A Joint Approach to the Study of S / P-Type Habitable Zones in Binary Systems: New Results

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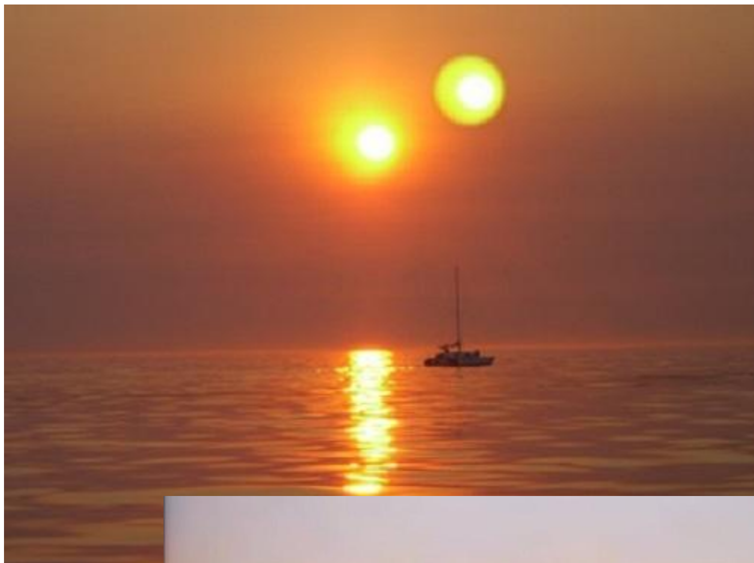
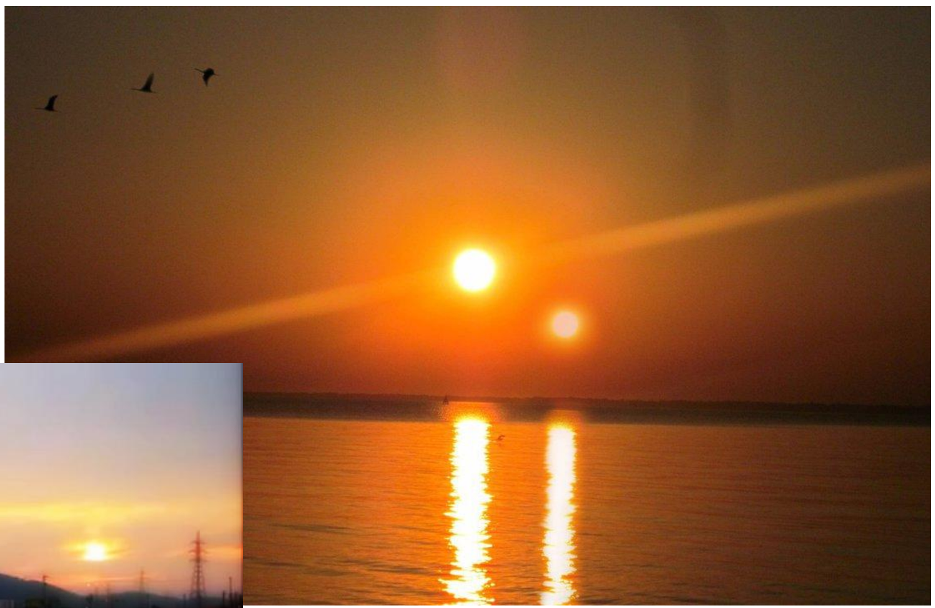
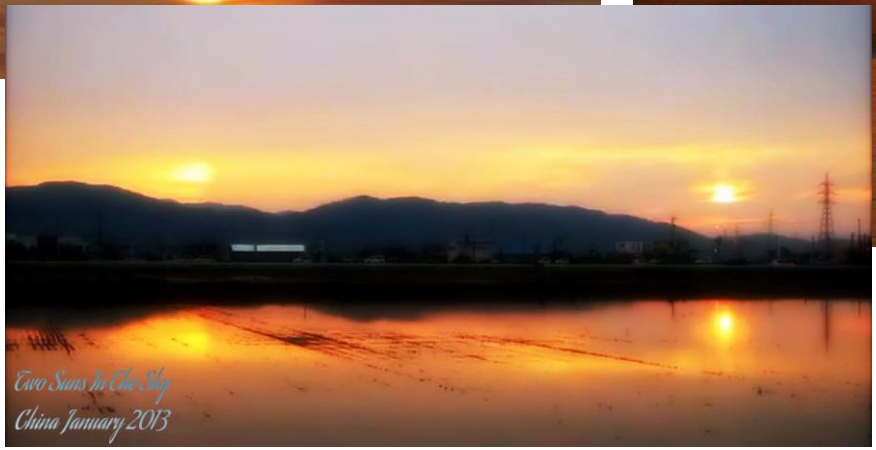
Two Suns in the Sky ?
… more often than you think!

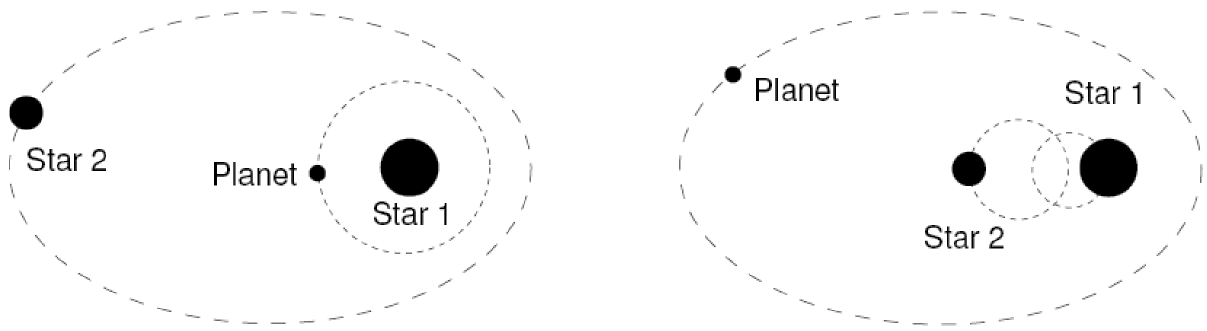






S-type vs. P-type [Habitable] Orbits

Coined by: R. Dvorak, R. 1982, Oesterreichische Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse, Sitzungsberichte Abt. 2, 191 (10), 423



S-Type: Planet orbits one star (single)

P-type: Planet orbits both stars (pair)

Example: Study of Kepler-16

(Quarles et al. 2012)

HABITABILITY OF EARTH-MASS PLANETS AND MOONS IN THE KEPLER-16 SYSTEM

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ABSTRACT

We demonstrate that habitable Earth-mass planets and moons can exist in the Kepler-16 system, known to host a Saturn-mass planet around a stellar binary, by investigating their orbital stability in the standard and extended habitable zone (HZ). We find that Earth-mass planets in satellite-like (S-type) orbits are possible within the standard HZ in direct vicinity of Kepler-16b, thus constituting habitable exomoons. However, Earth-mass planets cannot exist in planetary-like (P-type) orbits around the two stellar components within the standard HZ. Yet, P-type Earth-mass planets can exist superior to the Saturnian planet in the extended HZ pertaining to considerably enhanced back-warming in the planetary atmosphere if facilitated. We briefly discuss the potential detectability of such habitable Earth-mass moons and planets positioned in satellite and planetary orbits, respectively. The range of inferior and superior P-type orbits in the HZ is between 0.657–0.71 AU and 0.95–1.02 AU, respectively.

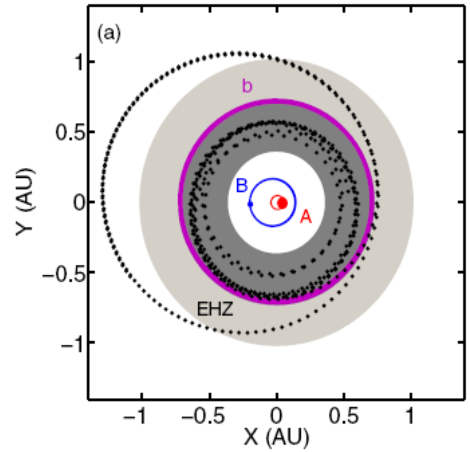
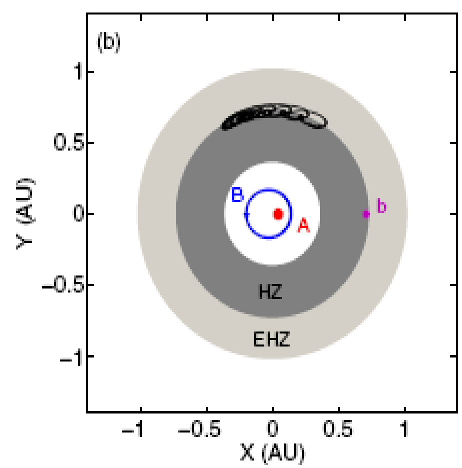
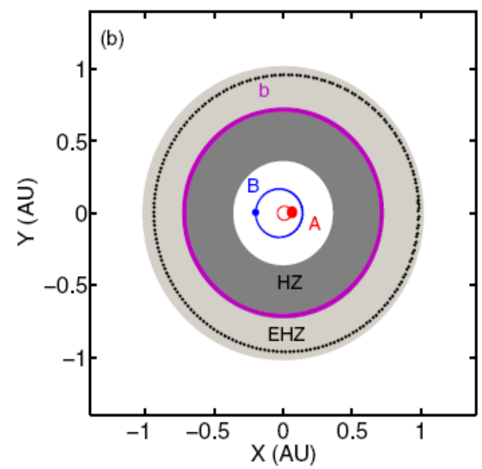


Table 1
Stellar and Planetary Parameters of Kepler-16

Parameter	Value[a]
Distance (pc)	∼61
F_B/F_A	0.01555 ± 0.0001
M_1 ($M_\odot$)	0.6897 ± 0.0035
M_2 ($M_\odot$)	0.20255 ± 0.00066
$T_{eff,1}$ (K)	4450 ± 150
R_1 ($R_\odot$)	0.6489 ± 0.003
P_b (d)	41.079220 ± 0.000078
a_b (AU)	0.22431 ± 0.00035
e_b	0.15944 ± 0.00061
M_p (M_J)	0.333 ± 0.016
a_p (AU)	0.7048 ± 0.0011
e_p	0.0069 ± 0.001
ρ_p (g cm^{-3})	0.964 ± 0.047

Note. [a] Data as provided by Doyle et al. (2011). All parameters have their usual meaning.





CBP- cont'd

CBPs ***candidates*** (non-transiting, not Kepler)

Target	CBP orbit [AU]	CBP mass [MJup]	
PSR B1620-26	23	2.5	Timing (1st CBP)
CM Dra	1.2	1.5 – 3	Photometry
HD 202206	2.55	2.44	RV
V 471 Tau	12	4.6 – 111	Timing
SZ Her	17, 27	190, 220	Timing
RZ Dra	24	70	Timing
RR Cae	5	4	Timing
HW Vir	4.7, 13	14.3, 30 – 120	Timing
NSVS 14256825	2, 2.9	2.8, 8	Timing
HU Aqr	4	7	Timing
HS 0705+6700	3.5	32	Timing
HS 2231+2441	5	14	Timing
UZ For	2.8, 6	7, 7.7	Timing
NY Vir	3.3, 5	2.3, 2.2	Timing
NN Ser	3.4, 5	2.3, 7	Timing
QS Vir	6, 7	9, 57	Timing
DP Leo	8	6	Timing
2M J01033563	84	12 – 14	Imaging
DT Vir	1168	8.5	Imaging

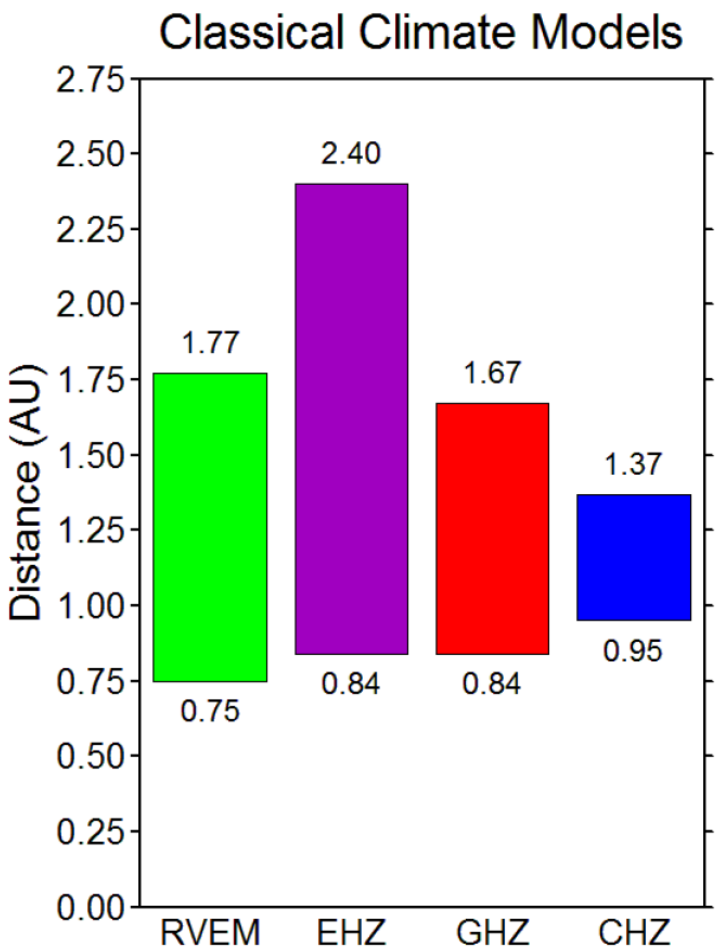
Focus of Study

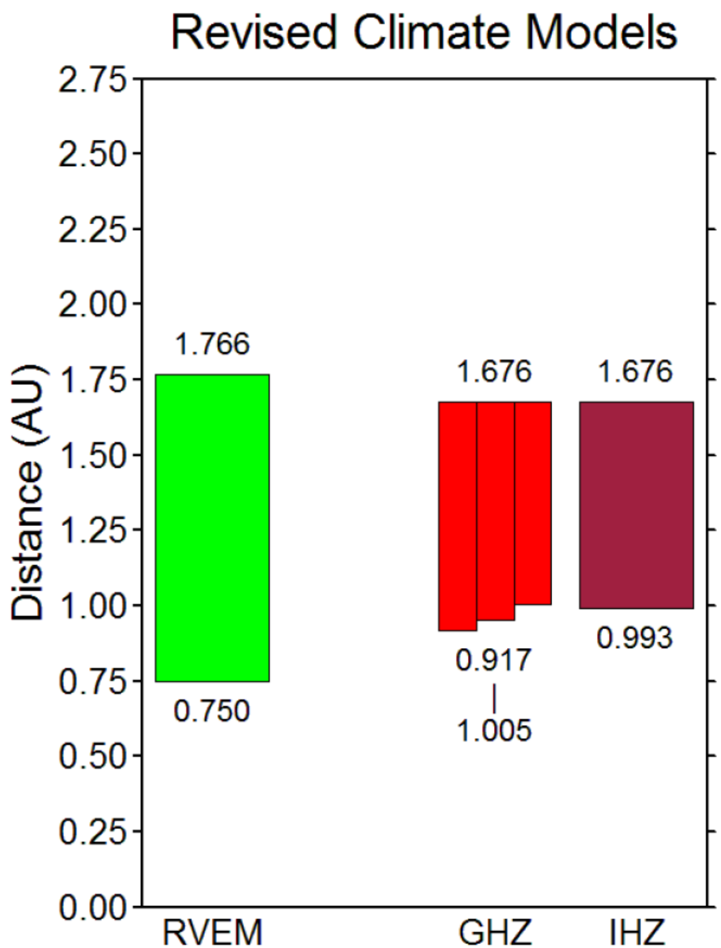
- Aim: Study of Habitability (to be more precise: CLI-HZ) in Stellar Binary Systems
- Authors of previous work: (selected list)

  S. Eggl, N. Haghighipour, N.R. Hinkel, L. Kaltenegger, S.R. Kane, P.A. Mason, E. Pilat-Lohinger

- Key Problem: Exploring Binary Habitability for general systems defined by $L_{1,2}$, $T_{1,2}$, $M_{1,2}$, $2a_{bin}$, e_{bin}, and an adequate choice of the planetary climate model
- Goal: Identifying Type of Habitability:
- S-Type ... P-Type ... none ... both ... OR: Is the S/P-type habitability TRUNCATED by the requirement of planetary orbital stability, referred to as: ST / PT?

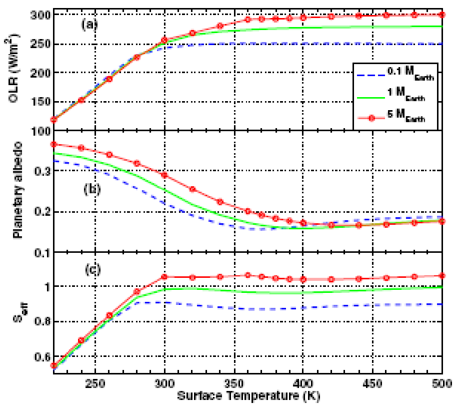
Comparison: Classical vs. Revised



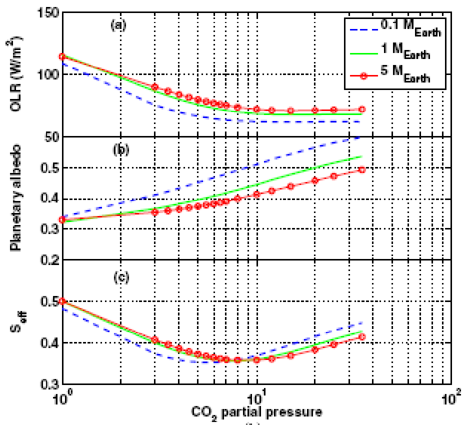


CLI-HZ Developing Updates

Kopparapu et al. (2013, 2014)



(a)



(b)

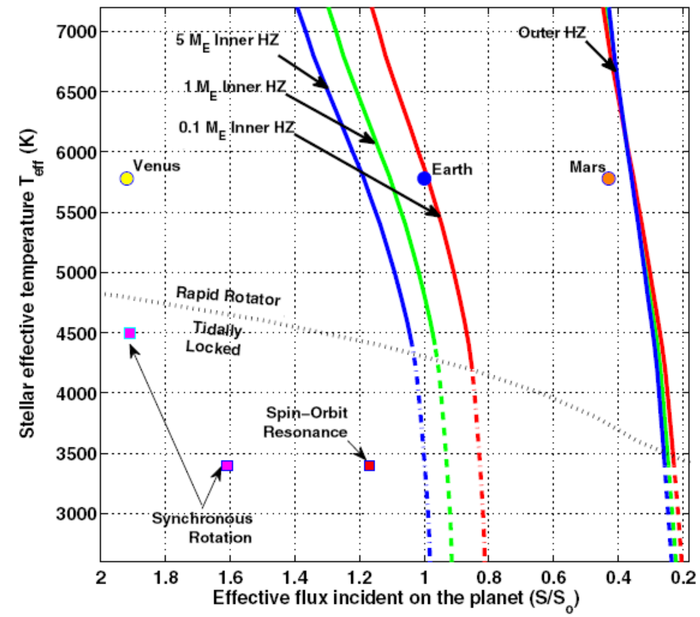


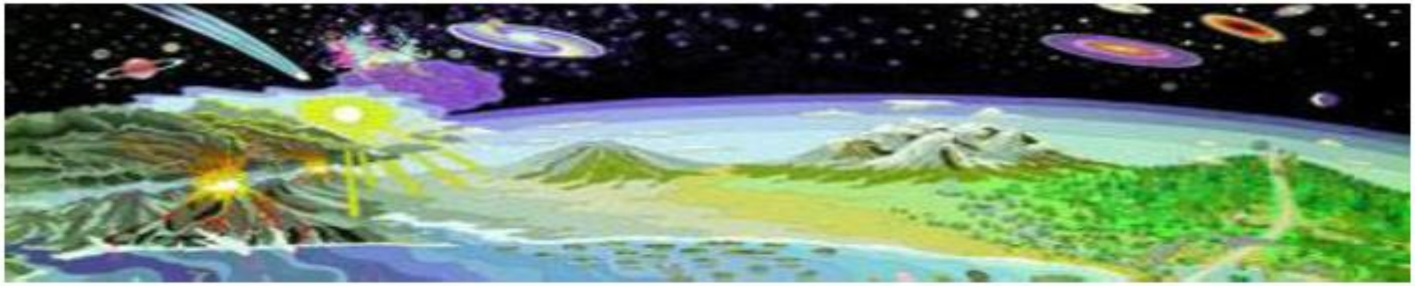
Table 1
Habitable Zone Distances around Our Sun from Our Updated 1D Climate Model

Model	Inner Habitable Zone			Outer Habitable Zone	
	Moist Greenhouse	Runaway Greenhouse	Recent Venus	Maximum Greenhouse	Early Mars
This paper	0.99 AU	0.97 AU	0.75 AU	1.70 AU	1.77 AU
Kasting et al. (1993)	0.95 AU	0.84 AU	0.75 AU	1.67 AU	1.77 AU

Notes. For comparison, estimates from Kasting et al. (1993) are also shown.

Binary Systems

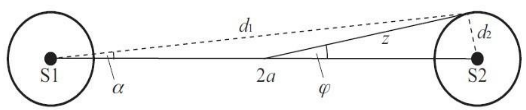
(Cuntz 2014, Cuntz 2015, & ongoing work by Zh. Wang, B. L. Quarles)

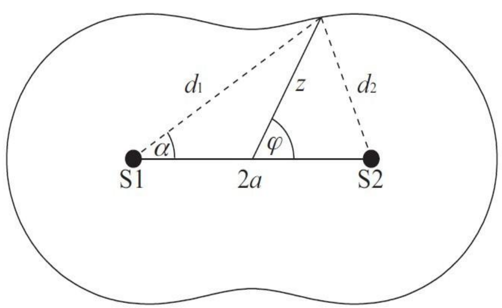


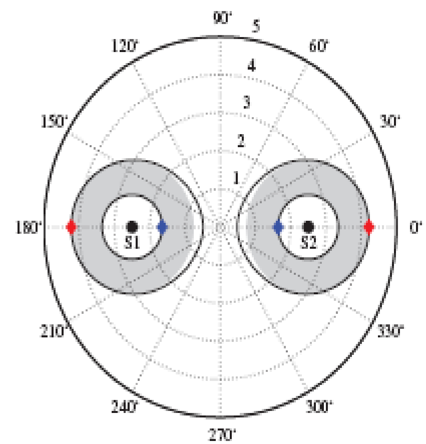
Key Features:

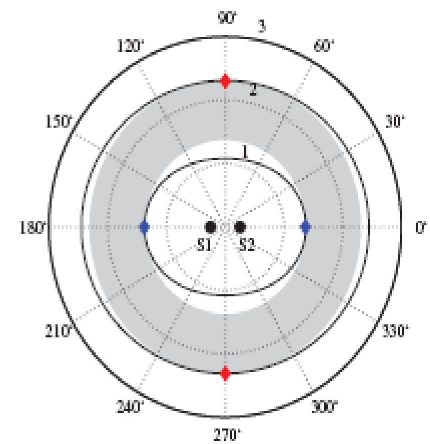
(1) The consideration of a joint constraint including orbital stability and a habitable region for a system planet through the stellar radiative energy fluxes ("radiative habitable zone"; RHZ) .
(2) The provision of a combined formalism for the assessment of both S-type and P-type habitable zones; in particular, detailed mathematical criteria are presented for which kind of system S-type and P-type habitable zones are realized.
(3) Consideration of circular or elliptical orbits for the stellar binary components.
(4) Applications of the attained approach to different types of stars, particularly main-sequence stars.
(5) High flexibility for setting the inner and outer limits of the RHZs (as defined in single star systems), which allow to treat the "classical" conservative and general HZs, and also allow for modifications in the RHZ limits informed by existing (and future) multi-dimensional planetary climate models.

Methodology









$$\sum_{i=1}^{N} \frac{L_i}{S_{\mathrm{eff},i\ell k} d_i^2} = \frac{L_\odot}{s_{\ell k}^2}$$

Methodology: Solution of fourth order polynomial with the set of algebraic solutions constraint by additional conditions

Methodology, cont'd

Table 2. Habitability Limits for the Sun, s_ℓ

Description	Indices		Models			
...	ℓ	k	Kas93		Mis00	Kop1314
...	...	...	5700 K	5780 K	...	5780 K
...	...	...	(AU)	(AU)	(AU)	(AU)
Recent Venus	1	1	0.75	0.77	...	0.750
Runaway greenhouse effect	2	1	0.84	0.86	...	0.950
Runaway greenhouse effect	2	0	...	...	...	1.005
Runaway greenhouse effect	2	2	...	...	...	0.917
Moist greenhouse effect	3	1	0.95	0.97	...	0.993
Earth-equivalent position	0	1	0.993	$\equiv 1$	...	$\equiv 1$
First CO_2 condensation	4	1	1.37	1.40	...	...
Maximum greenhouse effect, no clouds	5	1	1.67	1.71	...	1.676
Early Mars	6	1	1.77	1.81	...	1.768
Maximum greenhouse effect, 100% clouds	7	1	...	...	2.40	...

The RHZs (radiative habitable zones) of S-type or P-type orbit, constituting an annulus around each star (S-type) or both stars (P-type), can be determined by

$$\mathrm{HZ}(z) = \mathrm{Min}(\mathcal{R}(z,\varphi))|_{s_{\ell,\mathrm{out}}} - \mathrm{Max}(\mathcal{R}(z,\varphi))|_{s_{\ell,\mathrm{in}}}$$

Furthermore, orbital stability of the planet need to be taken into account as well.

$$\sum_{i=1}^{N} \frac{L_i}{S_{\mathrm{eff},i\ell k} d_i^2} = \frac{L_\odot}{s_{\ell k}^2}$$

S-type upper limit: $\frac{a_{\mathrm{cr}}}{a} = 1.60 + 4.12\mu + \mathcal{F}_{\mathrm{P}}(\mu, e_{\mathrm{b}})$

P-type lower limit: $\frac{a_{\mathrm{cr}}}{a} = 0.464 - 0.38\mu + \mathcal{F}_{\mathrm{S}}(\mu, e_{\mathrm{b}})$

Methodology, cont'd

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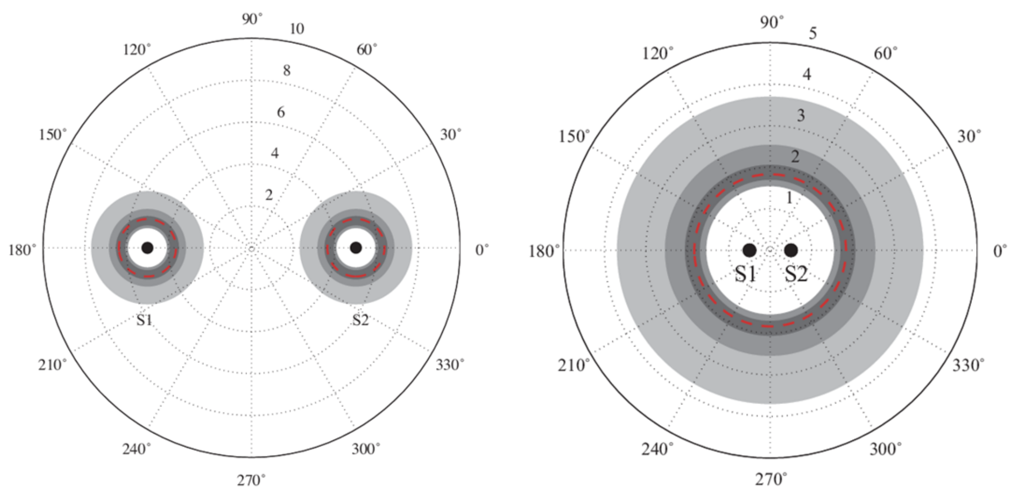
Width of Binary HZs

Combining both constrains, P/PT-type habitable zones are given as

$$\text{Width}\ (P/PT) = \text{HZ}_{\text{out}} - \text{Max}(\text{HZ}_{\text{in}}, a_{\text{cr}})$$

whereas S/ST-type habitable zone are given as:

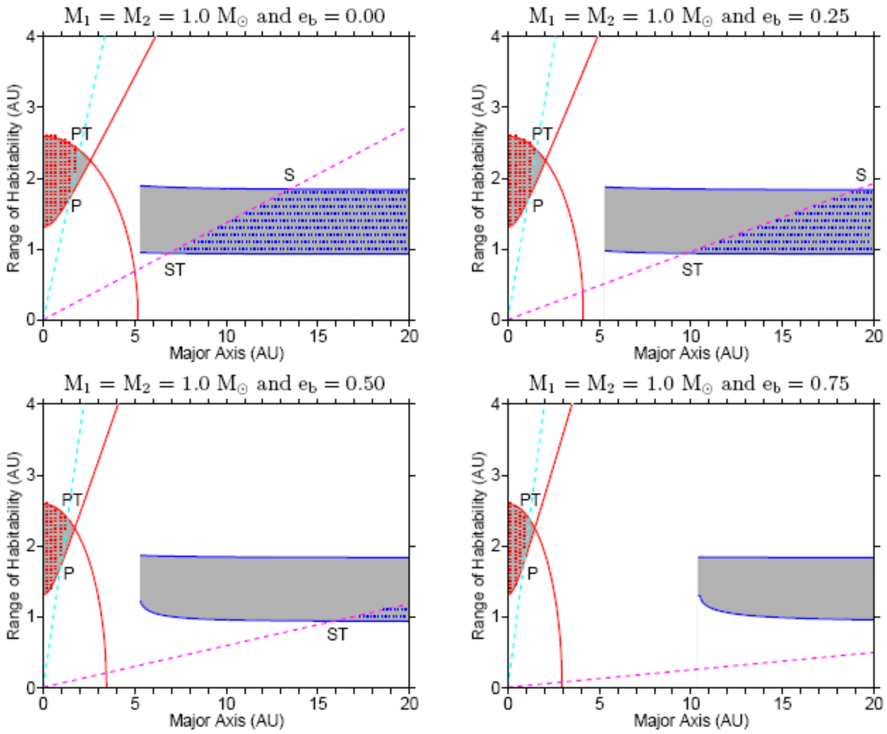
$$\text{Width}\ (S/ST) = \text{Min}(\text{HZ}_{\text{out}}, a_{\text{cr}}) - \text{HZ}_{\text{in}}$$

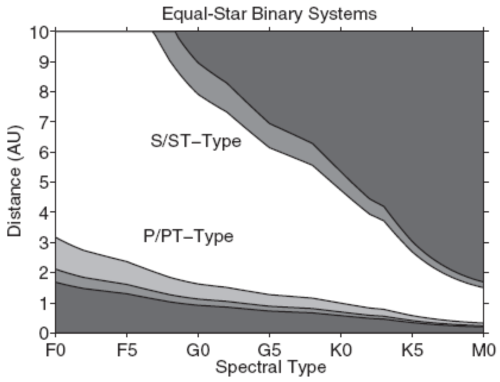


(a) (b)

Climatological HZs in Binaries

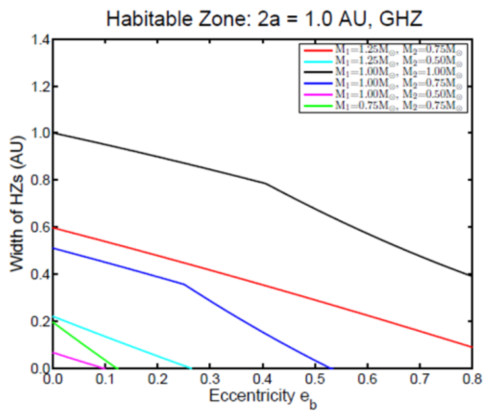
[equal-mass systems, w & w/o ellipticity]

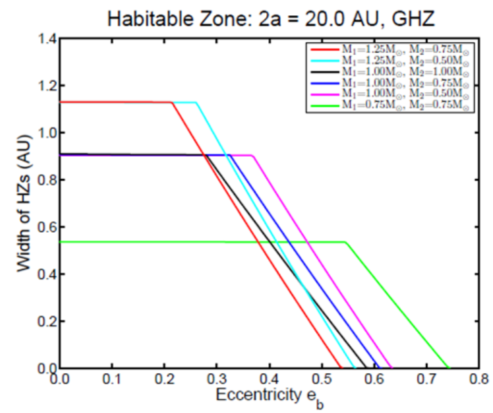


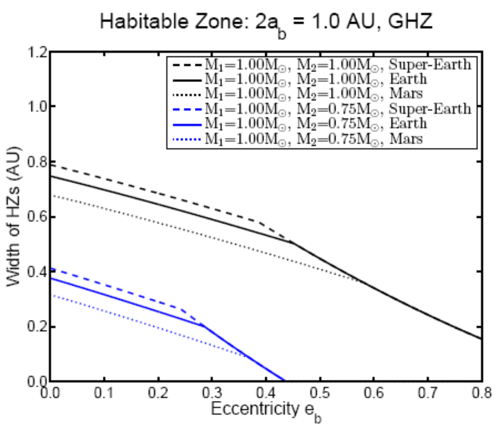


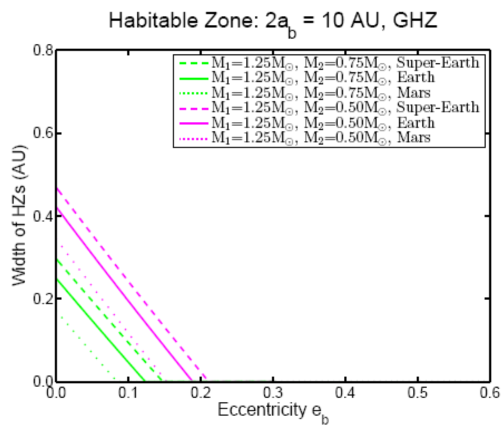
Examples

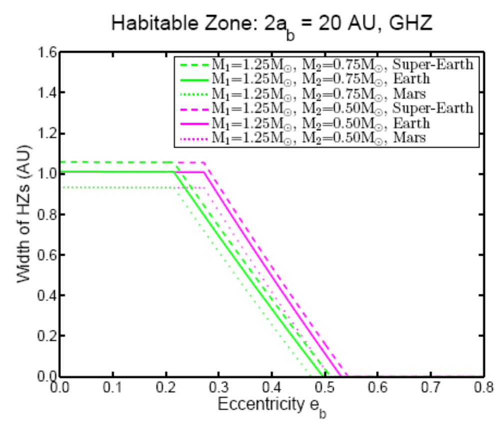
(2016, to be submitted)











Key Findings

Favorable Prospects:

S-Type Habitability:

- Large Separation Distance, $2a_{\rm bin}$
- Nearly Circular Orbit, $e_{\rm bin} \simeq 0$
- High Luminosities of the Stellar Components, L_1, L_2

P-Type Habitability:

- Small Separation Distance, $2a_{\rm bin}$
- Nearly Circular Orbit, $e_{\rm bin} \simeq 0$
- High, but <u>Balanced</u> Luminosities of the Stellar Components, L_1, L_2

P-Type Habitability Paradox:

$2a_{\rm bin} = 1$ AU, $e_{\rm bin} = 0$, GHZ

Case 1

$M_1 = M_2 = 1\ M_\odot$

$L_1 + L_2 = 2\ L_\odot$

$\Delta(\mathrm{HZ}) = 2.32$ AU - 1.57 AU $=$ 0.75 AU

Case 2

$M_1 = 1.2\ M_\odot$, $M_1 = 0.8\ M_\odot$

$L_1 + L_2 = 2.5\ L_\odot$

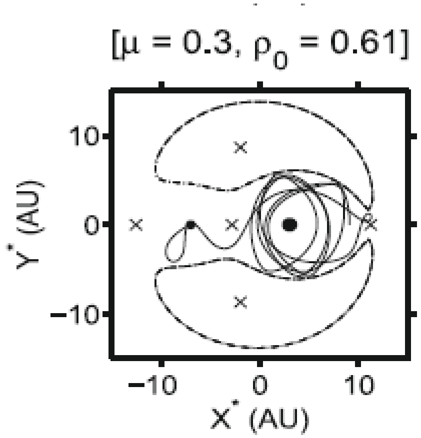
$\Delta(\mathrm{HZ}) = 2.45$ AU - 1.87 AU $=$ 0.58 AU (a 25% decrease!)

Steps Ahead

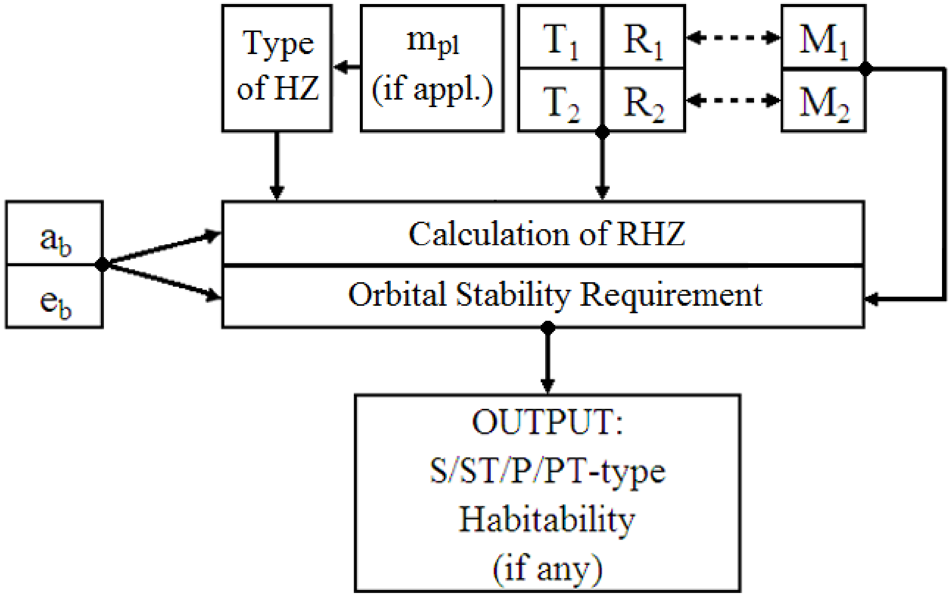
- Excursions of planets from the CLI-HZ permitted !? (Williams & Pollard 2002)
- Multiple (n>2) Stellar Systems --- Chaos Theory
- Effects of UV, EUV, (Super-)Flares, Energetic Particles; possible approach: Introduction of other types of "habitable zones"

  Example: UV-Habitable Zone (Buccino 2006; Sato et al. 2014; Sato & Cuntz 2016)

- Finally: Expansions to solvents other than H_2O



Code BinHab (online, hosted by UT Arlington)



BinHab Link:

University of Texas at Arlington (UTA)

http://physbinhab.uta.edu/