PROSPECTS FOR HABITABLE „EARTH“ IN KNOWN EXOPLANETARY SYSTEMS

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The study of Jones et al.:

- studied 111 exoplanetary systems (confirmed by August 2004)

- can Earth-mass planets be dynamically stable and remain confined to the habitable zone (HZ) of these systems long enough for life to emerge?

- detailed investigation of 7 systems
- orbital computations – hybrid orbital integrator

- a stellar evolution model has been used to obtain the HZs throughout the main-sequence lifetime

Classical Habitable Zone

- **Zone around a star**

  where liquid water can exist

  on the surface of a terrestial-like planet

Short review on studies of the HZ

- 1965/66 first discussions about the HZ (by Huang) → inner/outer border defined by the high/low temperature
- 1978 first computations by Hart (including the increase of luminosity) → a very small continuously habitable zone (CHZ) in the Sosys and no CHZ for low-mass stars
- CHZ of Hart is too small – he ignored important effects
- Carl Sagan

In the early 1990s James Kasting et al:

- took into account the effects of albedo and greenhouse gases

- they used a climate model to estimate the width of the HZ around our Sun

- for other main sequence stars

- → requirements for Earth-like planets:

(i) CO_2 /H_2O/N_2 atmospheres

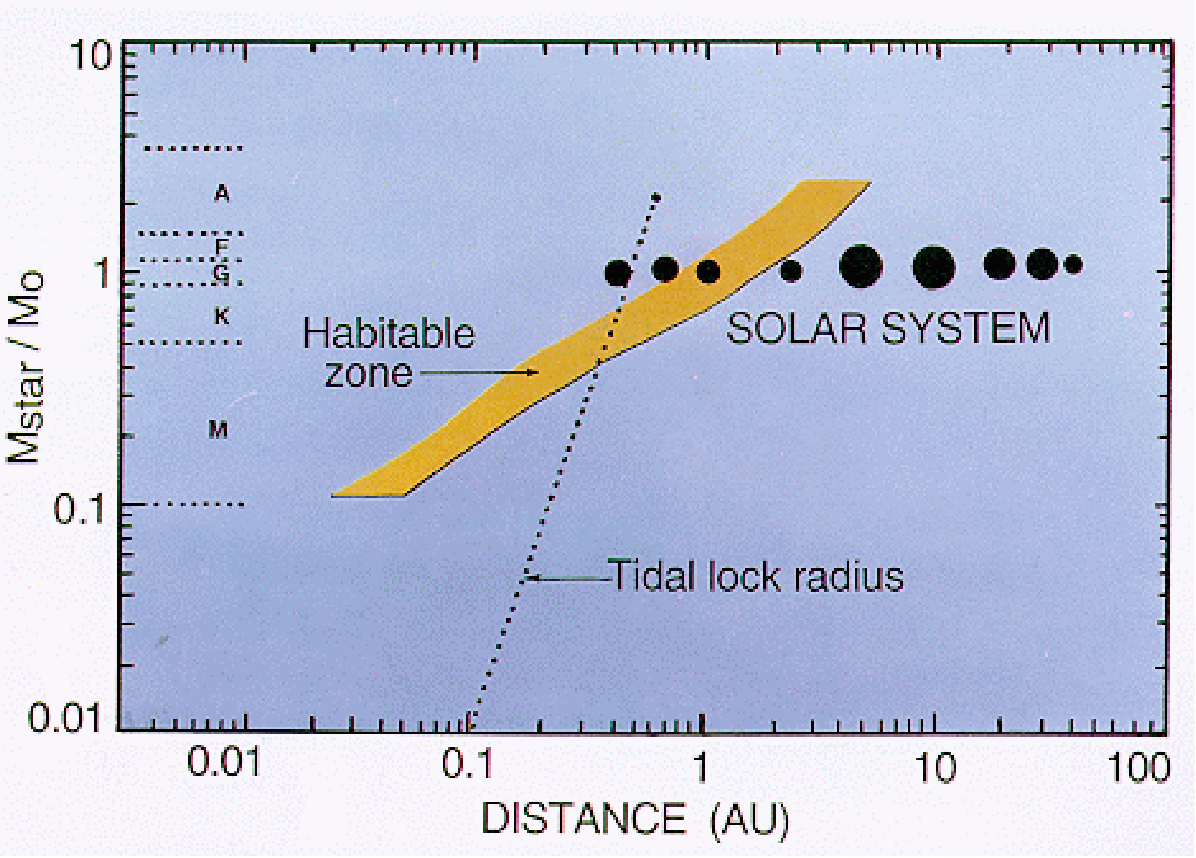
(ii) presence of liquid water on the planet‘s surface

The study of Jones et al. (2005)

- Boundaries for the HZ originating with Kasting et al. (1993)

- **Inner boundary** is the maximum distance from the star at which a runaway greenhouse effect would lead to the evaporation of all surface water

- **Outer boundary** is the maximum distance at which a cloud-free CO_2 atmosphere could maintain a surface temperature of 273 K based on the definition given by Kasting et al. (1993).



Habitable Zone

- **This zone depends on:**
  - **the spectraltype , the mass , the age, …. of the star**
  - **the orbit of the planet**
  - **the mass, the composition, the atmosphere , ……of the planet**
  - **the parameters of other planets in this system (mass, orbit, …)**

Determination of the boundaries

- from Kasting et al (1993):

the **critical stellar flux S_b** for each boundary

S_b depends mainly on the *luminosity* and to some extent on T_e of the star and is given in units of the solar constant

The boundary

- is the distance d [AU]:

$$d = \mathrm{sqrt}[L / S_b(T_e)]$$

L....luminosity [solar units]

T_e... effective temp.

Model of stellar evolution

- a more recent model than that used by Kasting et al.:
- **Mazzitelli (ApJ 340,p.249, 1989) –** computed MS and RG evolutionary tracks for Pop. II and I stars in the range of 0.7 Msun up to 1 Msun (up to the helium flash) and he found that the core mass values are about 4 % (or 0.020 Msun) larger than those evaluated by other authors.

- Details of this model can also be found in Underwood et al. (Int.J.Astrobiology,2,p.289, 2003)
- Result for the Sun is given in fig.1

Boundaries for the HZ of the Sosys

- see fig. 2
- note that using this model

  Mars would be in the HZ

  Venus is just interior to the inner boundary

habitable planets in EPS

- see e.g. fig. 3:

(i) determine the HZ with the aid of the stellar evolution model

(ii) the influence of the giant planet (2 lines):

one at a distance $\mathbf{n_{int}R_H}$ interior to the periastron of the giant planet and

one at a distance $\mathbf{n_{ext}R_H}$ exterior to the apastron

$\mathbf{R_H}$ is the Hill radius of the giant planet and $\mathbf{n_{int}/n_{ext}}$ depend on the eccentricity of the giant planet

Some notes on the eccentricity of the Earth-like planet

- **Williams and Pollard** (Int.J.Astrobiology, 1,p.61, 2002):

  an Earth would be habitable as long as its semi-major axis remain in the HZ → the habitability limit for e for an Earth is probably between 0.5 and 0.7
- **Jones:** e usually less than 0.3 and rarely exceeds 0.4

Obtaining R_H, n_{int} and n_{ext}:

- detailed study of 7 systems (see table 1)

- orbital computations using mercury integrator package of Chambers → switch to a Bulirsch Stoer integrator when the Earth-mass planet comes within $3R_H$ of the giant planet

- integation time: 1000Myrs

Results

- see fig. 4 and 5
- Table 3 shows the values for the 7 systems → n_{int} and n_{ext} are sensitive to m_G/m_{star} and a_G

Habitability of 111 exoplanetary systems

- star evolution model applied to a grid of reference stars of various masses and metallicities Z:

  - masses: 0.5,0.6, ..., 1.4, 1.5 MSun

  - metallicity: 0.007484, 0.01186, 0.0188, 0.0298, 0.04722

- determine L and Te from the stellar evolution model throughout the main-sequence life;

  - for the sun (fig.1) was achieved with a ZAMS mass fraction of helium of 0.267 and a metallicity of 0.0188 (reasonable values according to M.Tosi)

- Helium content Y for the other stars is given by the empirical relation

$$Y=0.243+(dY/dZ)Z$$

- 0.243 is the primordial helium mass fraction
- dY/dZ is a very uncertain quantity (Tosi, priv.comm), which was set to 2.0 (reasonable value)

HZ - plots

- Each EPS was given the HZ of its nearest grid star in accord with the real system‘s measured mass and metallicity
- Together with the gravitational reach of the giant planet → habitability for EPS (fig. 6 and 7)
- 6 configurations (see fig. 8)

habitable Earth-like planets

- Results are summarized in table 5:

  - order according their „sometime“ configuration (in multiple-planet systems, the innermost planet defines the order)
  - RH = 1.3 x minimum mass
  - ? denotes a star of unknown age
  - the present eccentricity and semi-major axis of the giant planet has been used
  - binary systems: the gravitational effect of the binary was not included
  - if the star is already a giant – its written in „Now“ → no habitable planet now

Alternative Stellar Model Parameters

- for the Sun: Y=0.269 and Z=0.020 → only slightly different from the original solar values

- fig.9 shows the HZ for different Y and Z values for a 0.9 solarmass star → an increase in - Y decreases the main-sequence lifetime and

  - an increase in Z increases the main-sequence lifetime

→ **the habitability for the great majority of known exoplanetary systems is thus robust under changes in stellar model parameters**

Comparison with other work

- Jones et al. (2001, 2003)
- Jones & Sleep (2002, 2003)
- Noble et al. (2002) – 3 systems
- Laughlin et al. (2002) – 1system
- Dvorak et al. (2003a,b) – 1 system/paper
- Asghari et al. (2004) – 5 systems
- Erdi et al. (2004) – 3 systems
- Rivera & Haghighipour (2004) – 4 systems
- Menou & Tabachnik (2003) – 85 systems
- Turnbull & Tarter (2003) – 55 systems

- **there is broad agreement**
- **some of the orbits that have survived for 1-20 Myrs would very probably not have survived for 1000 Myrs**

Conclusion

- **somewhat less the half of the 111 EPS could have had an habitable Earth-mass planet for at least 1000 Myrs**
- **for config. 2 and 4 (hot-Jupiter): habitability if Earth-mass planet can form after the migration of the giant through the HZ**
- **investigation is needed for the orbital stability of putative large satellites of giant planets moving in the HZ**