Habitability of Exoplanets

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2010

Overview

- The detection of exoplanets
- Definition of life and habitability
- Definition of the habitable zone (HZ)
  - Earth-system-model
  - Geodynamic model
  - Dynamic habitability
- The HZ in the solar system & around other main sequence stars

The detection of exoplanets

- Direct imaging

  planets larger than Jupiter, hot, great distance to parent star

- Transits

  planetary orbits with right alignment

- Astrometry

  large planetary orbits, long observation time

- Radial velocity

  high S/N ratio → nearby stars

- Gravitational microlensing

Definition of life and habitability

- Life:

  >self-sustained system of organic molecules in liquid water immersed in a source of free energy<

  → <u>liquid water</u>

- Habitability:

  Conditions under which life - as we know it - can emerge and exist.

Definition of the habitable zone (HZ)

- >>The HZ around a given central star is defined as the region within an earth-like planet might enjoy the moderate surface temperatures required for advanced life forms. <<

  (**S. Franck et al., 2001,** *Planetary habitability: is Earth commonplace in the Milky Way?*)
- Circumstellar HZ and galactic HZ
- Criteria for liquid water:

  →temperature

  Distance to central star, planetary size, biological and geological evolution of the planet, atmosphere, obliquity, eccentricity

Earth-system-model

- The model consists of the components:
  - solid earth,
  - hydrosphere,
  - atmosphere,
  - and biosphere.
- It couples:
  - the increasing solar luminosity,
  - the silicate-rock-weathering rate,
  - and the global energy balance
- to estimate:
  - the partial pressure of atmospheric and soil carbon dioxide,
  - the mean global surface temperature,
  - and the biological productivity as a function of time.

Earth-system-model

Radiation balance equation:

$$\frac{L}{4\pi R^2}\left[1-\alpha\left(T_{surf},P_{atm}\right)\right]=4I_R\left(T_{surf},P_{atm}\right)$$

α…albedo

P_{atm}… CO_2 concentration in atmosphere

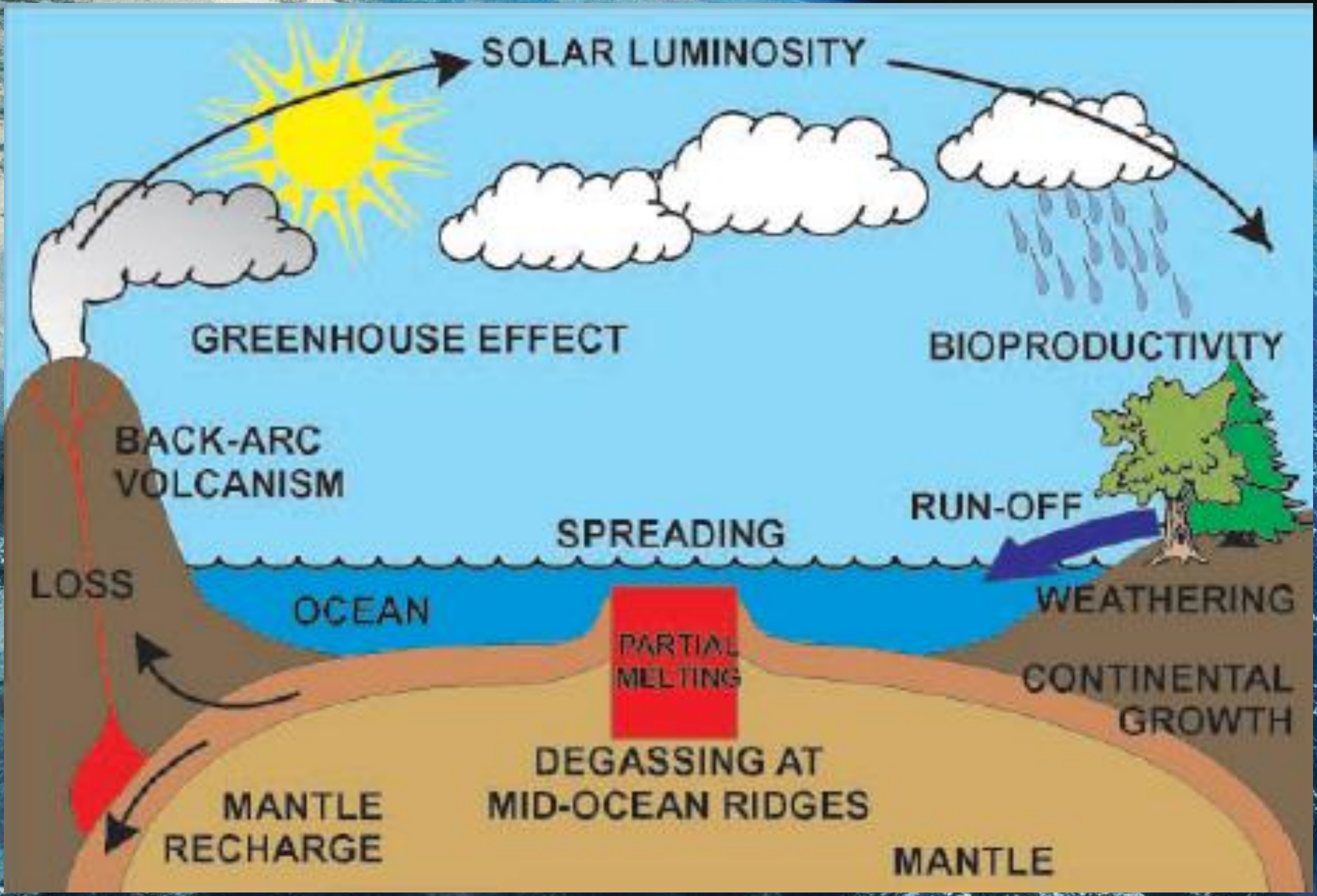
I_R… outgoing infrared flux

Stefan Boltzmann: $I_R=\sigma T^4_{bbr}$ $T_{bbr}=T_{surf}-\Delta T_{greenhouse}(P_{atm},T_{surf})$

Increasing insolation due to increasing H-burning rate!

→ Increasing temperature

The global carbon cycle



The global carbon cycle

- Main process for the regulation of the atmospheric composition and climate with respect to increasing insolation.
- Silicate-rock-weathering:

  Weathering plants transport CO_2 from atmosphere to soil → silicates transform CO_2 → weaker greenhouse effect → self regulation

Silicate-rock-weathering

- Main sink in for atmospheric carbon dioxide

- Chemical reactions:

$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

$CO_2 + MgSiO_3 \rightarrow MgCO_3 + SiO_2$

!! Higher mean global temperature → increase in weathering

Global mean weathering rate

$$\frac{F_{wr}}{F_{wr,0}} = \left(\frac{a_{H^+}}{a_{H^+,0}}\right)^{0.5} exp\left(\frac{T_{surf} - T_{surf,0}}{13.7\ K}\right)$$

- Describes the climate in respect to the surface temperature and CO_2 concentration in atmosphere and soil
- aH^+ … *activity of H^+ in fresh soil water, depending on P_{soil} and T_{surf};*

  outlines the role of CO_2 concentration in the soil

Bioproductivity

- Amount of produced biomass

$$\frac{\Pi}{\Pi_{max}} = \Pi_T(T_{surf}) \cdot \Pi_P(P_{atm}) = \max\left(\left(1 - \left(\frac{T_{surf} - 50°C}{50°C}\right)^2\right)\left(\frac{P_{atm} - P_{min}}{P_{1/2} + (P_{atm} - P_{min})}\right), 0\right)$$

- $\Pi_{max} = 2\Pi_0$ (assumption)
- $P_{1/2}$ defined by $\Pi_P(P_{1/2} + P_{min}) = 1/2$ for a fixed value $P_{min} = 10^{-5}$ bar
- Maximum productivity for a given P_{atm} at 50°C surface temperature, zero productivity for ≤ 0°C and ≥ 100°C

Evolution of CO_2 concentration

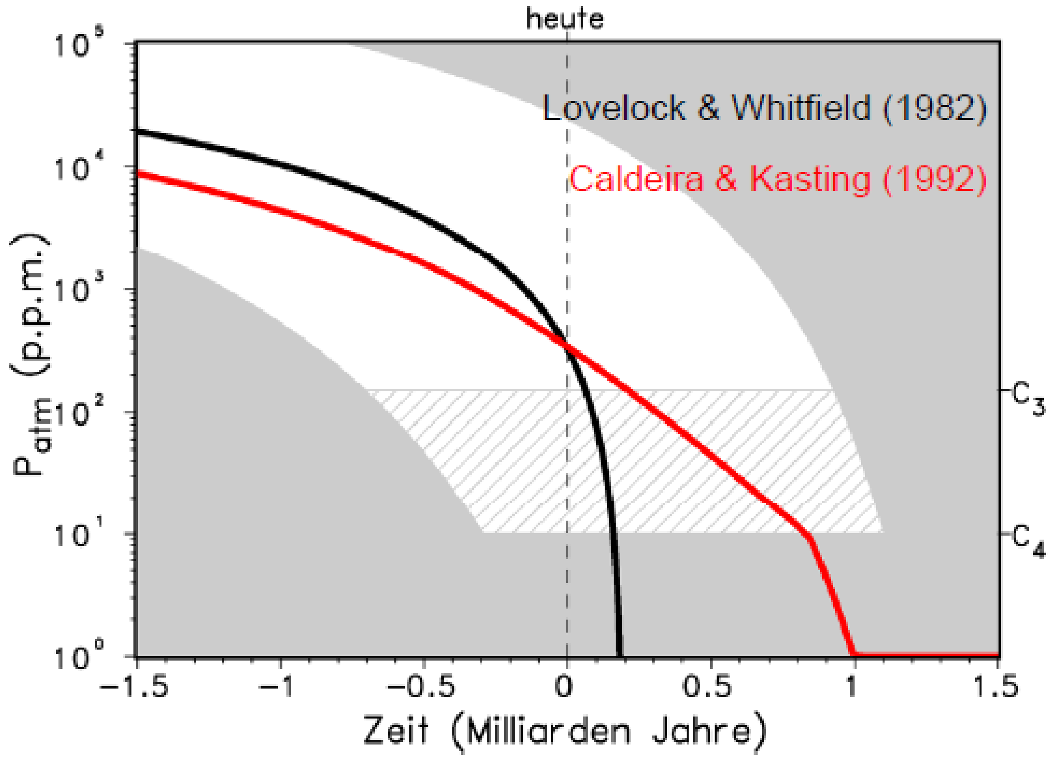


Abbildung 2.9: Ergebnisse der Berechnungen des zeitlichen Verlaufs des atmosphärischen CO_2-Gehalts von Lovelock und Whitfield (1982) und Caldeira und Kasting (1992). Der weiße Korridor bezeichnet den Bereich von Umweltbedingungen, in dem Biomasseproduktion möglich ist, im schraffierten Bereich allerdings nur durch C_4-Pflanzen. (nach Bounama et al. 2004)

Bioproductivity

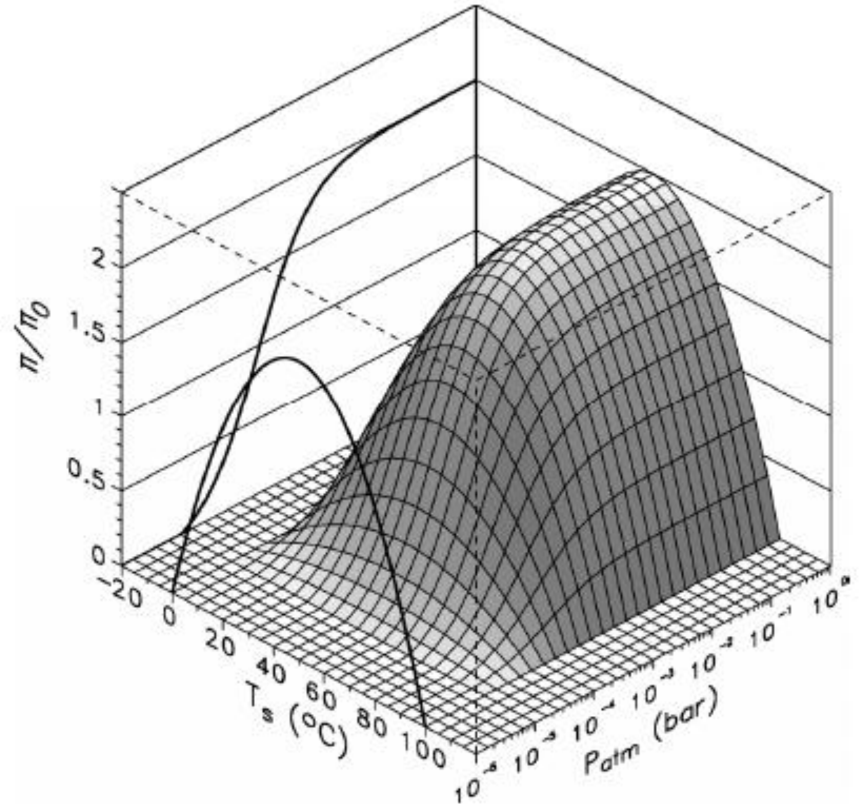


Abbildung 2.11: Die biologische Produktivität Π normalisiert auf den heutigen Wert Π_0 als Funktion der Oberflächentemperatur T_s und des atmosphärischen CO_2-Partialdrucks P_{atm}. (Franck et al. 2001)

Geodynamic model

- Balance between CO_2 sink and sources

$$\frac{\partial P_{atm}}{\partial t} = F_{source} - F_{wr} \qquad \frac{F_{source}}{F_{source,0}} = \frac{S}{S_0}$$

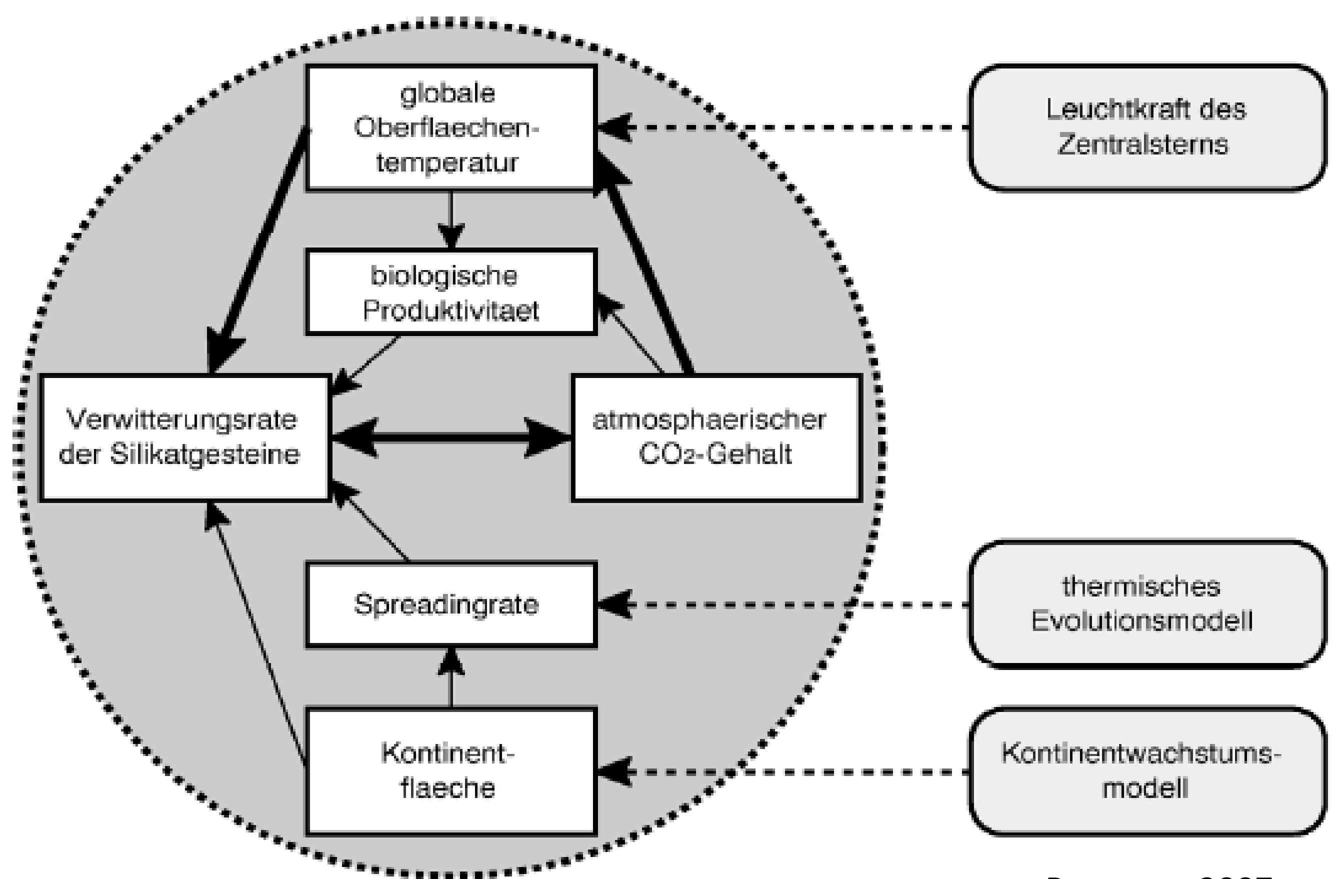
S…. Spreadingrate

- Weathering only on continental area →
- $f_{wr}(T_{surf}, P_{atm}) = \frac{f_{sr}}{f_A} =: GFR(t)$ **G**eophysical **F**orcing **R**atio
- Radiation balance equation →

$$f_{wr}(T_{surf}, L, R) = \frac{f_{sr}}{f_A} =: GFR(t)$$

Geodynamic model

Calculating the weathering rate for geological history and planetary future when continental area and spreading rate are known.



Bounama 2007

Dynamic habitability

- Orbital stability:
  - Required over a biologically significant time
  - Giant planets influence the stability of smaller ones
  - Hill radius: $R_H = \left(\frac{m}{3M}\right)^{1/3} a$ m…planet Mass, M… star mass, a…semimajor axis, e…eccentricity
  - Boundaries for unstable orbits:

$$R_{int} = a(1-e) - n_{int}(e) R_H$$

$$R_{ext} = a(1+e) - n_{ext}(e) R_H$$

The HZ in the solar system

$$HZ := \left\{R \mid \Pi\left(P_{atm}(R,t), T_{surf}(R,t)\right) > 0\right\}$$

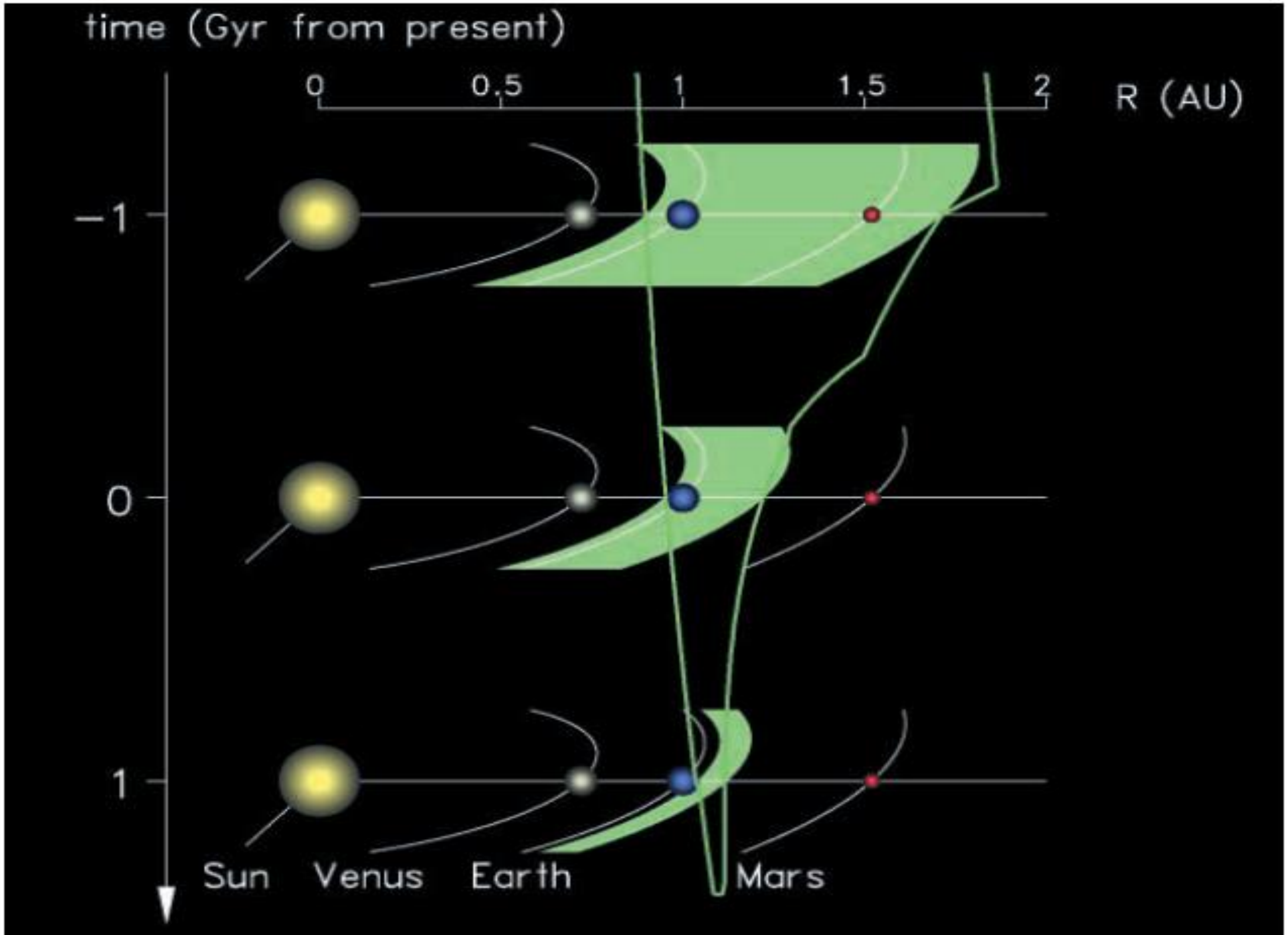
- *most conservative case*: R= 0.95 AU to 1.37 AU
- *least conservative case*: R= 0.75 AU to 1.90 AU
- *intermediate case*: R= 0.84 AU to 1.77 AU

(Kasting et al.)

__Inner radius__: loss of planetary water

__Outer radius__: maximum possible greenhouse heating, CO_2 condensation → albedo

The HZ in the solar system



Franck et al. 2001

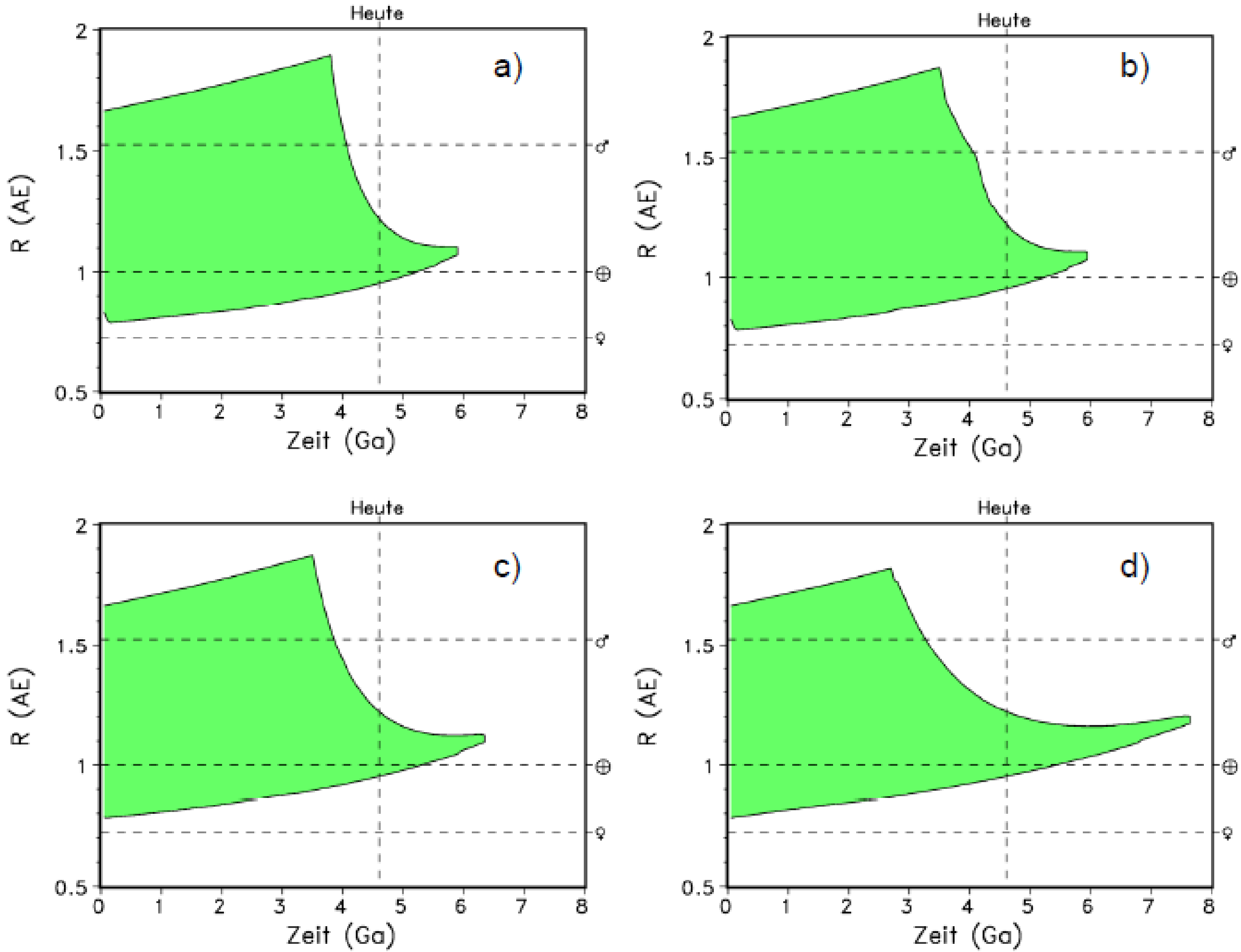


Abbildung 2.16 Die photosynthetisch-aktive habitable Zone (grüner Abstandsbereich in AE) im Sonnensystem in Abhängigkeit von der Zeit für vier verschiedene Kontinentwachstumsszenarien: a) verspätetes lineares Wachstum, b) episodisches Wachstum (Condie 1990), c) lineares Wachstum, d) konstante Kontinentfläche. Die horizontalen gestrichelten Linien markieren den Abstand der Venus (♀), der Erde (⊕), und des Mars (♂) zur Sonne. Die Ergebnisse basieren auf GFR_1.

Bounama 2007

The HZ around main sequence stars

- Massive stars → short time HZ; sudden end of main sequence
- $M>2.2\ M_{sun}$ → H burning < 0.8 Gyr; earth-like planet needs up to 0.8 Gyr habitable conditions
- No read giants → $1.1 – 2.2\ M_{sun}$
- Only geodynamics between 0.6 and $1.1\ M_{sun}$ → $t < t_{max} = 6.5$ Gyr
- Tidal locking $< 0.6\ M_{sun}$

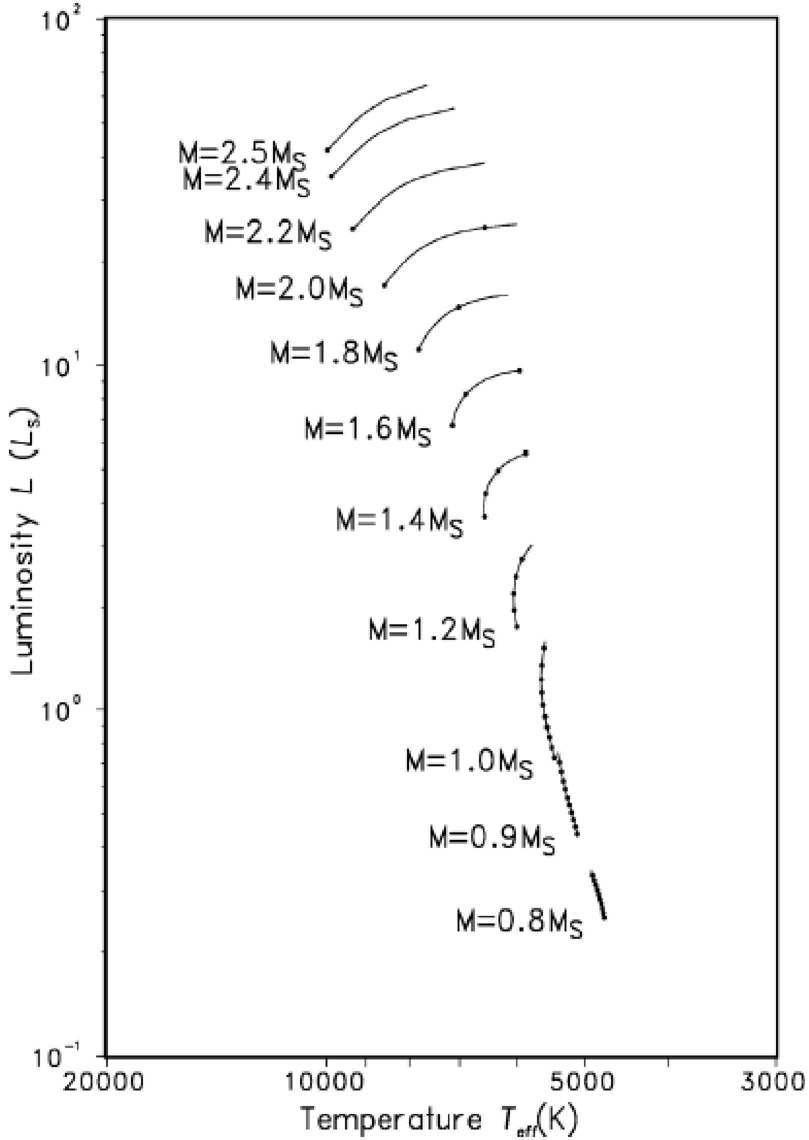


Abbildung 2.15: Das Hertzsprung-Russell-Diagramm (Leuchtkraft L in Abhängigkeit von der effektiven Temperatur T_{eff}) für Zentralsterne im Massebereich 0,8 bis 2,5 M_s. Es wurde nur die Hauptreihenentwicklung berücksichtigt. Aufeinander folgende Punkte für die massenspezifischen Graphen markieren einen Zeitschritt von 1 Ga. (Franck et al. 2000b)

Franck et al. 2001

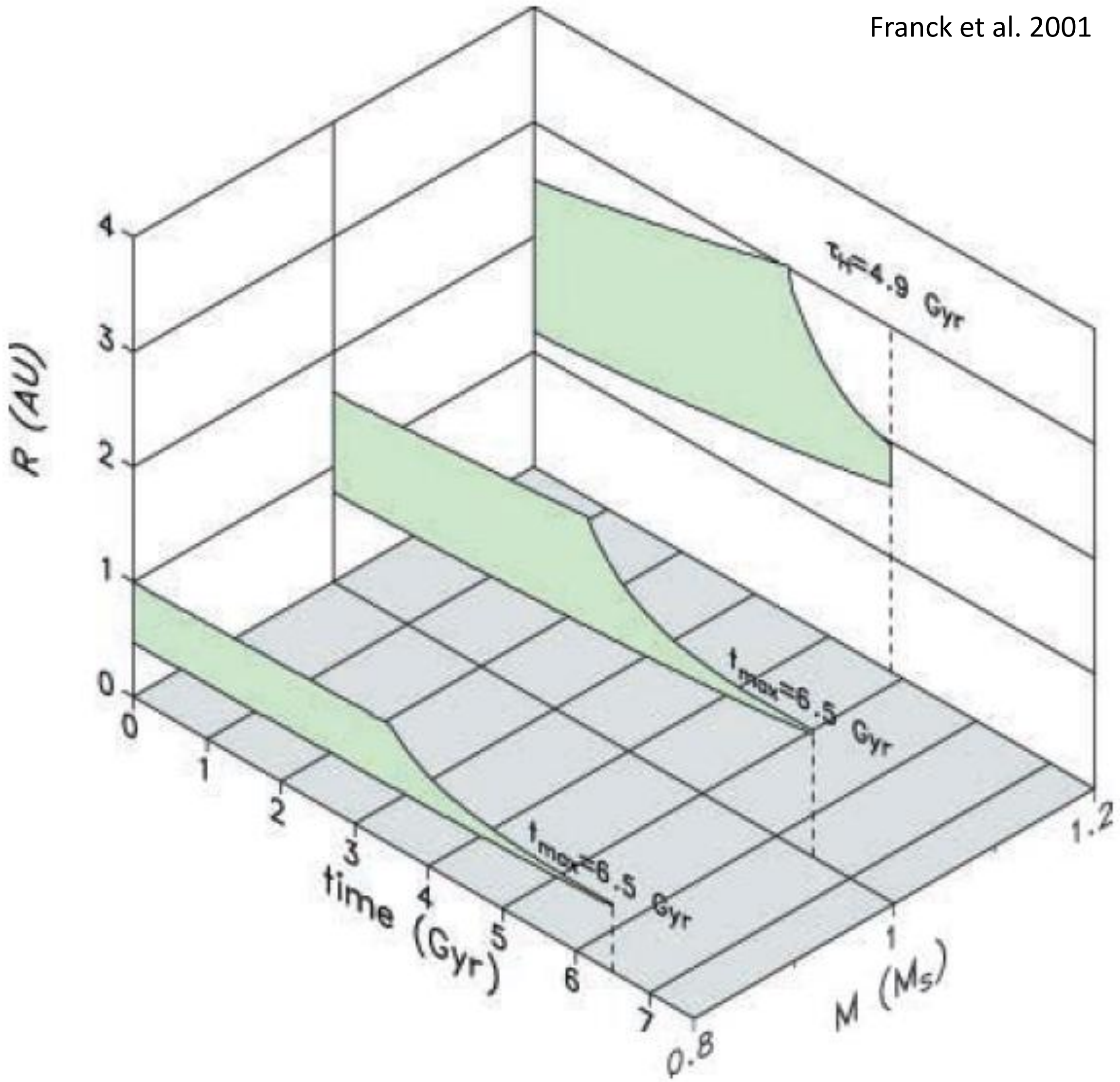
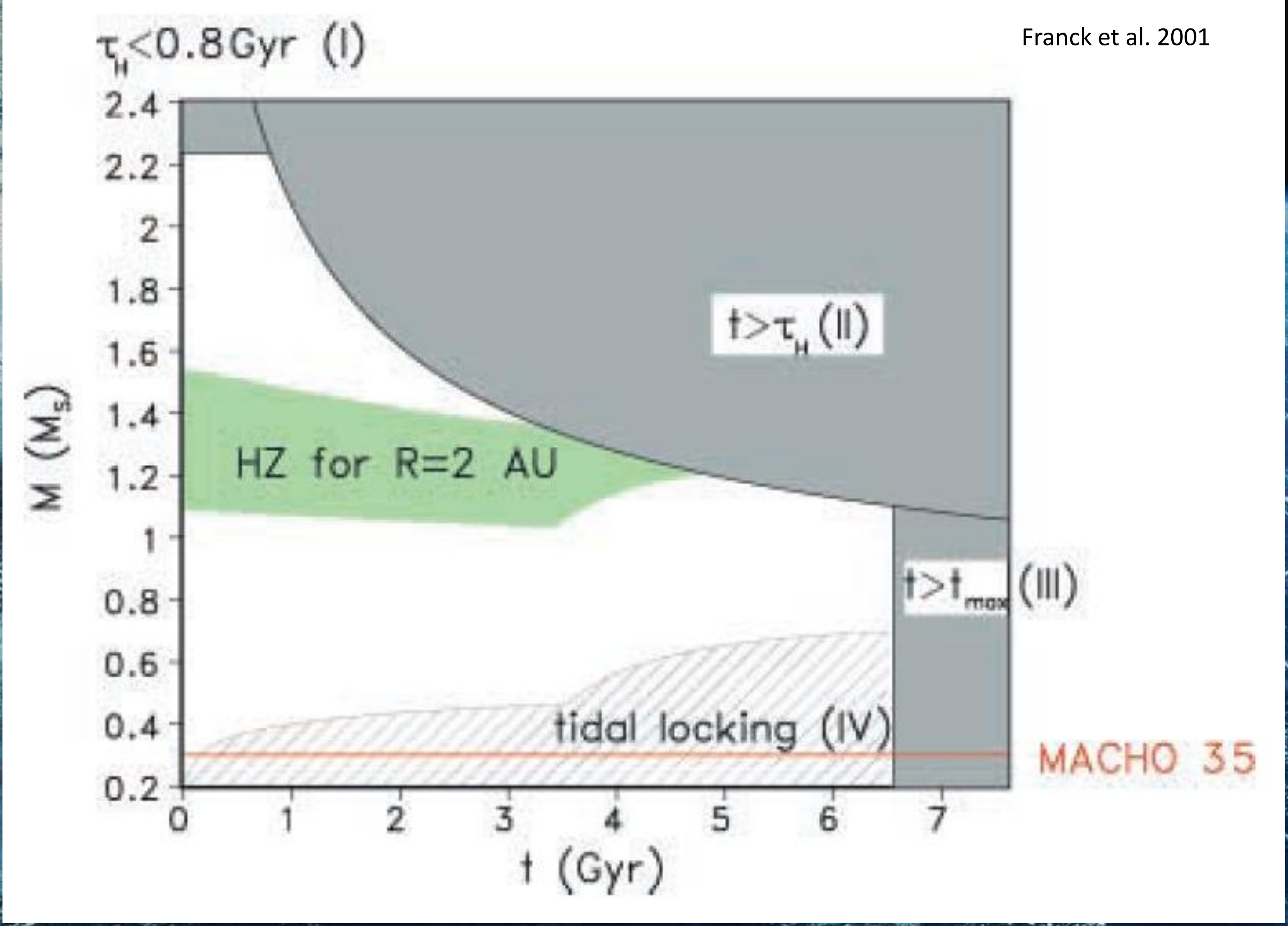


Fig. 8 Graphs of the width and position of the HZ derived from the geodynamic model for three different stellar masses M (0.8, 1.0, 1.2 M_s). t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main sequence limiting the life span of more massive stars

The HZ for a 0.3 M_{sun} star



Statistics

- **86** exoplanetary systems examined:

- **54** potential dynamic habitable earth like planets
- **20** systems with giant planet in HZ and possibly habitable moon or Trojan planet
- **12** systems without chance for the existence of dynamic habitable planets

- ***18*** *systems with better perquisites for life than solar system → principle of mediocrity*

References

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- **Thermische Evolution und**

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