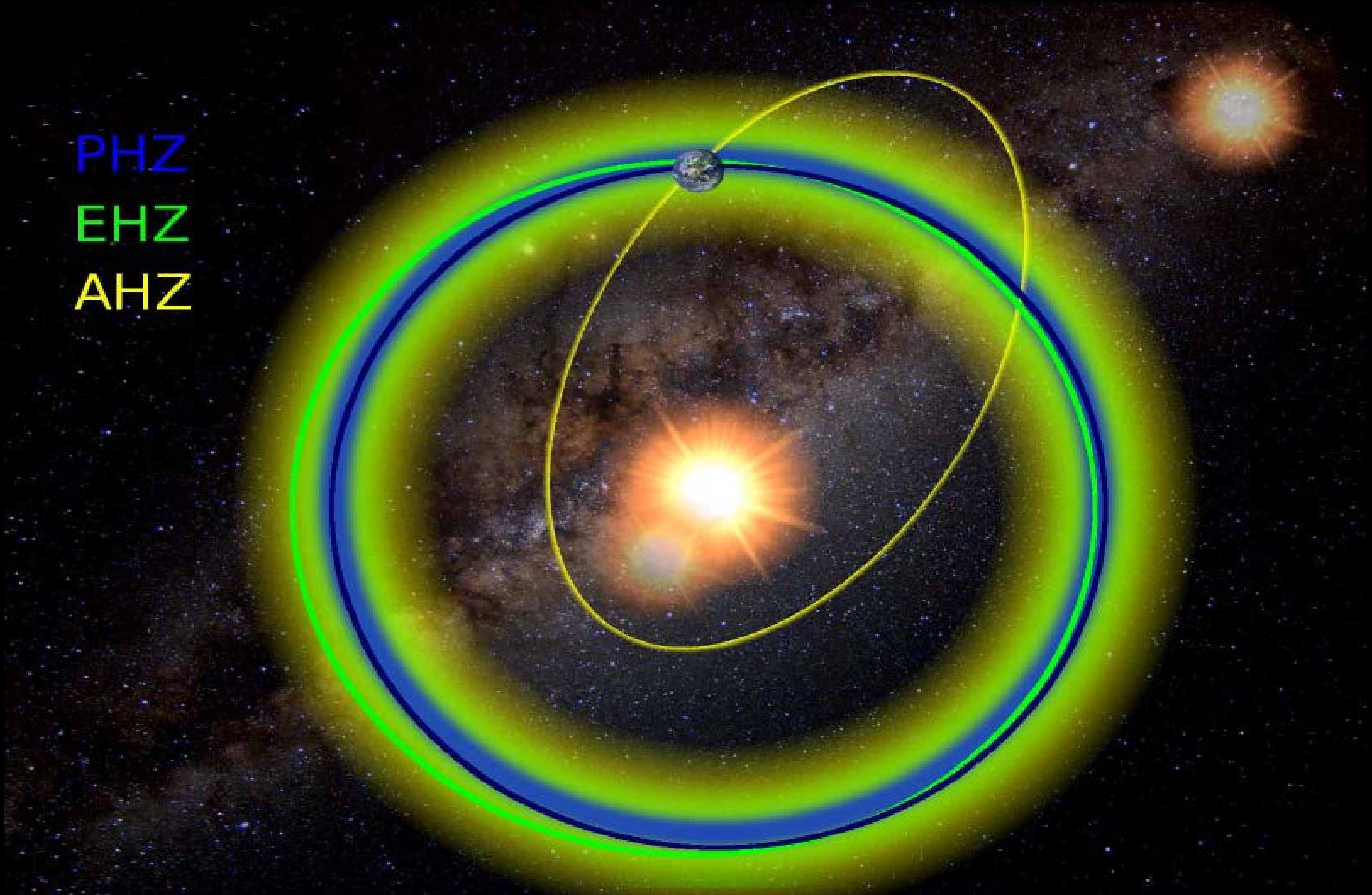
2) **AHZ** (Average Habitable Zone): planet is on average within habitable insolation limits ($S_I \leq < S_{tot} >_t \leq S_O$)

3) **EHZ** (Extended Habitable Zone): planet is almost always within habitable insolation limits ($S_I \leq < S_{tot} >_t \pm \sigma \leq S_O$), where σ^2 is the effective insolation variance

STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

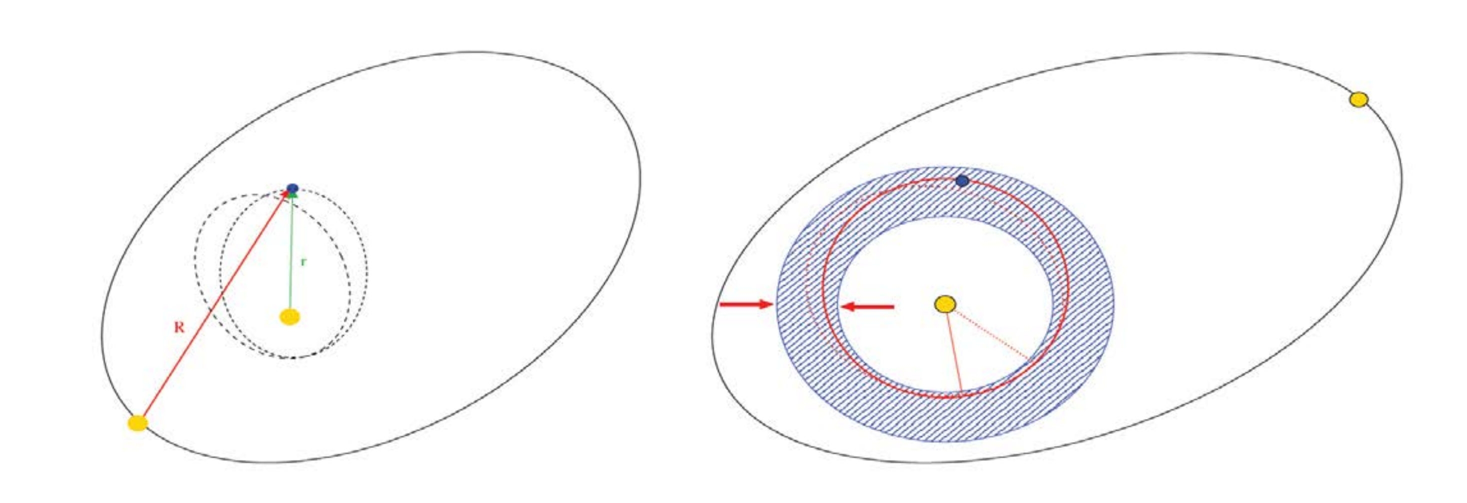


How to construct all those habitable zones?

Star-Planet Interactions and the Habitable Zone

PHZ:

L_i=luminosities



$$r_p^{\min} = a_p(1 - e_p^{\max})$$

$$r_p^{\max} = a_p(1 + e_p^{\max})$$

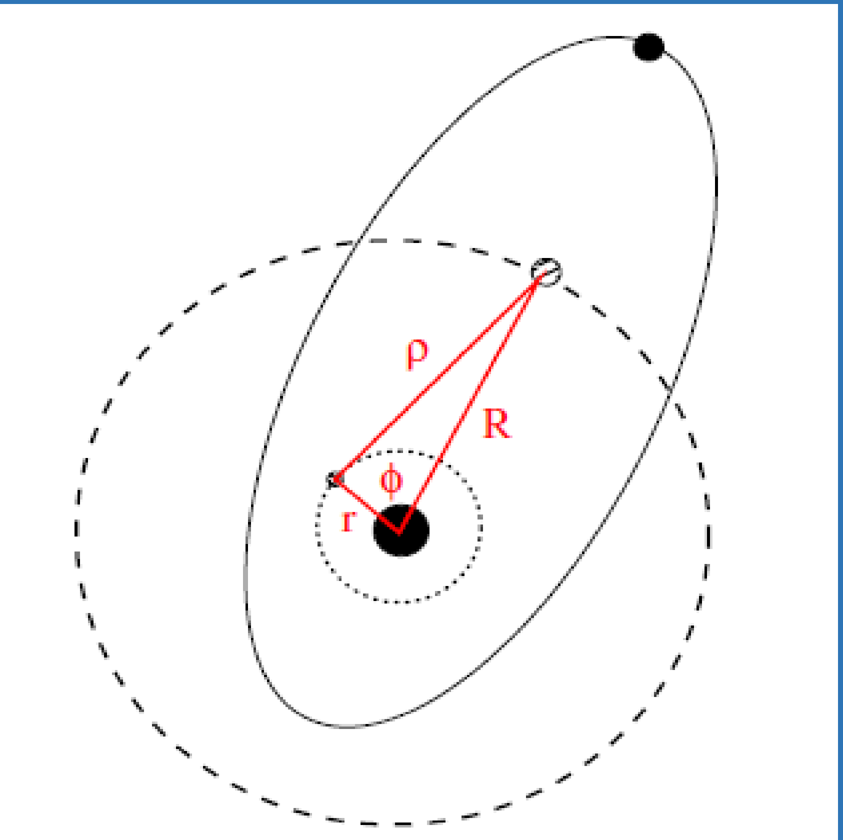
$$r_p^{\min} \le r_p^{PHZ} \le r_p^{\max}$$

Min. Insolation: $$1 \le \frac{L_1}{S_{O,1} a_p (1 + e_p^{\max})^2} + \frac{L_2}{S_{O,2}[a_b(1 + e_b) + a_p(1 + e_p^{\max})]^2}$$

Max. Insolation: $$\max \begin{cases} \dfrac{L_1}{S_{I,1} a_p (1 - e_p^{\max})^2} + \dfrac{L_2}{S_{I,2}[a_b(1 - e_b) - a_p(1 - e_p^{\max})]^2} \\ \dfrac{L_1}{S_{I,1} a_p (1 + e_p^{\max})^2} + \dfrac{L_2}{S_{I,2}[a_b(1 - e_b) - a_p(1 + e_p^{\max})]^2} \end{cases} \le 1$$

AHZ: $\rho^2 = R^2 + r^2 - 2rR\cos(\phi)$

$$< S_{tot} >_t = < S_1 >_t + < S_2 >_t$$



$$< S_1 >_t = \frac{L_1}{P_1}\int_0^P \frac{dt}{r^2(t)} = \frac{L_1}{r_*^2}$$

$$< S_2 >_t = \frac{L_2}{P_2}\int_0^P \frac{dt}{\rho^2(t)} = \frac{L_2}{R_*^2 - r_*^2}$$

with $r_* = a_p(1 - < e_p^2 >)$ and $R_* = a_b(1 - e_b^2)$

Average insolation minimum condition:

$$1 \le \frac{L_1}{S_{O,1} r_*^2} + \frac{L_2}{S_{O,2}(R_*^2 - r_*^2)} = < S_O >_t$$

Average insolation maximum condition:

$$< S_I >_t = \frac{L_1}{S_{I,1} r_*^2} + \frac{L_2}{S_{I,2}(R_*^2 - r_*^2)} \le 1$$

Star-Planet Interactions and the Habitable Zone

Extended insolation minimum condition: $1 \leq \langle S_O \rangle_t - \sigma_O$

Extended insolation maximum condition: $\langle S_I \rangle_t + \sigma_I \leq 1$, where

$$\sigma_X^2 = \frac{L_1^2}{X_1^2 r_*^4}\left(-1 + 3\langle e_p^2 \rangle - 3\langle e_p^2 \rangle^2 + \langle e_p^2 \rangle^3\right) +$$

$$\frac{L_1^2}{X_1^2 r_*^4}\sqrt{1 - \langle e_p^2 \rangle}\left(1 - \frac{\langle e_p^2 \rangle}{2} - \frac{\langle e_p^2 \rangle^2}{2}\right) - \frac{2L_2^2 r_*^2}{X_2^2 (r_*^2 - R_*^2)^3} -$$

$$\frac{2L_1 L_2}{X_1 X_2 (r_*^4 - r_*^2 R_*^2)}\left[1 - (1 + \langle e_p^2 \rangle)\sqrt{1 - \langle e_p^2 \rangle}\right], \quad X \in \{S_I, S_O\}$$

Orbital stability: Holman & Wiegert (1999)

$$a_c = [(0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e + (0.586 \pm 0.061)\mu e + (0.150 \pm 0.041)e^2 + (-0.198 \pm 0.074)\mu e^2]a_b$$

S-type

$$a_c = [(1.60 \pm 0.04) + (5.10 \pm 0.05)e + (-2.22 \pm 0.11)e^2 + (4.12 \pm 0.09)\mu + (-4.27 \pm 0.17)e\mu + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e^2\mu^2]a_b,$$

P-type

where a_c is the critical semi-major axis, a_b is the binary semi-major axis, e is the binary eccentricity and $\mu = m_2/(m_1+m_2)$, m_1 and m_2 being the stellar masses.

Orbital stability: Holman & Wiegert (1999)

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+

Fast Lyapunov Indicator (FLI), Froeschlé et al. (1997), Pilat-Lohinger & Dvorak (2002).

Description of orbital evolution: Georgakarakos (2003,2005)

Secular evolution

$$H = -\frac{Gm_1m_2}{2a_S} - \frac{G(m_1+m_2)m_3}{2a_T} + Q_1 + Q_2 + Q_3,$$

where

$$Q_1 = -\frac{1}{8}\frac{Gm_1m_2m_3a_S^2}{(m_1+m_2)a_T^3\left(1-e_T^2\right)^{3/2}}\left(2+3e_S^2\right),$$

$$Q_2 = \frac{15Gm_1m_2m_3(m_1-m_2)a_S^3e_Se_T}{64(m_1+m_2)^2a_T^4\left(1-e_T^2\right)^{5/2}}\cos\left(g_S-g_T\right)\left(4+3e_S^2\right),$$

$$Q_3 = -\frac{15}{64}\frac{Gm_1m_2m_3^2a_S^{7/2}e_S^2\left(1-e_S^2\right)^{1/2}}{(m_1+m_2)^{3/2}M^{1/2}a_T^{9/2}(1-e_T^2)^3}\left[5\left(3+2e_T^2\right)+3e_T^2\cos 2(g_S-g_T)\right]$$

da/dt=0

+ short period terms

$$\boldsymbol{e}_1 = -\frac{\boldsymbol{r}}{r} + \frac{1}{\mu}(\dot{\boldsymbol{r}}\times\boldsymbol{h}),$$

where $\boldsymbol{h} = \boldsymbol{r}\times\dot{\boldsymbol{r}}$ and $\mu = G(m_1 + m_2)$

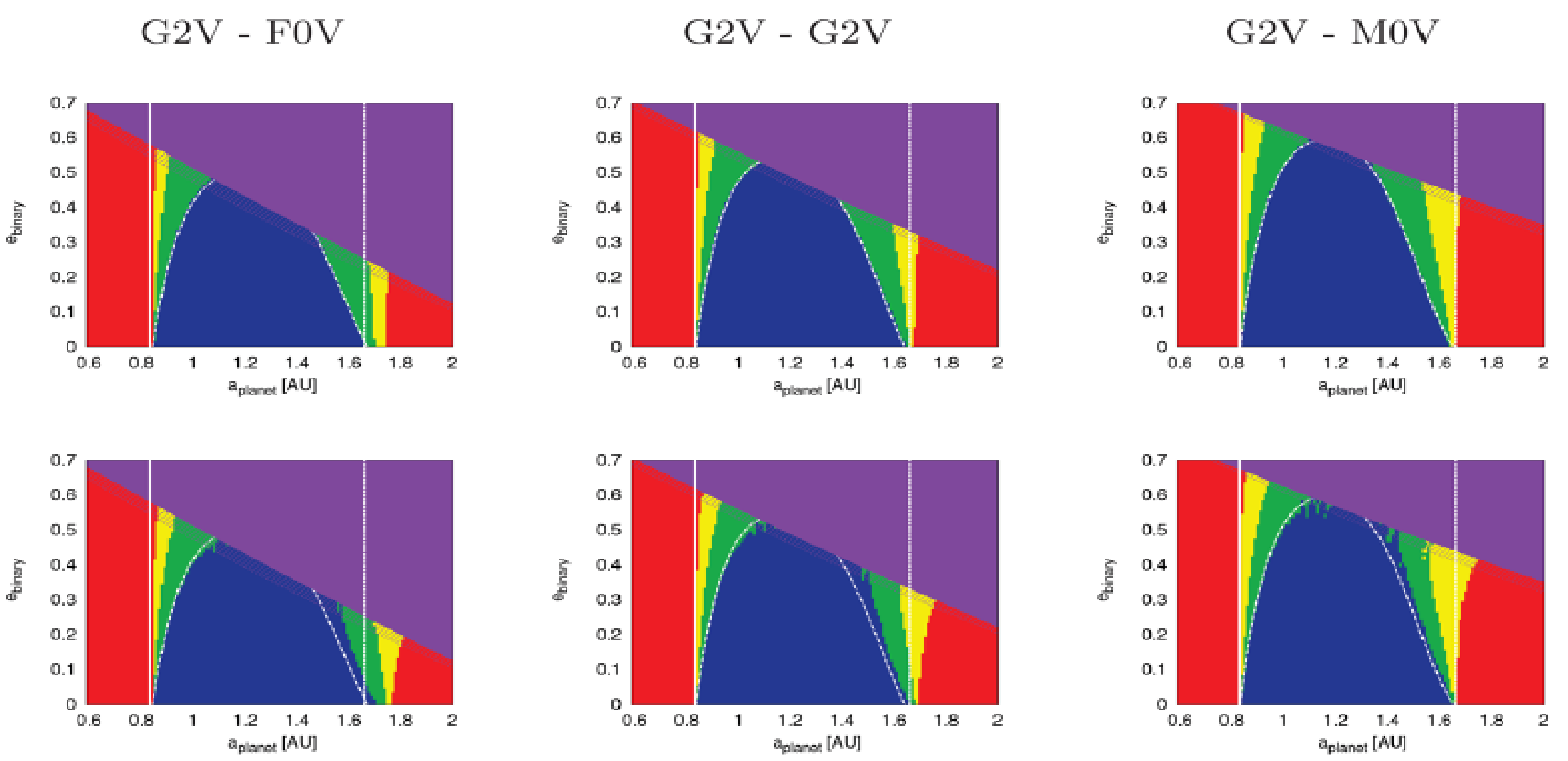
STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

Description of orbital evolution: Georgakarakos (2003,2005)

$$
\begin{aligned}
\overline{e^2_{\rm in}} = {} & \frac{m_3^2}{M^2}\frac{1}{X^4(1-e^2)^{9/2}}\left\{\frac{43}{8}+\frac{129}{8}e^2+\frac{129}{64}e^4+\frac{1}{(1-e^2)^{3/2}}\left(\frac{43}{8}+\frac{645}{16}e^2+\frac{1935}{64}e^4+\frac{215}{128}e^6\right)+\frac{1}{X^2(1-e^2)^3}\right.\\
& \times\left[\frac{365}{18}+\frac{44327}{144}e^2+\frac{119435}{192}e^4+\frac{256105}{1152}e^6+\frac{68335}{9216}e^8\right.\\
& \left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{365}{18}+\frac{7683}{16}e^2+\frac{28231}{16}e^4+\frac{295715}{192}e^6+\frac{2415}{8}e^8+\frac{12901}{2048}e^{10}\right)\right]\\
& +\frac{1}{X(1-e^2)^{3/2}}\left[\frac{61}{3}+\frac{305}{2}e^2+\frac{915}{8}e^4+\frac{305}{48}e^6+\frac{1}{(1-e^2)^{3/2}}\left(\frac{61}{3}+\frac{854}{3}e^2+\frac{2135}{4}e^4+\frac{2135}{12}e^6+\frac{2135}{384}e^8\right)\right]\\
& +m_*^2X^{2/3}(1-e^2)\left[\frac{225}{256}+\frac{3375}{1024}e^2+\frac{7625}{2048}e^4+\frac{29225}{8192}e^6+\frac{48425}{16384}e^8+\frac{825}{2048}e^{10}\right.\\
& \left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{225}{256}+\frac{2925}{1024}e^2+\frac{775}{256}e^4+\frac{2225}{8192}e^6+\frac{25}{512}e^8\right)\right]\\
& +m_*^2\frac{1}{X^{4/3}(1-e^2)^2}\left[\frac{8361}{4096}+\frac{125415}{8192}e^2+\frac{376245}{32768}e^4+\frac{41805}{65536}e^6\right.\\
& \left.\left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{8361}{4096}+\frac{58527}{2048}e^2+\frac{877905}{16384}e^4+\frac{292635}{16384}e^6+\frac{292635}{524288}e^8\right)\right]\right\}+2\left(\frac{C}{B-A}\right)^2.
\end{aligned}
$$

- analytical expression for $\bar{e}_p$ (with the potential of estimating e_p^{max})
- analytical expression for $\langle e_p^2 \rangle$

Results: S-type (Eggl et al. 2012)



top: analytic estimates, bottom: simulation, $a_b = 10AU$ (Eggl et al. 2012)

Blue=PHZ
Green=EHZ
Yellow=AHZ
Red=Non Habitable
Magenta=H&W (1999)
Magenta lines=FLI
Vertical white lines=KHZ
Dotted white lines=e_p^{max} numerical

Results: S-type

Table 3

Percentages of Planetary Orbits Classified Identically via a Numerical Simulations and Analytical Estimates as Presented in Section 6

[AU]	G2–M0 (%)				G2–G2 (%)				G2–F0 (%)			
a_b	Total	PHZ	EHZ	AHZ	Total	PHZ	EHZ	AHZ	Total	PHZ	EHZ	AHZ
10	**95.9**	97.4	99.8	98.3	**94.4**	97.4	99.2	98.0	**93.6**	95.8	98.5	98.2
20	**98.8**	99.3	99.5	99.8	**98.5**	99.2	99.6	99.6	**98.5**	99.5	99.4	99.6
30	**99.0**	99.5	99.7	99.9	**99.2**	99.7	99.6	99.8	**98.9**	99.8	99.4	100.0
40	**99.2**	99.5	99.6	99.9	**99.3**	99.9	99.6	100.0	**99.0**	99.8	99.5	99.8
50	**99.2**	99.6	99.7	99.9	**99.4**	99.7	99.7	99.9	**99.4**	99.8	99.7	99.9

Note. Three binary component configurations have been investigated; the reference classifications were extracted from numerical orbit integrations and insolation simulations.

Eggl et al. (2012)

Star-Planet Interactions and the Habitable Zone

Monthly Notices of the Royal Astronomical Society

MNRAS **428**, 3104–3113 (2013) doi:10.1093/mnras/sts257

Circumstellar habitable zones of binary-star systems in the solar neighbourhood

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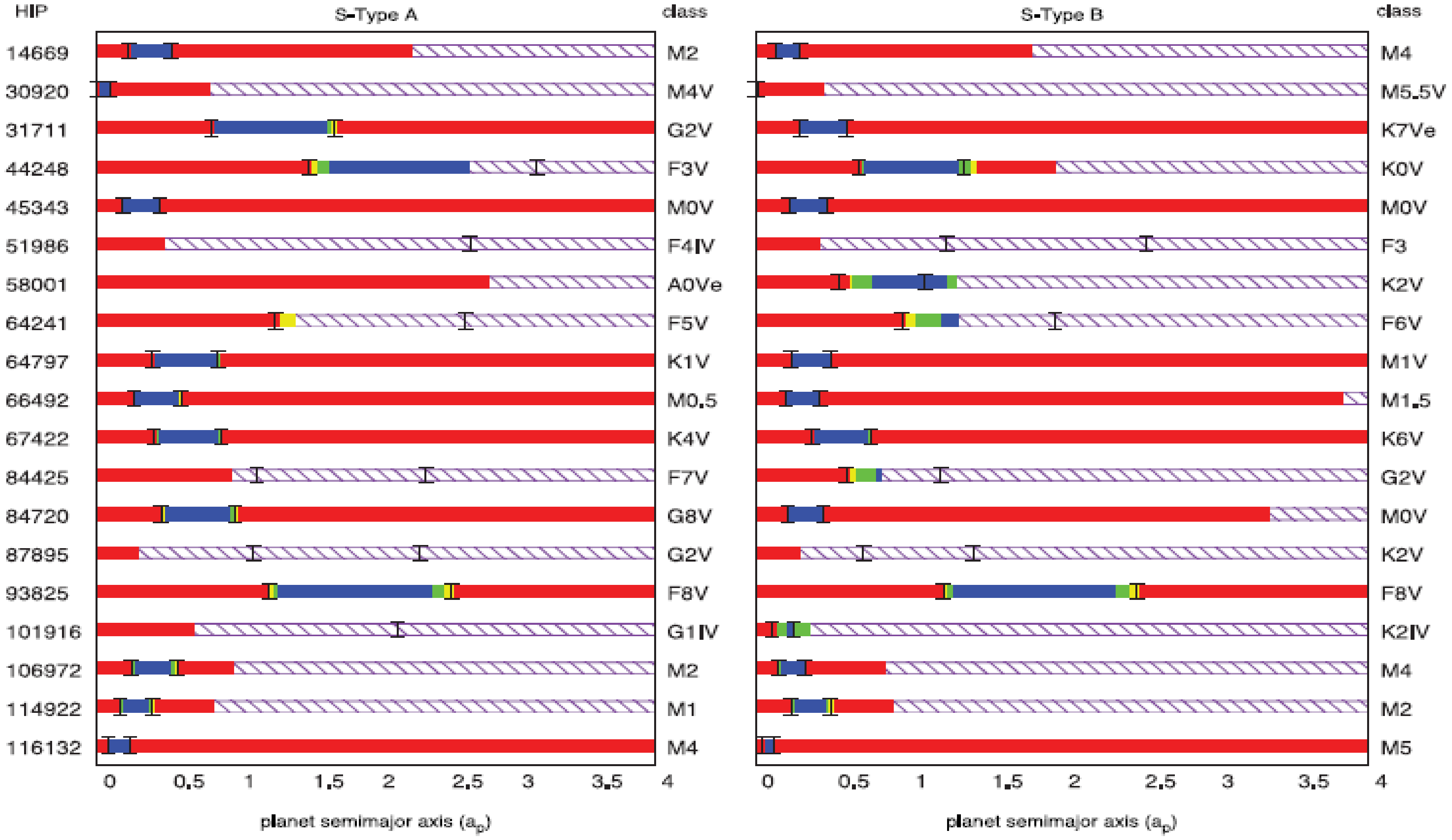
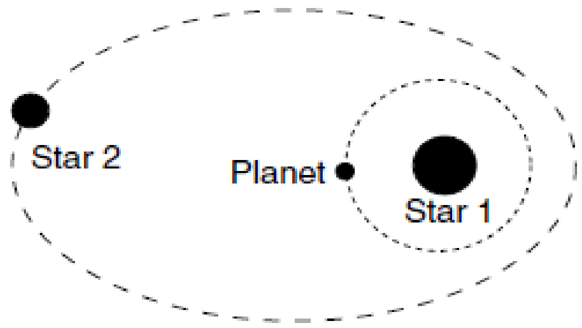
ABSTRACT

Binary and multiple systems constitute more than half of the total stellar population in the solar neighbourhood. Their frequent occurrence as well as the fact that more than 70 planets have already been discovered in such configurations – most notably the telluric companion of α Cen B – make them interesting targets in the search for habitable worlds. Recent studies have shown that despite the variations in gravitational and radiative environment, there are indeed circumstellar regions where planets can stay within habitable insolation limits on secular dynamical time-scales. In this paper, we provide habitable zones for 19 near S-type binary systems from the *Hipparcos* and Washington Double Star catalogue (WDS) catalogues with semimajor axes between 1 and 100 au. Hereby, we accounted for the combined dynamical and radiative influence of the second star on the Earth-like planet. Out of the 19 systems presented, 17 offer dynamically stable habitable zones around at least one component. The 17 potentially habitable systems contain 5 F, 3 G, 7 K and 16 M class stars. As their proximity to the Solar system ($d < 31$ pc) makes the selected binary stars exquisite targets for observational campaigns, we offer estimates on radial velocity, astrometric and transit signatures produced by habitable Earth-like planets in eccentric circumstellar orbits.

Star-Planet Interactions and the Habitable Zone

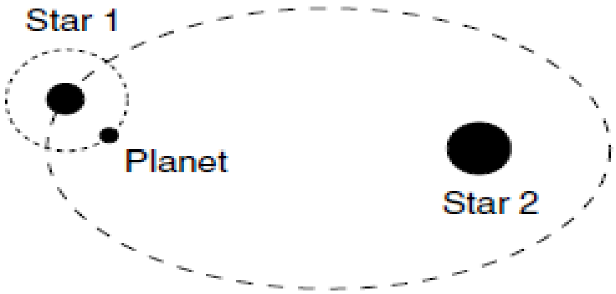


Eggl et al. (2013)



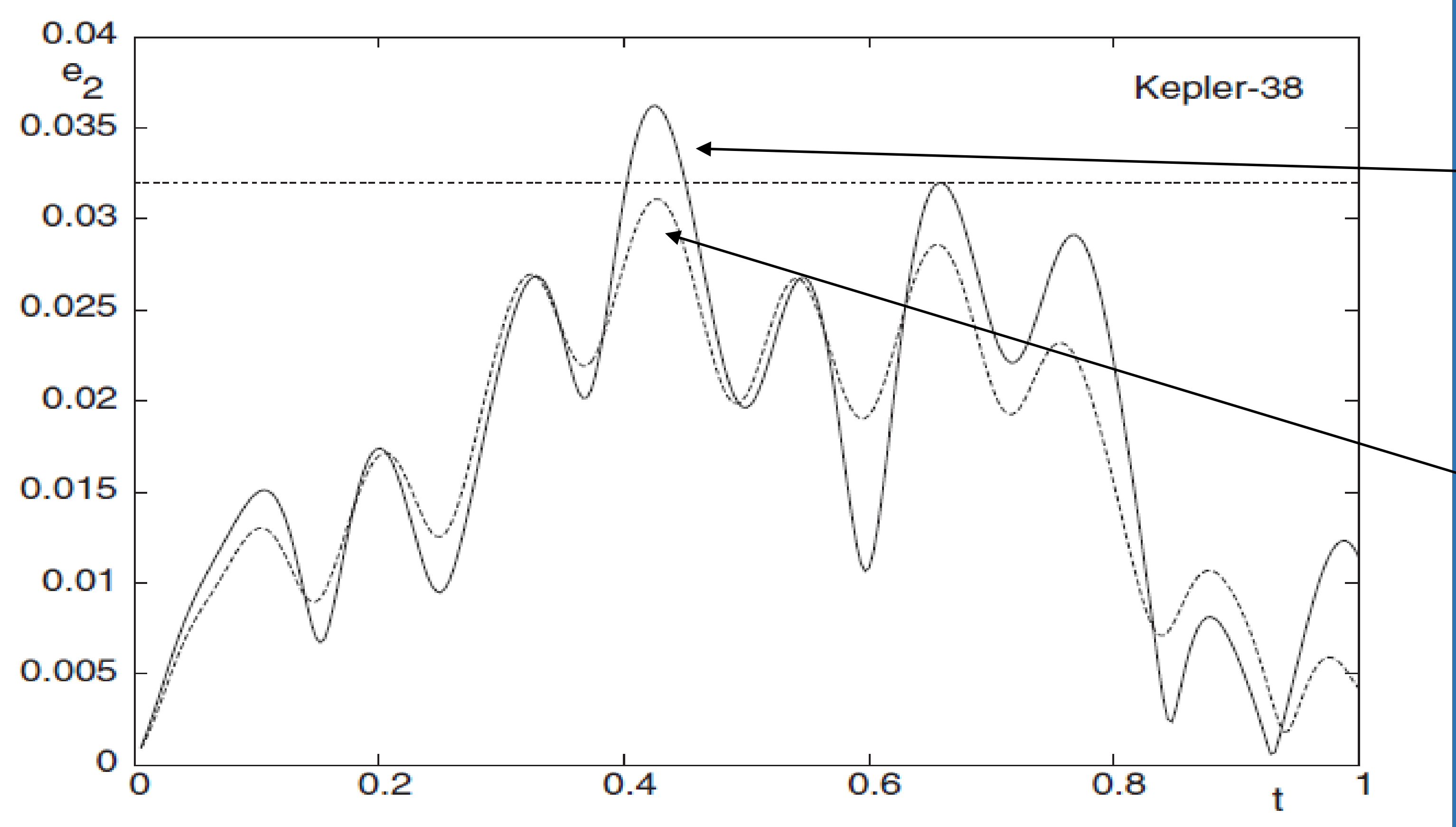
Type A

Type B



STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

P-type: Georgakarakos & Eggl (2014) (in preparation) - eccentricity estimates
Eggl & Georgakarakos (2014) (in preparation) – habitable zones



Numerics

Analytics

Georgakarakos & Eggl 2014

STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

More details about our model can be found in:

Eggl et al. 2012, ApJ, 752, 74.

AN ANALYTIC METHOD TO DETERMINE HABITABLE ZONES FOR S-TYPE PLANETARY ORBITS IN BINARY STAR SYSTEMS

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Other recent relevant papers:

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ON THE HABITABLE ZONES OF CIRCUMBINARY PLANETARY SYSTEMS

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

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STAR-PLANET INTERACTIONS AND THE HABITABLE ZONE

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THE ASTROPHYSICAL JOURNAL, 777:166 (13pp), 2013 November 10 doi:10.1088/0004-637X/777/2/166

CALCULATING THE HABITABLE ZONE OF BINARY STAR SYSTEMS. II. P-TYPE BINARIES

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CALCULATING THE HABITABLE ZONE OF BINARY STAR SYSTEMS. II. P-TYPE BINARIES

THE ASTROPHYSICAL JOURNAL, 780:14 (19pp), 2014 January 1 doi:10.1088/0004-637X/780/1/14

S-TYPE AND *P*-TYPE HABITABILITY IN STELLAR BINARY SYSTEMS: A COMPREHENSIVE APPROACH. I. METHOD AND APPLICATIONS

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Star-Planet Interactions and the Habitable Zone

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Habitable zones with stable orbits for planets around binary systems

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S-Type and *P*-Type Habitability in Stellar Binary Systems: A Comprehensive Approach II. Elliptical Orbits

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Although all the above papers followed the publication of Eggl et al. (2012)

i) they use the same atmospheric model (Kasting et al. 1993)

i) they assume Keplerian orbits of initially circular planets

SUMMARY AND CONCLUSIONS

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THANK YOU