Dynamical and physical properties of extrasolar planets

presented as part of the lecture
"Origin of Solar Systems"

Ronny Lutz, Anne Angsmann 2009-07-02

Outline

- Part 1 (Anne):
  - **Introduction, Detection methods**
- Part 2 (Ronny):
  - **Physical properties, Statistics**
- Part 3 (Anne):
  - **Dynamical properties, Atmospheres**
- Part 4 (Ronny):
  - **Habitability of exoplanets**

Outline

- Part 1 (Anne):
  - Introduction, Detection methods
- Part 2 (Ronny):
  - Physical properties, Statistics
- Part 3 (Anne):
  - Dynamical properties, Atmospheres
- Part 4 (Ronny):
  - Habitability of exoplanets

Outline

- Part 1 (Anne):
  - Introduction, Detection methods
- Part 2 (Ronny):
  - Physical properties, Statistics
- Part 3 (Anne):
  - Dynamical properties, Atmospheres
- Part 4 (Ronny):
  - Habitability of exoplanets

Physical properties - Statistics

All Catalogs

update : **23 June 2009**

All Candidates detected	**353 planets**
Candidates detected by radial velocity or astrometry *update : 23 June 2009*	278 planetary systems 327 planets 34 multiple planet systems
Transiting planets *update : 23 June 2009*	59 planetary systems 59 planets 0 multiple planet systems
Candidates detected by microlensing *update : 19 September 2008*	7 planetary systems 8 planets 1 multiple planet systems
Candidates detected by imaging *update : 24 November 2008*	9 planetary systems 11 planets 1 multiple planet systems
Candidates detected by timing *update : 25 November 2008*	4 planetary systems 7 planets 2 multiple planet systems

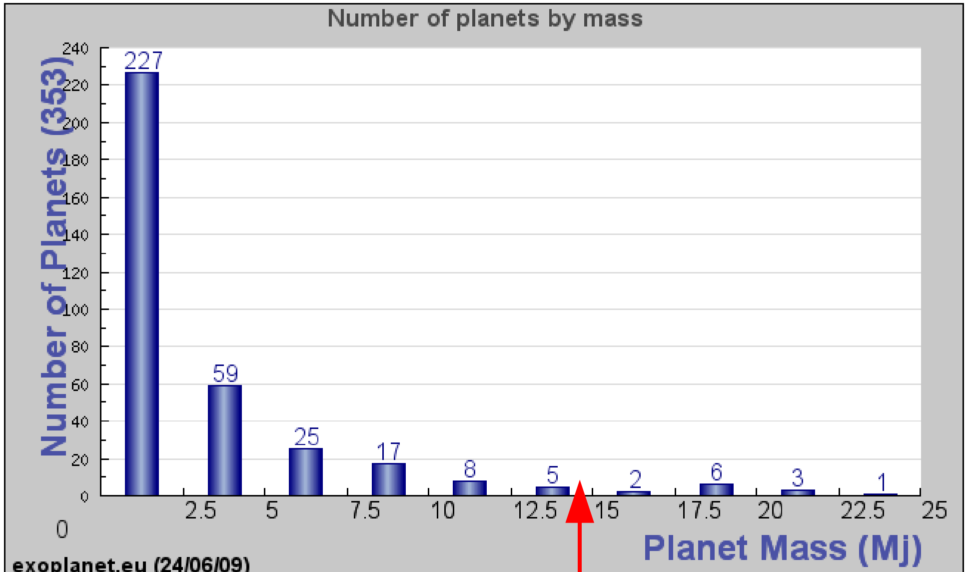
exoplanet.eu

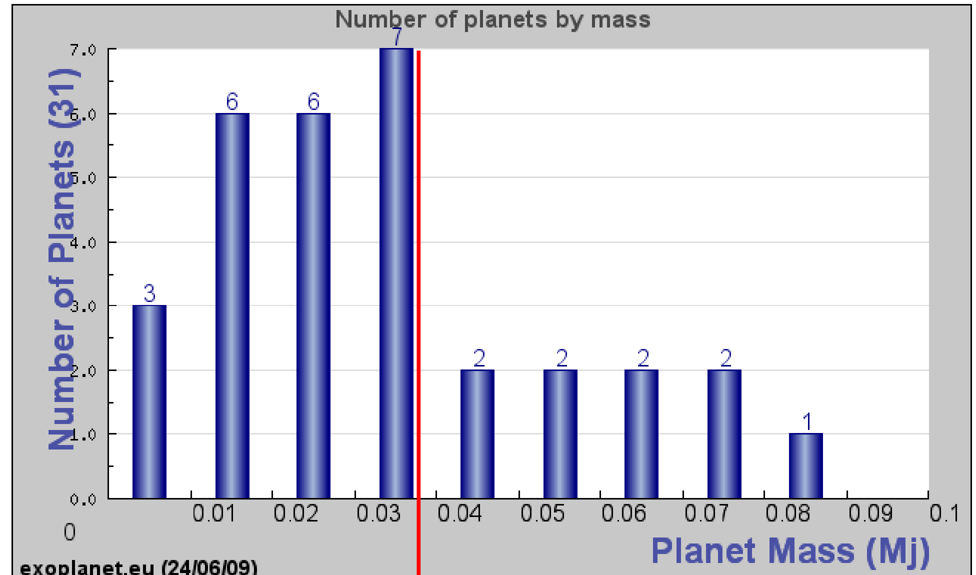
some "exo"-world records...

- **lowest mass** → PSR 1257+12b: **0.02M_E** (pulsar host); Gl 581e: **2M_E** (M-dwarf host)
- **highest mass** → HD 43848b: **25M_J = 8065M_E** (G-dwarf host)
- **shortest period** → CoRoT-7b: **0.85d** (K0-dwarf host)
- **longest period** → Fomalhaut b: **320000d** (A3-dwarf host)
- **closest to us** → eps Eridani b: **3.2pc** (K2-dwarf host)
- **lightest host star** → 2M1207: M8-dwarf with **0.025M_S**
- **most massive host star** → HD 13189: K2-giant with **4.5±2.5M_S**
- **most planets in a system** → 55 Cnc with **five planets** (G8-dwarf host)

1 $M_J \approx$ 318 M_E

Physical properties - Statistics





D-burning limit

terrestrial ? giant

$10M_E$

- planet vs. brown dwarf → deuterium burning limit $13.6M_J$
  → formation process (core accretion vs. core collapse)
- BD desert at ≈ $15\text{-}60M_J$
- terrestrial (solid) planet vs. (gaseous) giant planet → $10M_E$?, different formation ?

Physical properties - Statistics

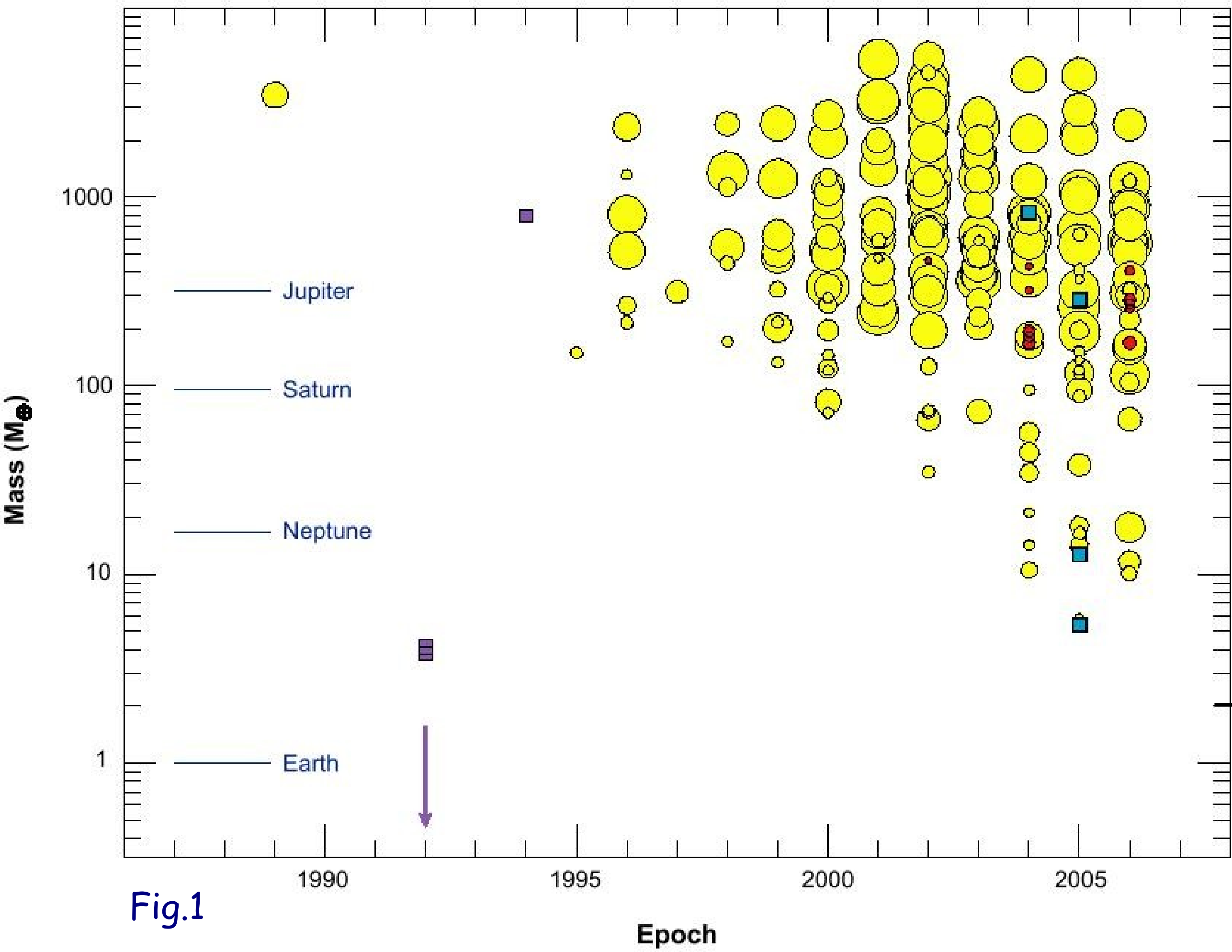
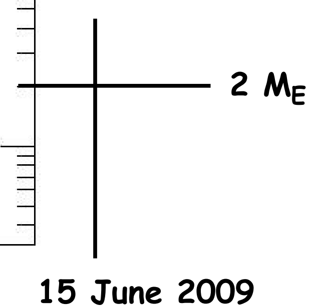


Fig.1



yellow circle: RV

red circle: transit

blue square: microlensing

purple square: pulsar timing

circle size prop. to orbital period

Physical properties - Statistics

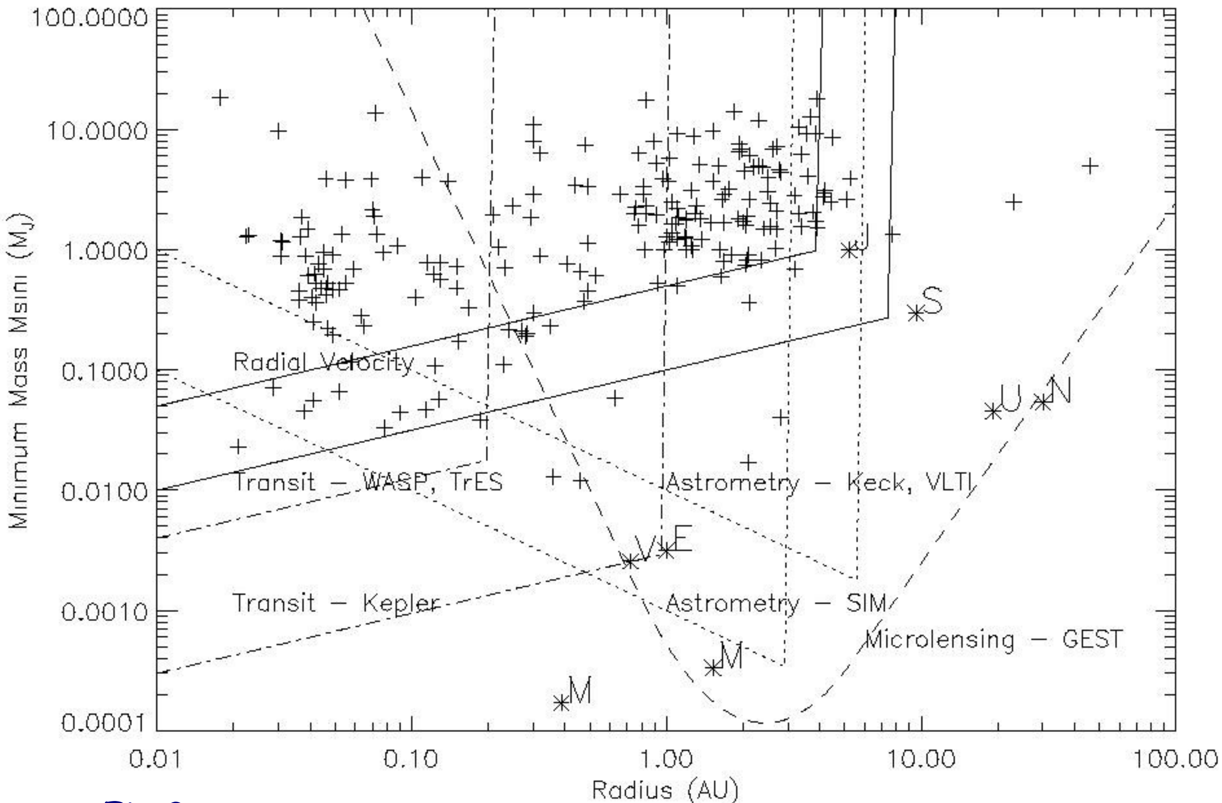


Fig.2

- **biases due to detection method and survey characteristics**

→ mainly giant planets (RV)

→ mainly solar-like hosts

- **well defined samples:**

(volume or magnitude limited)

CORALIE, HARPS, Lick/Keck/AAT

>1200 FGKM stars (main sequence)

stars with giant planets m > 0.2 M_J and a < 0.1AU: ≈ 1%

stars with giant planets m > 0.2 M_J and a < 5.0AU: ≈ 6%

Physical properties - Statistics

- **mass distribution**

  → **steep rise** towards lowest masses, but also obs. bias toward lowest masses

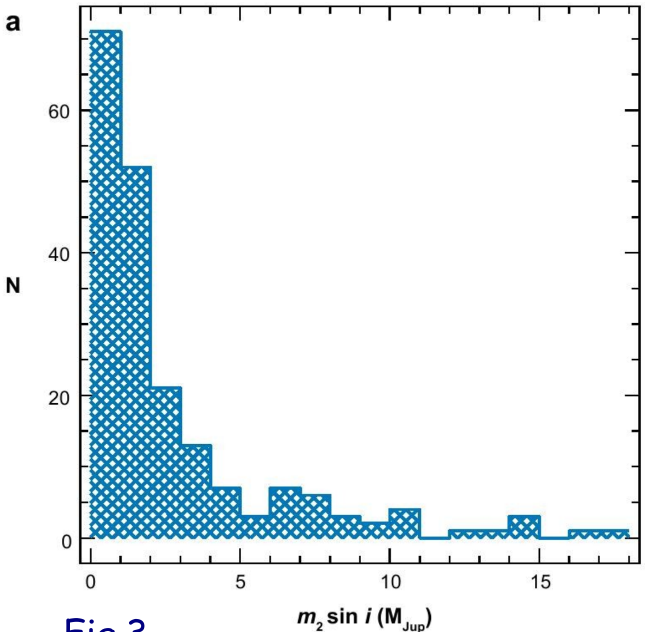


Fig.3

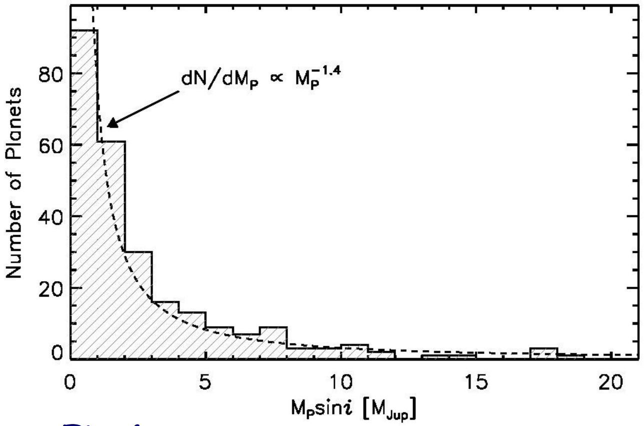


Fig.4

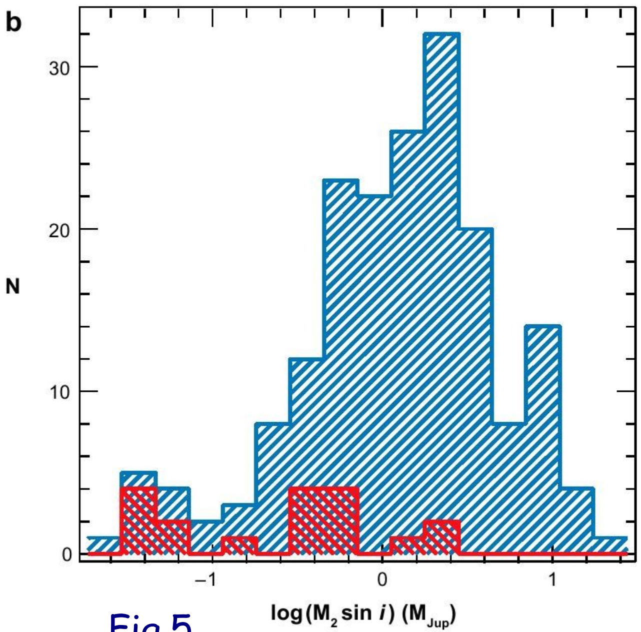


Fig.5

Physical properties - Statistics

- **period distribution and semimajor axis distribution**
  - → connected via 3rd Kepler: $M_{tot}P^2 = a^3$, eg. 1yr → 1AU, 10d → 0.09AU
  - → **period gap** (no observational bias)
  - → peak at 3d or 0.04AU (a result of migration?)
  - → peak at ≈250d or ≈0.8AU

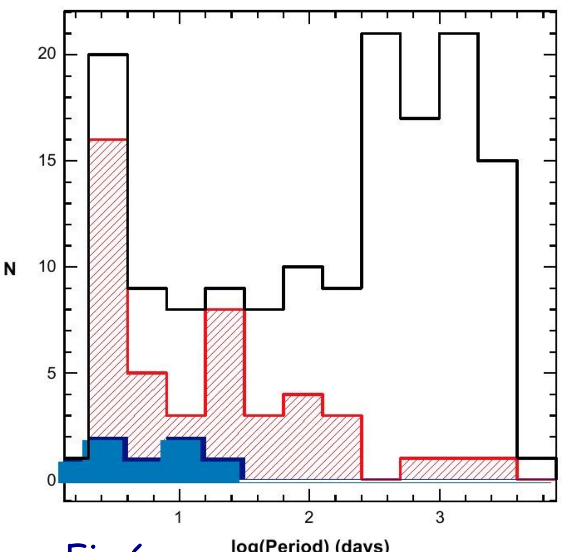


Fig.6
red: m sini < $0.75M_J$
blue: m sini < $21M_E$

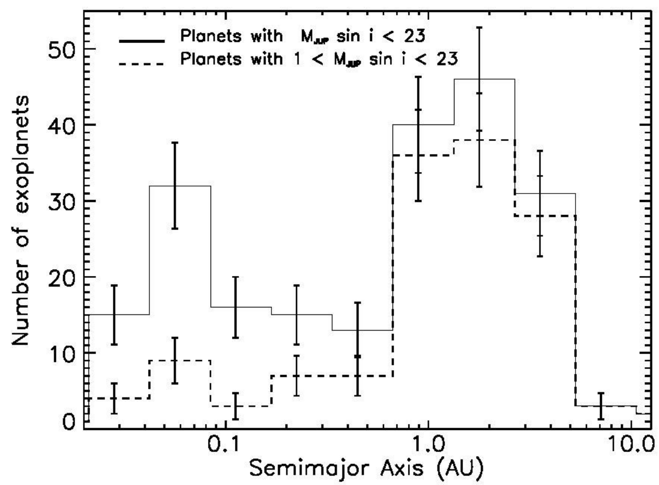


Fig.7

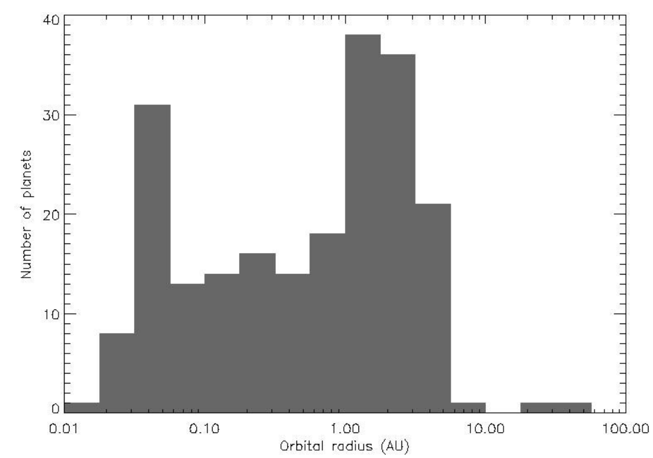


Fig.8

Physical properties - Statistics

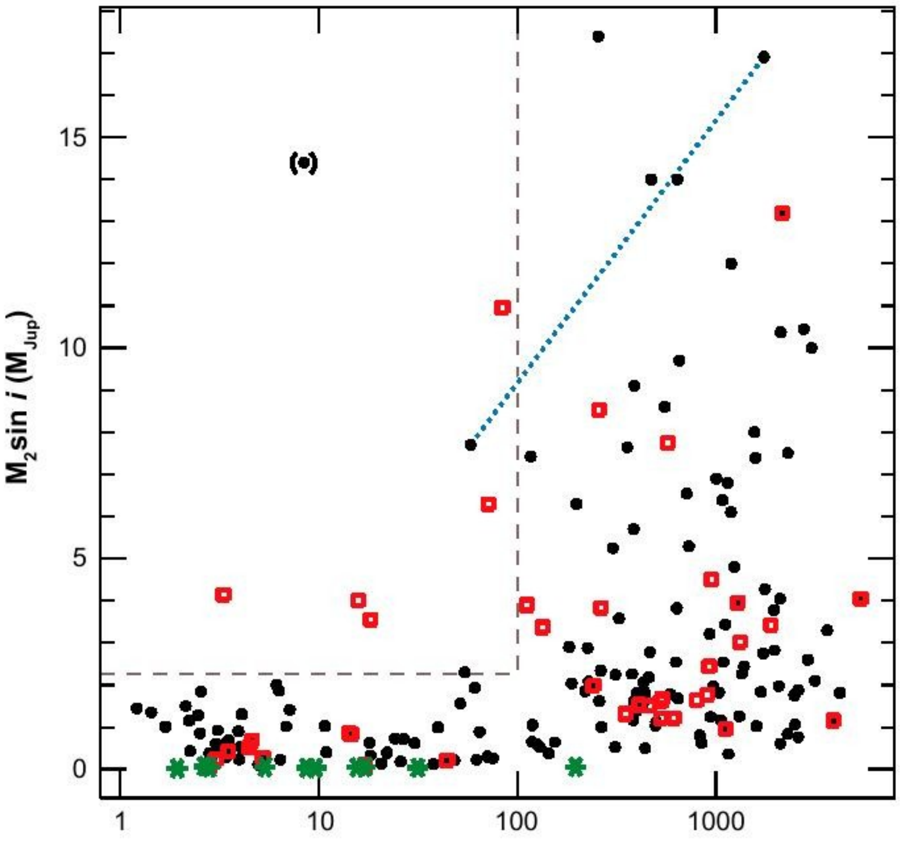


Fig.9

- mass vs. period
  - → lack of massive planets on short period orbits with $m > 2M_J$ and $p < 100d$ (0.4AU)
  - → lack due to mass transfer? evaporation? infall?
  - → no obs. bias
  - → short period peak due to low mass planets
  - → no difference between single hosts and binary hosts

Physical properties - Statistics

- eccentricity
  - → circularization for p < 6d
  - → median of 0.24 for p > 10d (0.09AU)
  - → no obvious difference in planet and stellar binary populations
  - → Solar System: very low eccentricities

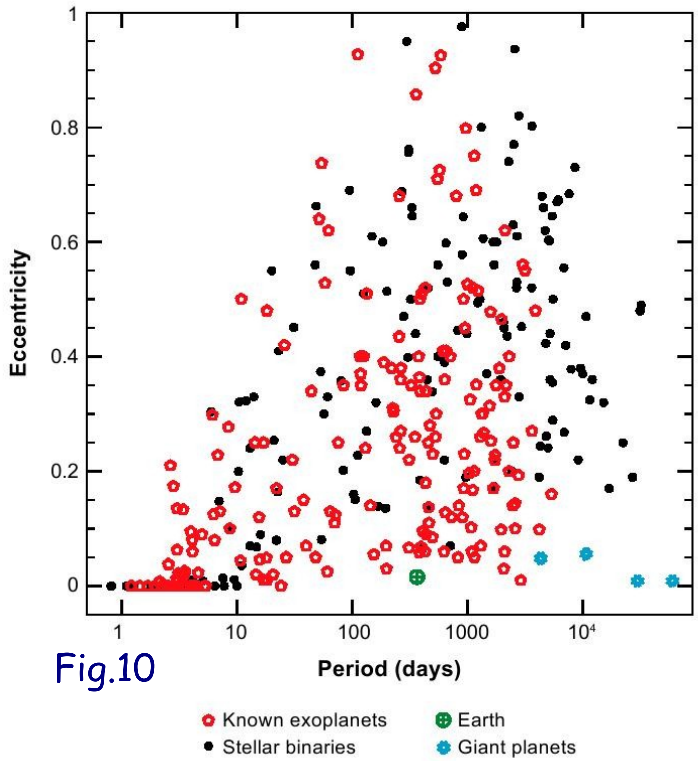


Fig.10

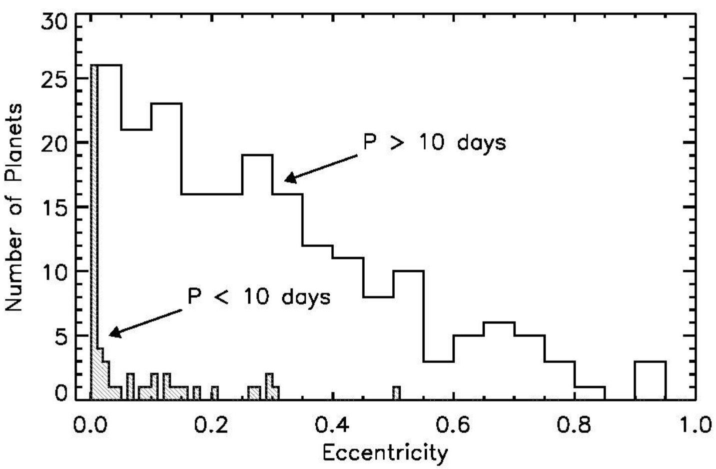


Fig.11

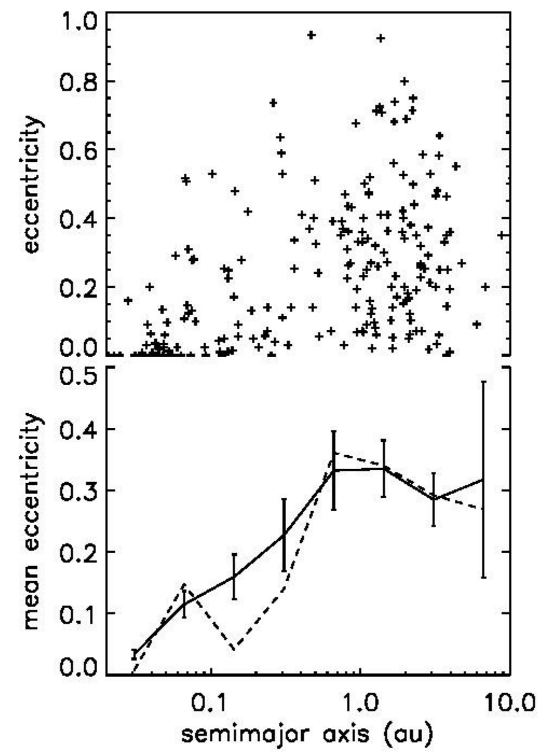


Fig.12

Physical properties - Statistics

- host star metallicity
  - → probability of finding a giant planet increases with host star metallicity
  - → no such trend for low-mass (solid) planets, but bad statistics so far
  - → metallicity excess due to external origin or conditions during formation?
  - → no trend with semimajor axis

red: Lick/Keck
blue: CORALIE

red: only < 0, flat distribution
blue: only > 0, power law
grey: for > -0.5

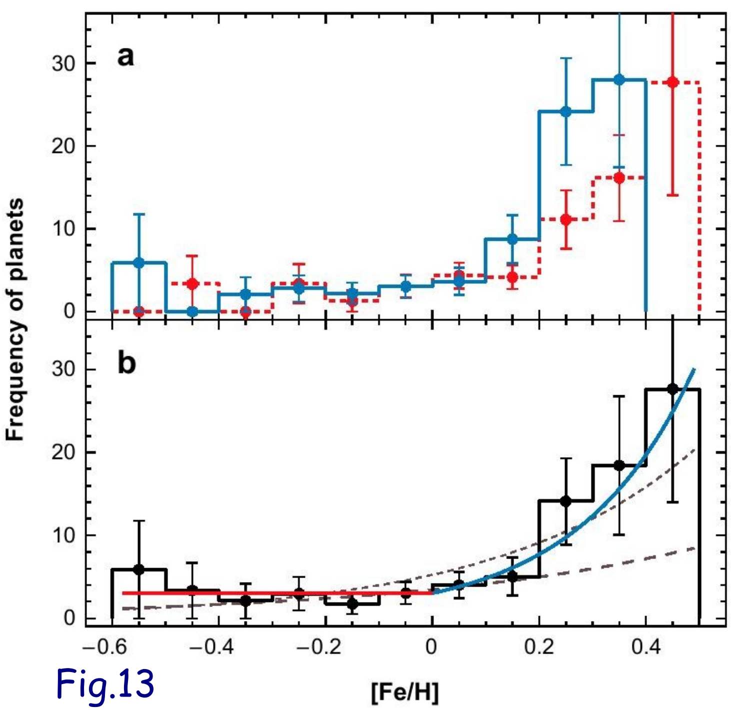


Fig.13

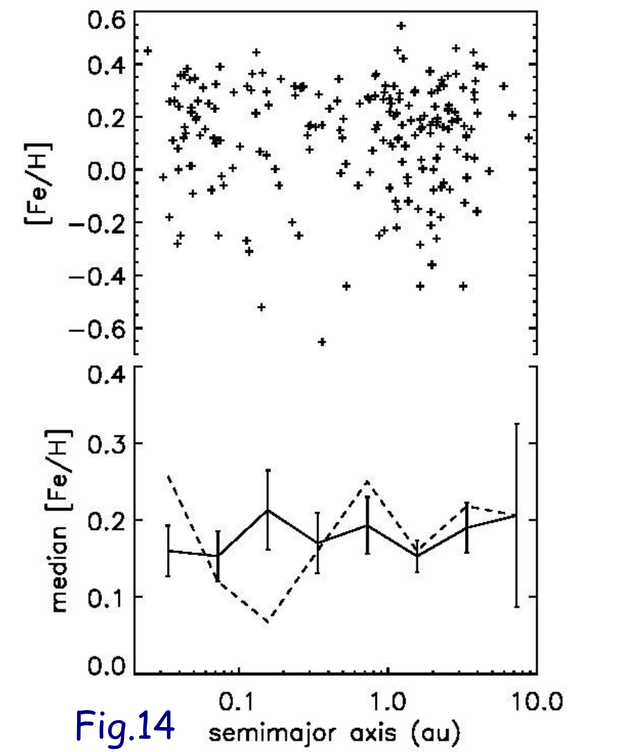


Fig.14

Physical properties - Statistics

- **host star mass**

  → probability for finding a planet is higher for higher mass host stars

  → observational bias due to sample limitations?

  → O,B,A stars too short lived?; 2nd generation planets around evolved stars?

  → low mass planets seem to be more common around M-dwarfs

  → no correlation with semimajor axis

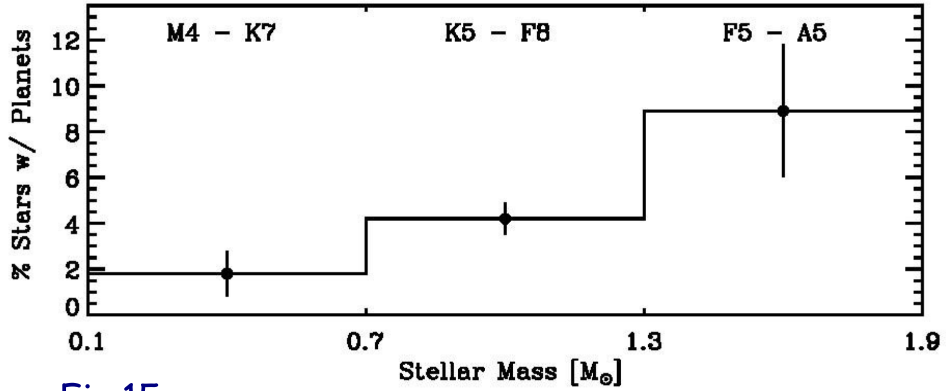


Fig.15

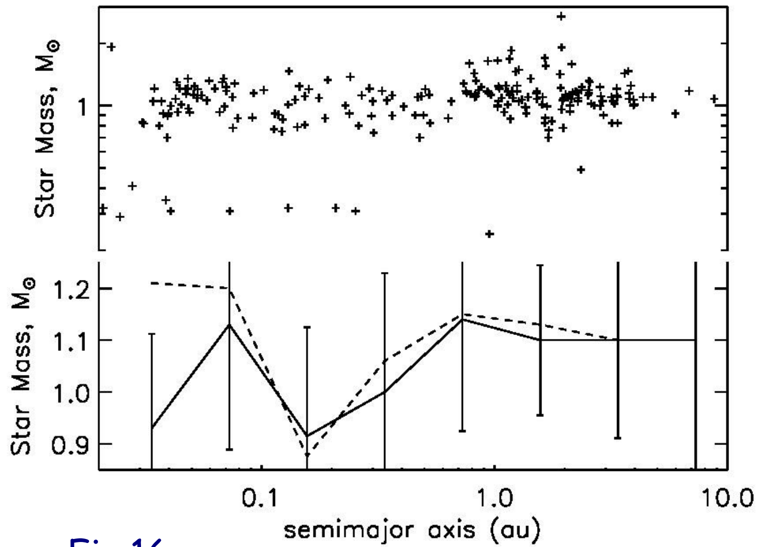


Fig.16

Physical properties - Statistics

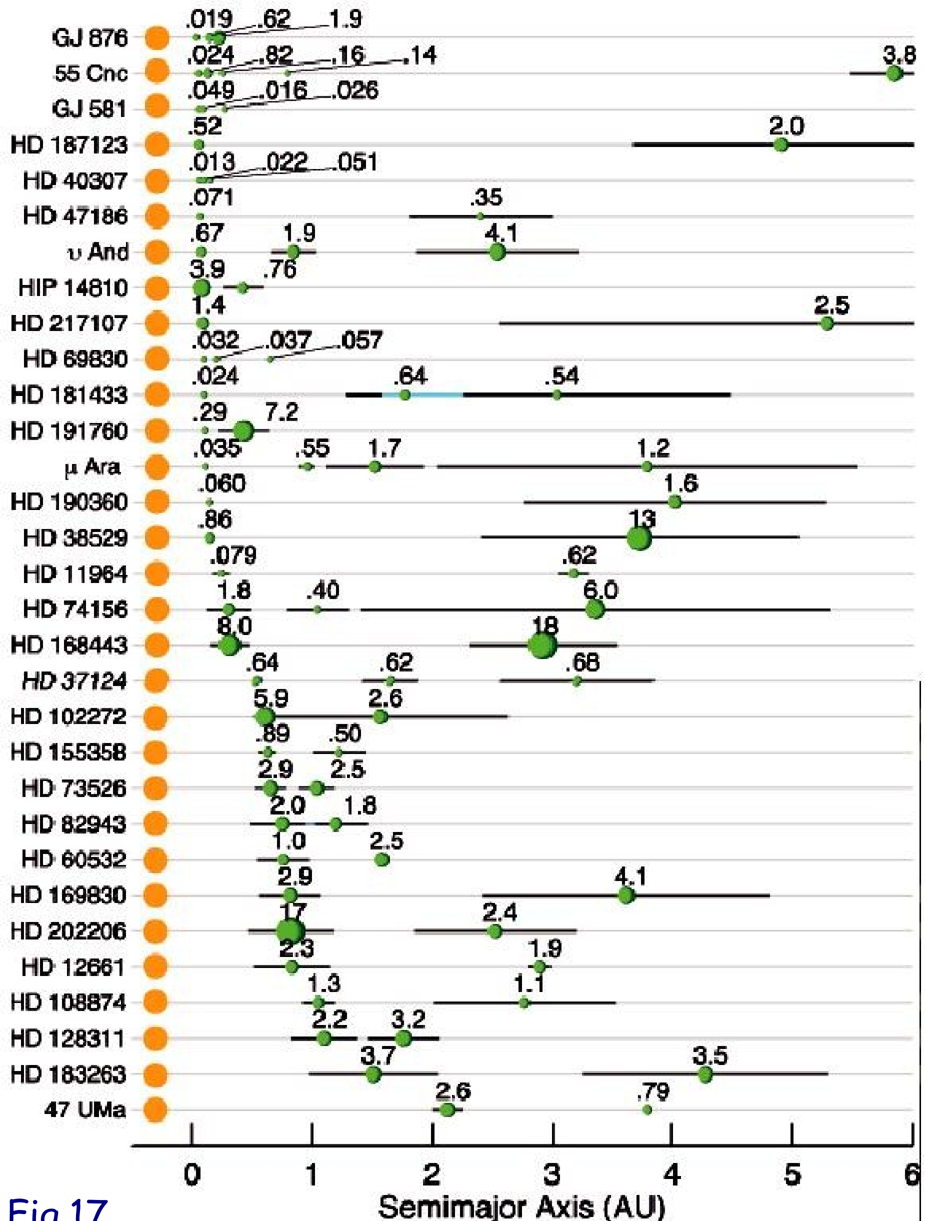


Fig.17

- **multiple-planet systems**
  - → high eccentricities for large orbits
  - → mean motion resonances
  - → orbital parameters seem to be indistinguishable from single planet systems
  - → **problems:** low amplitude RV signals from long period planets, which may easily be absorbed in a single-planet Keplerian orbit solution...

horizontal lines: periapse and apoapse in eccentric orbits
numbers: minimum masses in Jupiter masses

Summary (Part 2)

- 353 exoplanets, most are giants, bias due to detection method
- earth-mass planets will be found in the near future
- steep rise towards lower masses
- period gap
- no close-in massive planets
- circularization for close orbits
- whole range of eccentricities for large orbits
- metallicity excess

Outline

- Part 1 (Anne):
  - Introduction, Detection methods
- Part 2 (Ronny):
  - Physical properties, Statistics
- Part 3 (Anne):
  - Dynamical properties, Atmospheres
- Part 4 (Ronny):
  - Habitability of exoplanets

Outline

- Part 1 (Anne):
  - Introduction, Detection methods
- Part 2 (Ronny):
  - Physical properties, Statistics
- Part 3 (Anne):
  - Dynamical properties, Atmospheres
- Part 4 (Ronny):
  - Habitability of exoplanets

Habitability of exoplanets

- **habitability** → life, biology, chemistry
- **exoplanets** → astronomy, geology

} **Astrobiology**

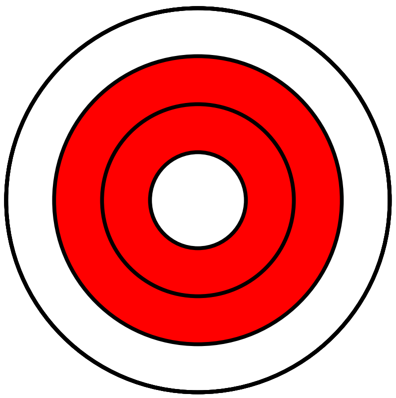
life (as we know it) is based on carbon and liquid water:

main bulding blocks: H, C, O, N, (P, S), liquid H_2O

Concept of the habitable zone (HZ)

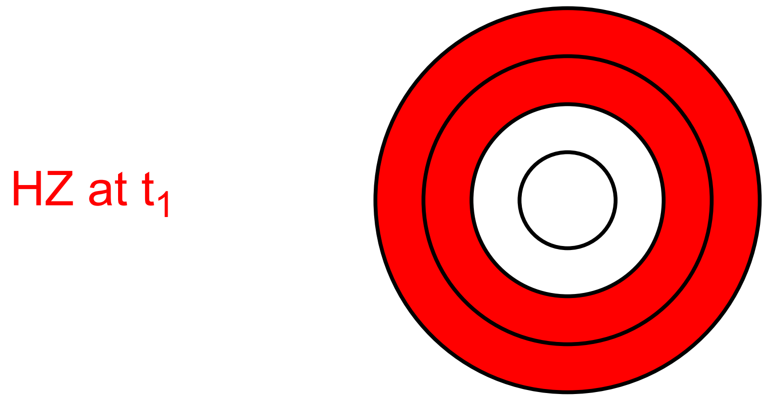
- **HZ:** distance from a star, where liquid water can exist on the surface
  - → **determined by T_S**
  - → **definition neither necessary nor sufficient**
  - → **habitability does NOT imply that an environment is inhabited**
- **CHZ:** region in which liquid water can be maintained throughout most of the star's lifetime
  - → **L of the host star increases with time → HZ moves outwards**

HZ at t_0



Concept of the habitable zone (HZ)

- **HZ:** distance from a star, where liquid water can exist on the surface
  - → **determined by T_S**
  - → **definition neither necessary nor sufficient**
  - → **habitability does NOT imply that an environment is inhabited**
- **CHZ:** region in which liquid water can be maintained throughout most of the star's lifetime
  - → **L of the host star increases with time → HZ moves outwards**



Concept of the habitable zone (HZ)

- **HZ:** distance from a star, where liquid water can exist on the surface

  → **determined by T_S**

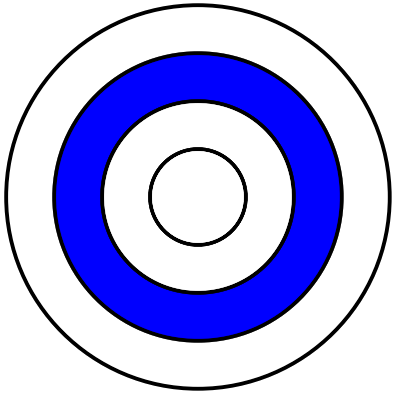
  → **definition neither necessary nor sufficient**

  → **habitability does NOT imply that an environment is inhabited**

- **CHZ:** region in which liquid water can be maintained throughout most of the star's lifetime

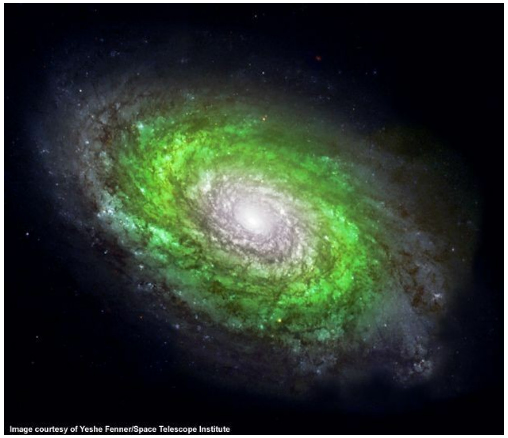
  → **L of the host star increases with time → HZ moves outwards**

CHZ



Concept of the habitable zone (HZ)

- **HZ:** distance from a star, where liquid water can exist on the surface
  - → **determined by T_S**
  - → **definition neither necessary nor sufficient**
  - → **habitability does NOT imply that an environment is inhabited**
- **CHZ:** region in which liquid water can be maintained throughout most of the star's lifetime
  - → **L of the host star increases with time → HZ moves outwards**



- **GHZ:** habitable regions in the galaxy
  - → **thin disk excluding the innermost and outermost parts**

Concept of the habitable zone (HZ)

• **boundaries for an earth-like rocky planet:**

→ inner edge: **water-loss, H-escape, runaway greenhouse**

→ outer edge: **condensation of atmospheric CO_2, formation of CO_2 clouds, increased albedo, runaway glaciation**

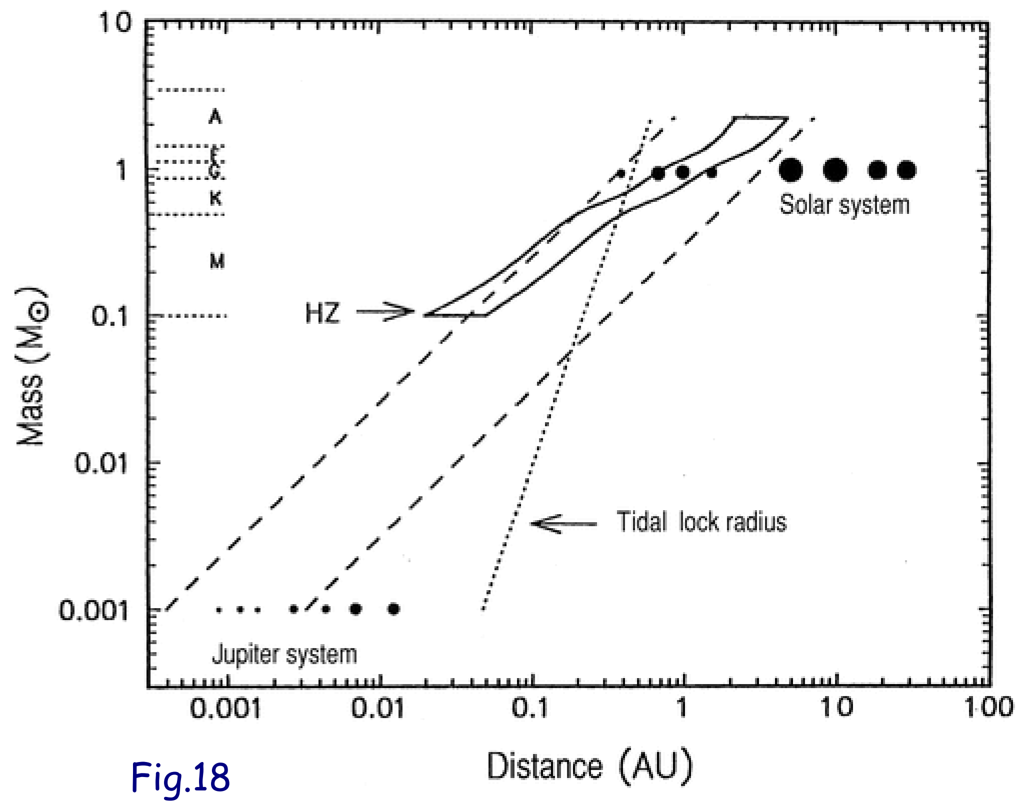


Fig.18

solar system: HZ ≈ 0.95 - 1.67 AU
CHZ ≈ 0.95 - 1.15 AU

Biosphere of a habitable planet

Earth's atmosphere: IR-spectrum →

- continuum → T_{eff}, T_S (255K, 288K)
- CO_2
- H_2O-vapour → strongest greenhouse gas
- O_3 (→ O_2)
- CH_4
- N_2
- chlorophyll

(O_3, CH_4, N_2, chlorophyll: biomarkers)

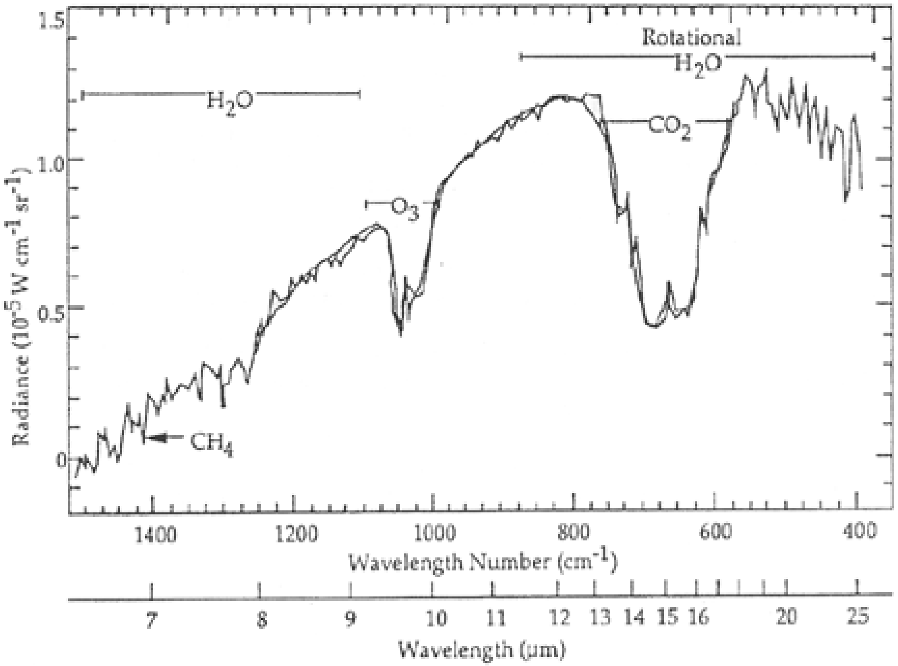


Fig.20

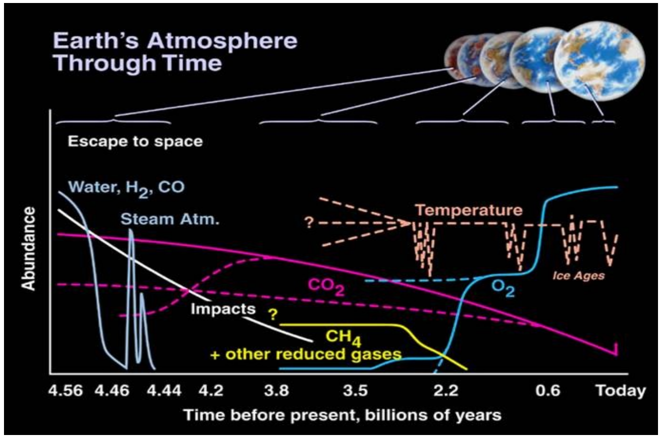
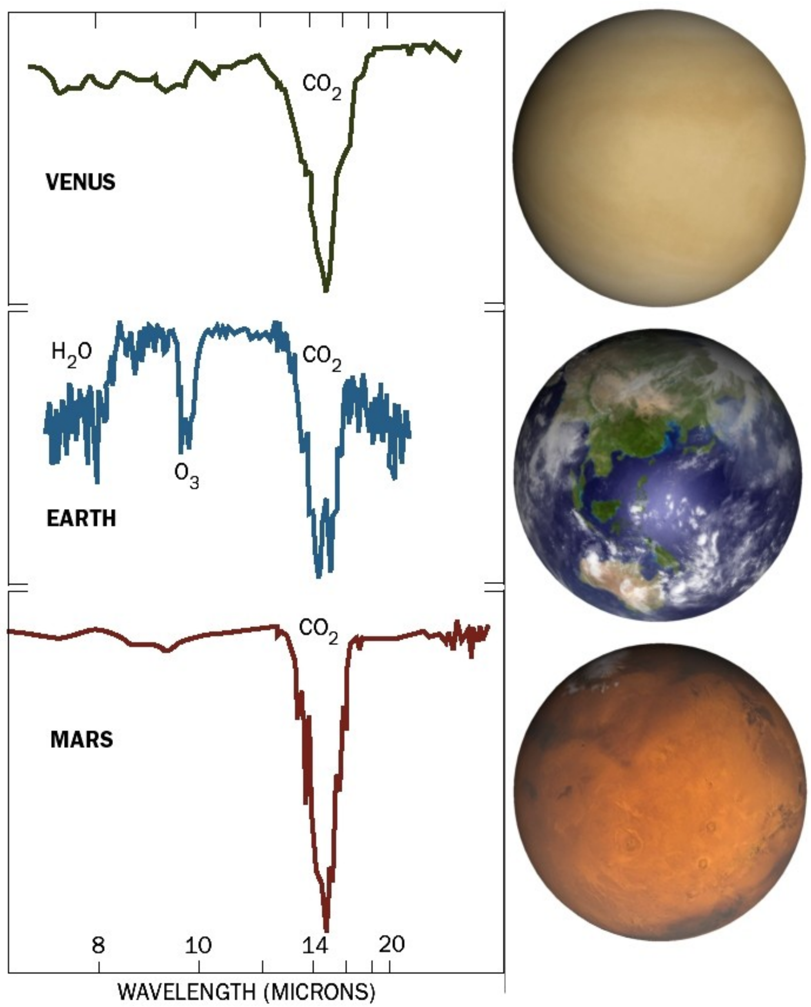


Fig.19

← reduction of CO_2, increase of O_2

biomass changes the atmosphere

Biosphere of a habitable planet



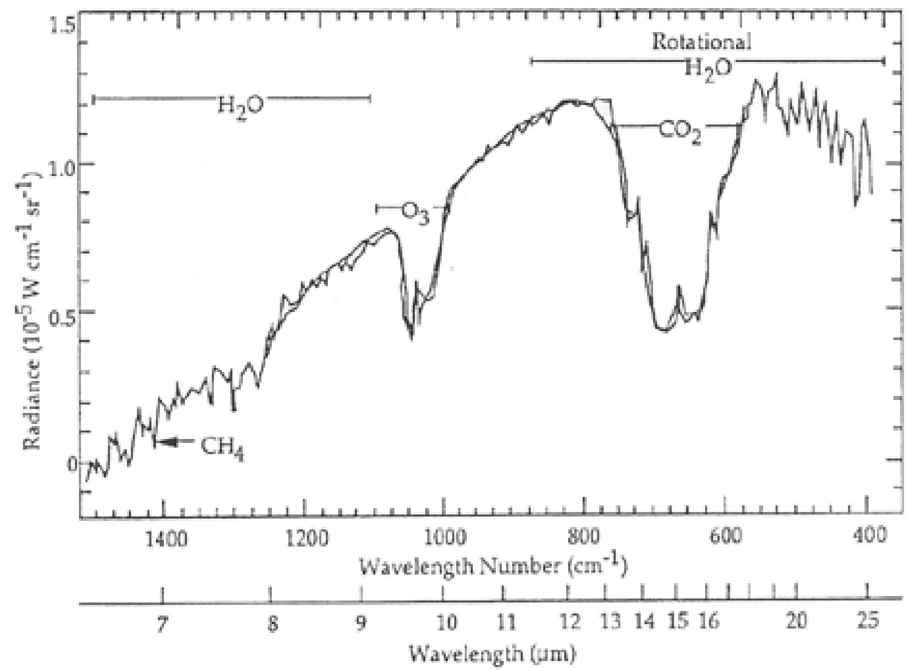


Fig.21

Climate of a habitable planet

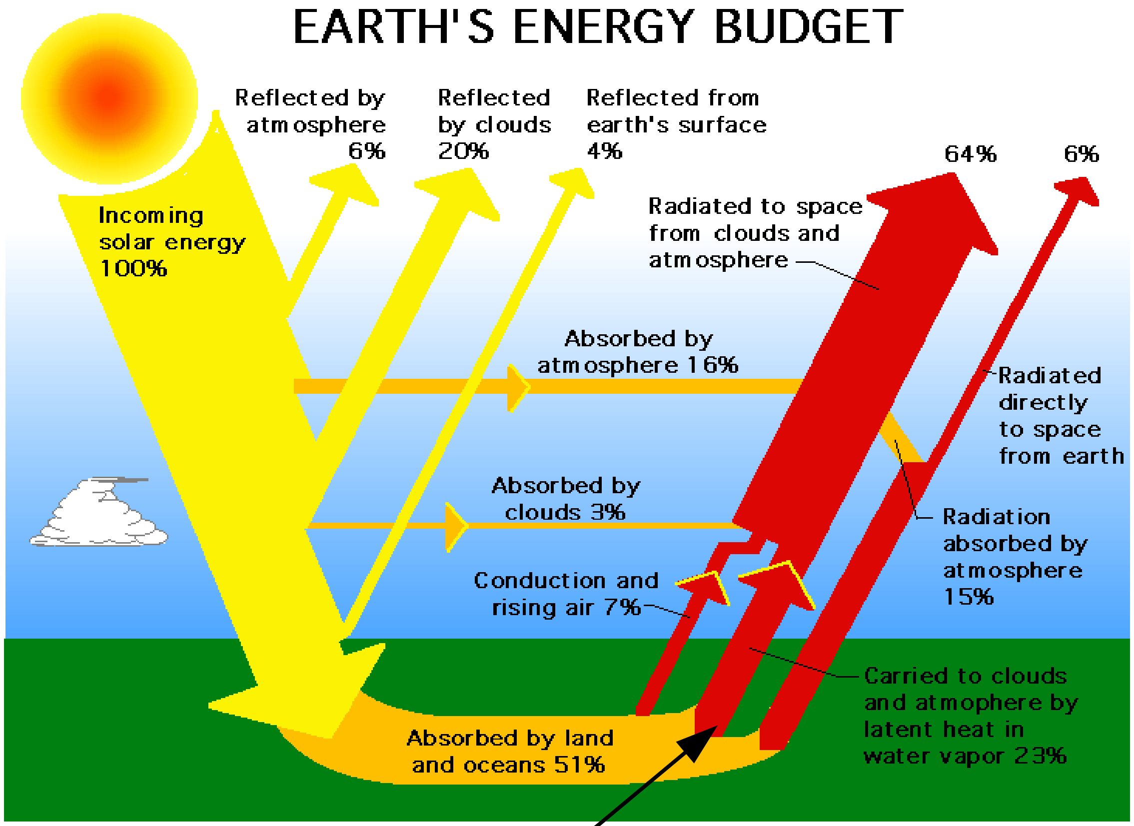


Fig.22

surface emitts in thermal IR

various factors can disturb this budget and therefore the climate → the habitability !

Climate of a habitable planet

feedback processes affect the climate:

- positive → destabilizing due to amplification of perturbations
- negative → stabilizing response to perturbations

positive feedbacks:	snow / ice cover	→ runaway glaciation
	atmospheric water vapour	→ runaway greenhouse

negative feedbacks: carbonate-silicate-cycle

($T_S \leftrightarrow F_{IR,out}$ interaction)

Factors influencing habitability

planetary properties:

- **climatic stability**
- **albedo** → cloud cover / ice+snow cover / ocean to land ratio
- **presence of an atmosphere** → protection from UV and impacts / pressure for liquid water
- **atmospheric composition** → volatiles / albedo
- **geological activity** → plate tectonics / volcanism / internal heat
- **magnetic field** → protection from charged particles
- **rotation** → dynamo / MF
- **obliquity** → moderate seasons
- **mass** → $>0.3M_E$ → maintain an atmosphere / activity

  $<10M_E$ → prevent massive H-He atmosphere
- **interaction with other planets** → orbital stability
- **eccentricity of the orbit** → climatic stability

Factors influencing habitability

external properties:

- **host star** → type

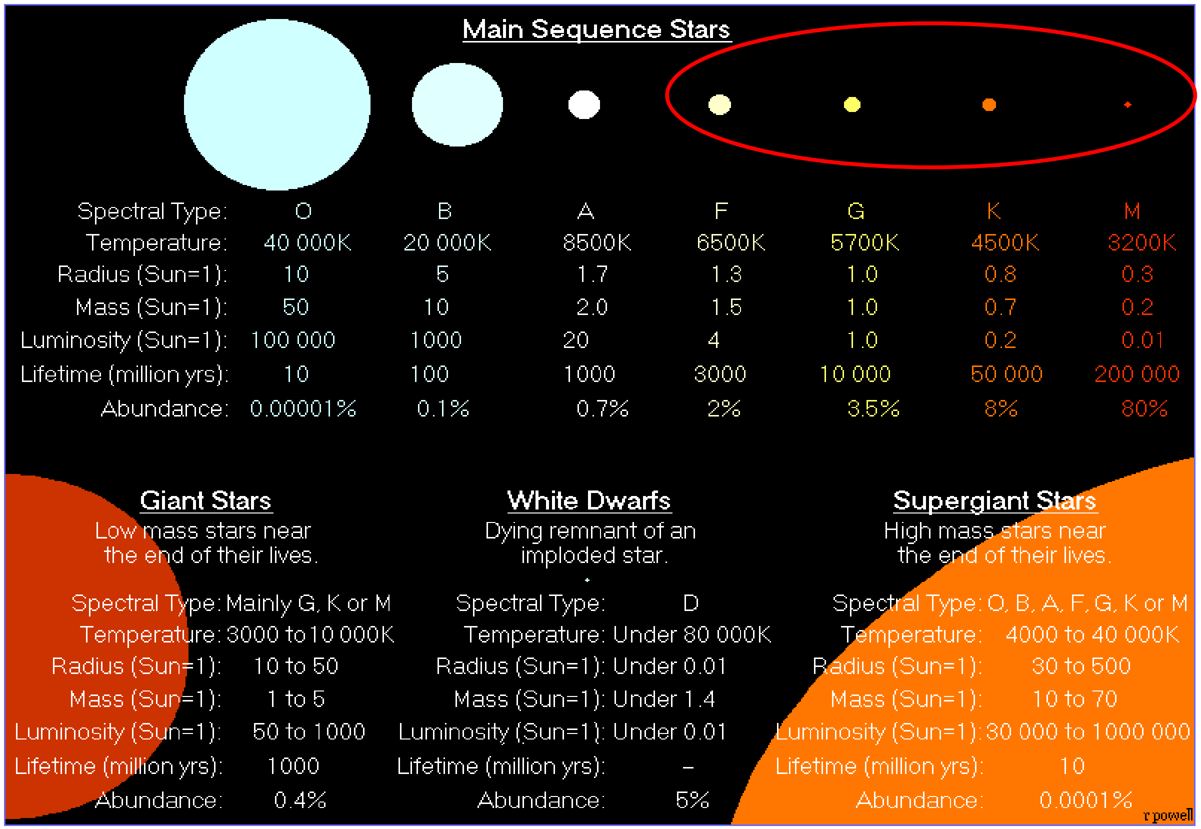


Fig.23

Factors influencing habitability

external properties:

- **host star** → type
- **presence of giant planets** → destabilizing: migration through HZ (inner giants)

  stabilizing: impact shielding / orbital stability due to outer giants ?
- **presence of a satellite** → Moon stabilizes Earth's obliquity (23.4°)
- **stability around binary / multiple hosts ?**
- **impacts of comets / meteorites** → positive: delivery of volatiles / water ice / (and life?)

  negative: destroying biospheres
- **tidal locking / synchronous rotation** → extreme hemispheres

Habitable exoplanets ?

examples:

- **Gliese 876d:** 7.5M_E around 0.32M_S M-dwarf (0.02 AU) → **too hot**
- **OGLE-05-390L b:** 5.5M_E at 2.1AU → **too cold**

Habitable exoplanets ?

examples:

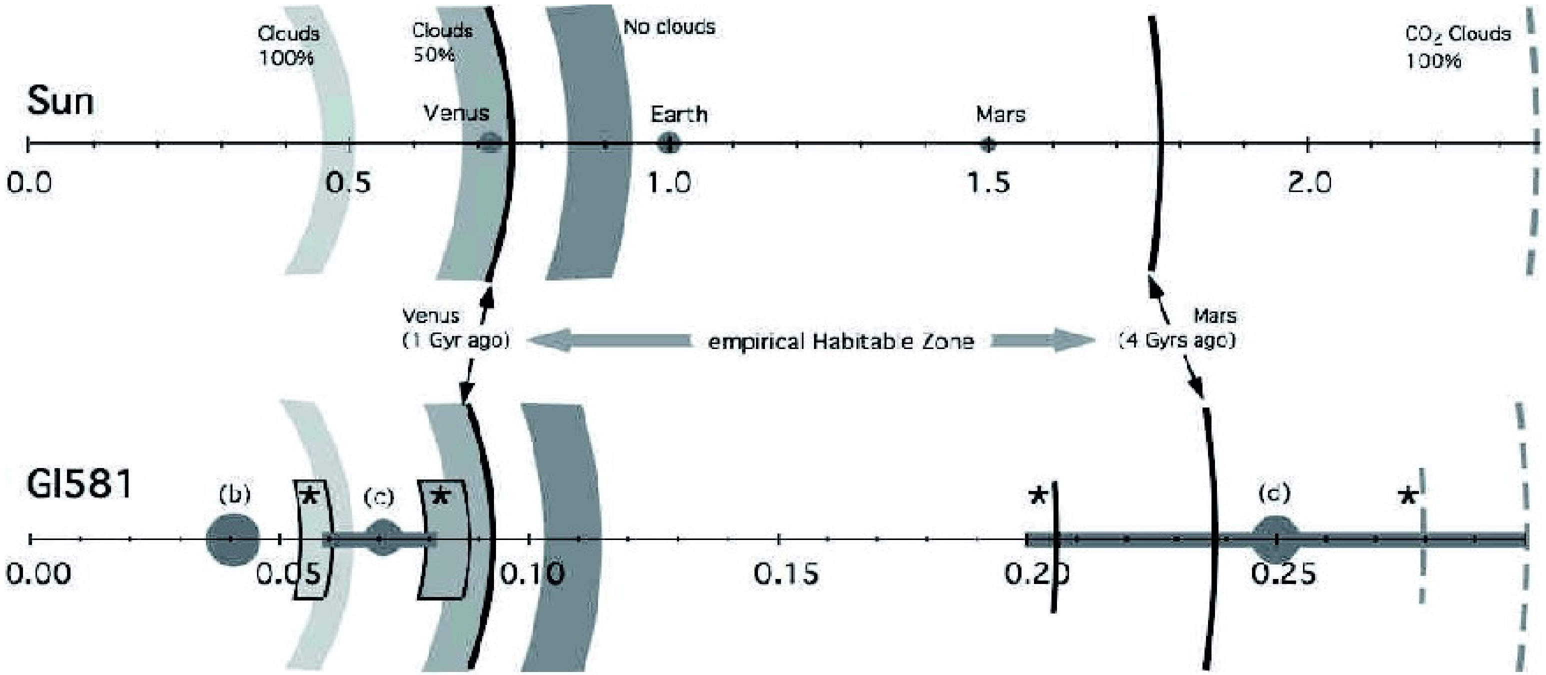


Fig.24

- **Gliese 581:** 0.31M_S M-dwarf, 3200K, 0.014L_S

  b: 15.6M_E at 0.04 AU → **outside HZ**

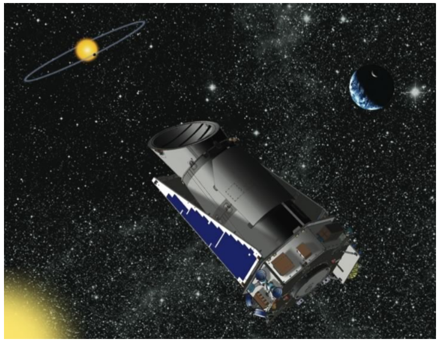
  c: 5M_E at 0.07 AU → **only habitable for high albedo → high cloud cover needed**

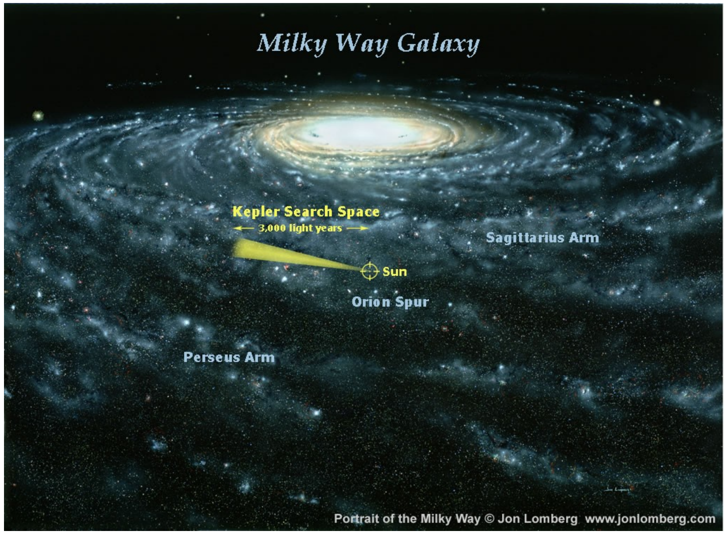
  d: 8.3M_E at 0.25 AU → **best candidate if M stays below 10M_E (i unknown)**

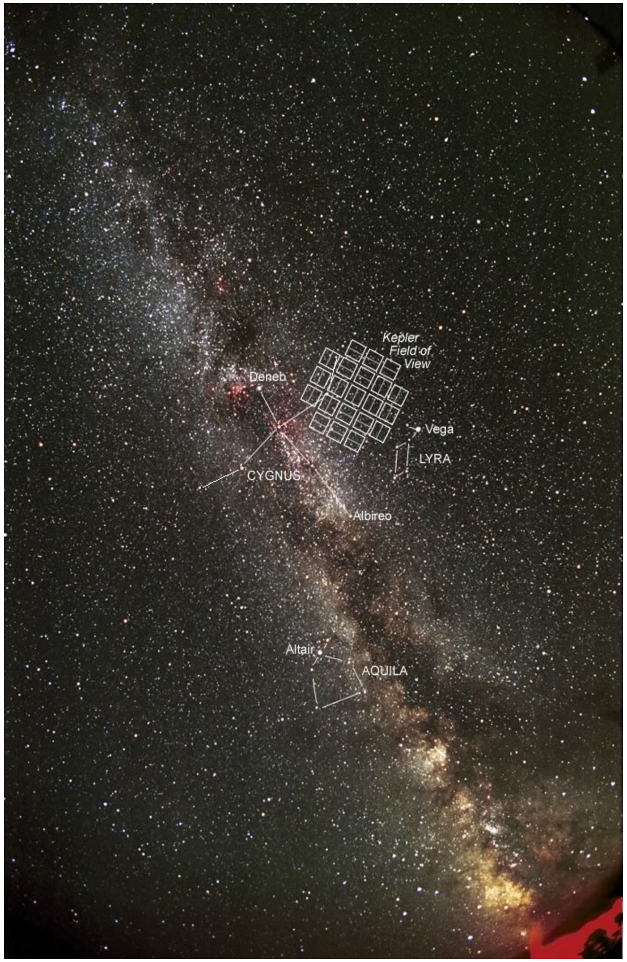
  e: 1.97M_E at 0.03AU → **outside HZ,** lowest mass known so far (17.06.2009)

Space missions – Kepler (NASA)

- 100000 stars simultaneously, 1.4m primary mirror, launched in Mar. 2009





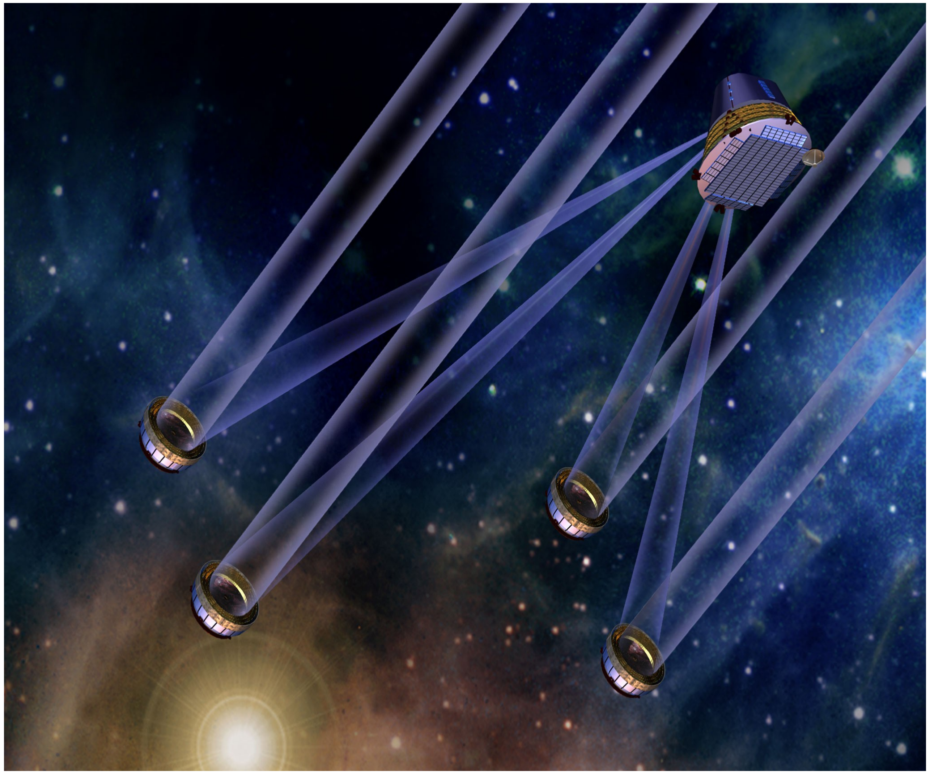


Figs.: kepler.nasa.gov

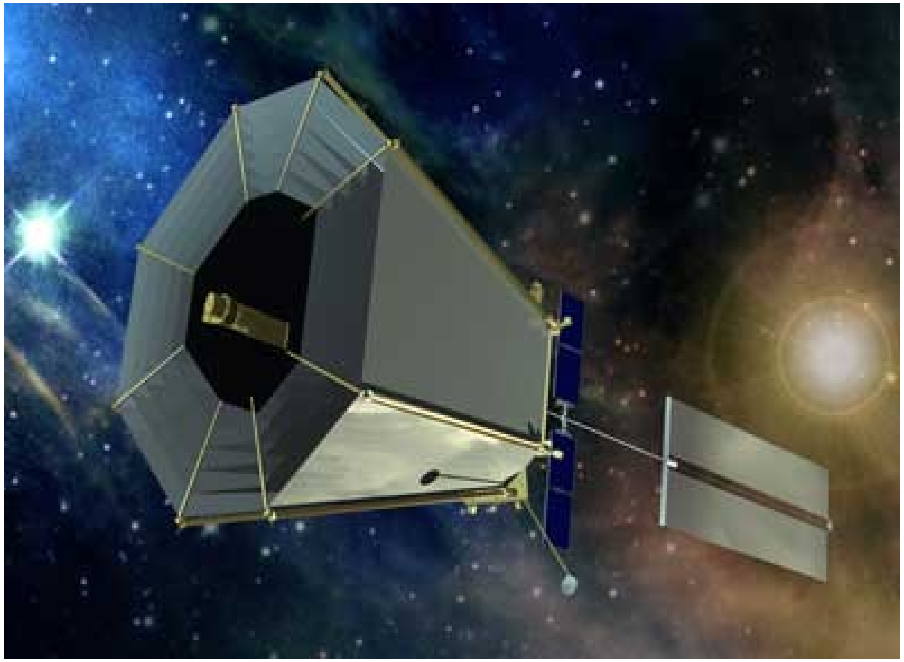
Space missions – TPF (NASA)

- indefinitely postponed, IR-Interferometer array or optical telescope

TPF-I



TPF-C



Figs.: nasa.gov

Space missions – Darwin (ESA)

- **6 IR telescopes (>3m) as Interferometer, launch 2015 or later**

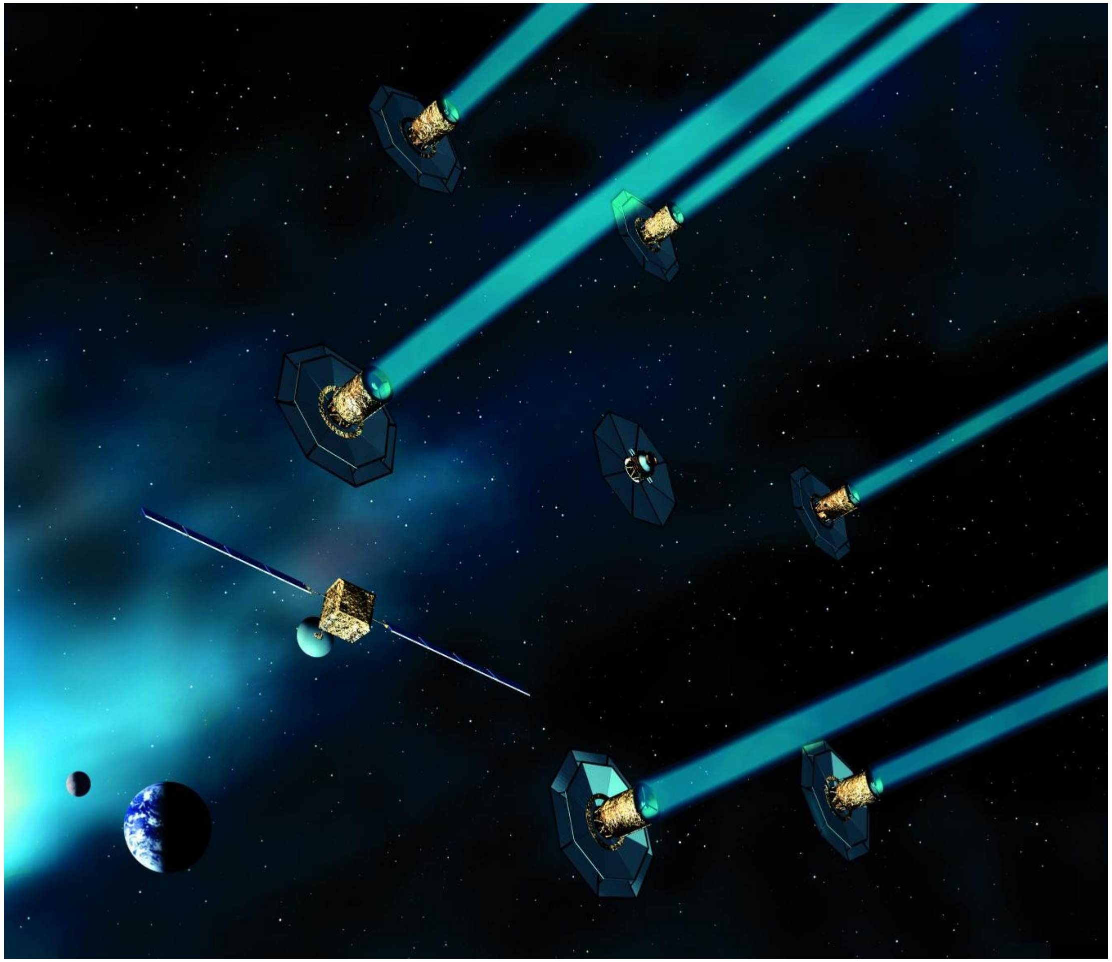


Fig.: esa.int

Summary (Part 4)

- definition of a "habitable zone"
- atmospheric features as biomarkers
- various factors (planetary and external properties) can influence habitability
- Gliese 581 system as most promising candidate

References

- Johnson, J.A. 2009, arXiv:0903.3059v1
- Mason, J. 2008, Exoplanets – Detection, Formation, Properties, Habitability, Springer
- Udry, S., Santos, N. 2007, ARAA, 45, 397
- www.exoplanet.eu

- Astrobiology Primer 2006, Volume 6, Number 5
- Gilmour, Sephton, An Introduction to Astrobiology, Open University
- Kasting et al. 1993, Icarus, 101, 108
- Kasting et al. 2003, ARAA, 41, 429
- Selsis et al. 2007, A&A, 476, 1373

Figures:

Fig.1: Udry&Santos (2007)
Fig.2: Mason (2008)
Fig.3: Udry&Santos (2007)
Fig.4: Johnson (2009)
Fig.5: Udry&Santos (2007)
Fig.6: Udry&Santos (2007)
Fig.7: Mason (2008)
Fig.8: Mason (2008)
Fig.9: Udry&Santos (2007)
Fig.10: Udry&Santos (2007)
Fig.11: Johnson (2009)
Fig.12: Mason (2008)
Fig.13: Udry&Santos (2007)
Fig.14: Mason (2008)
Fig.15: Johnson (2009)
Fig.16: Mason (2008)
Fig.17: Johnson (2009)
Fig.18: Kasting et al. (1993)
Fig.19: shayol.bartol.udel.edu/~rhdt/diploma/lecture_9
Fig.20: astrobiology.arc.nasa.gov
Fig.21: markelowitz.com/exobiology.htm
Fig.22: Image courtesy: NASA's ERBE program
Fig.23: www.atlasoftheuniverse.com
Fig.24: Selsis et al. (2007)

Additional material

Biosphere and climate of a habitable planet

the greenhouse effect:

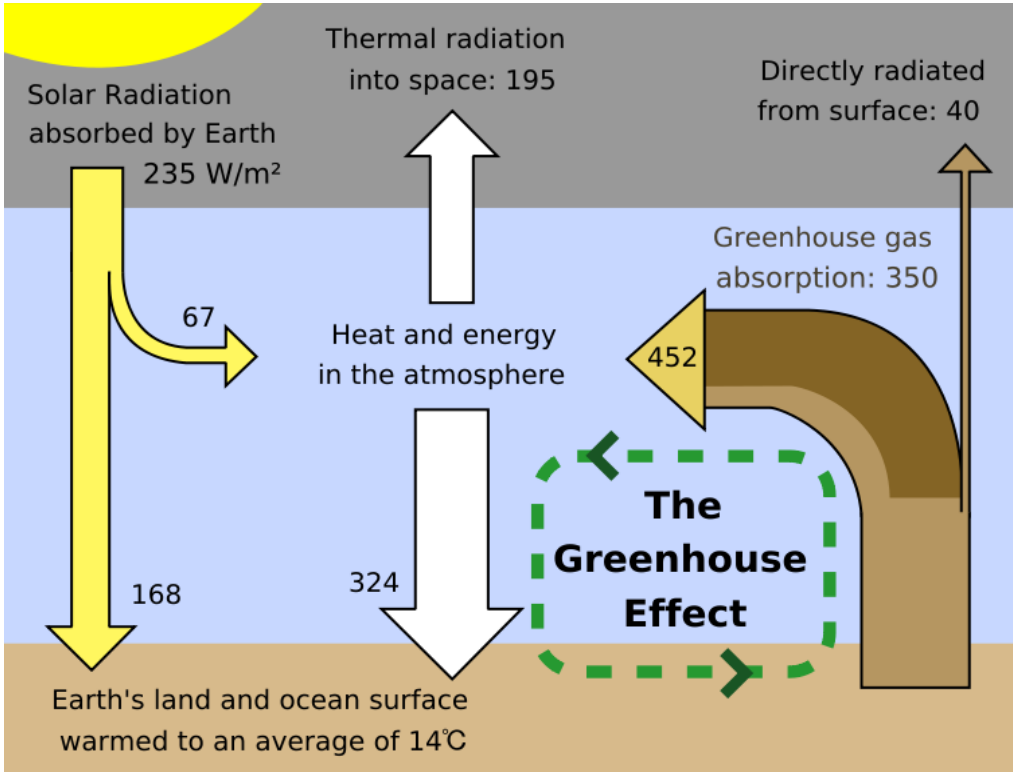
- raise of T_S because of greenhouse gases (H_2O-vapour, CO_2,...)

↓

- transparent in UV, V but absorbing in IR

↓

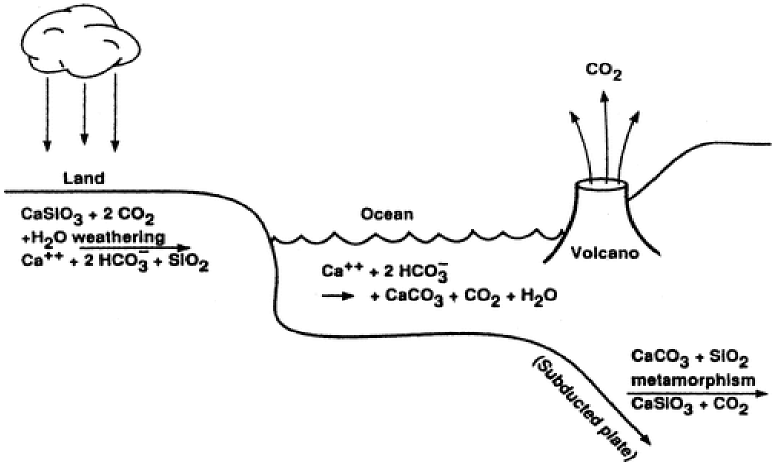
- emitted thermal IR radiation is re-emitted to the surface

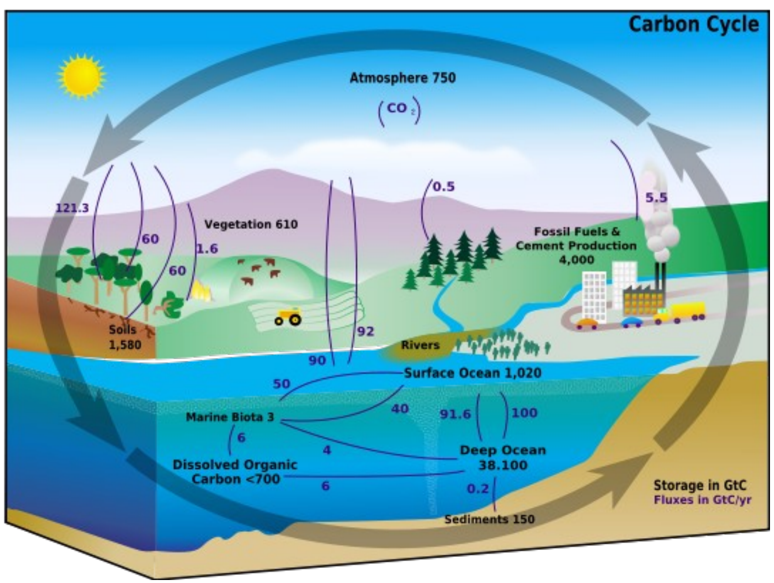


without the greenhouse effect, our Earth would be frozen !

→ in a positive feedback, this effect may become runaway !

Biosphere and climate of a habitable planet





the carbonate-silicate-cycle:

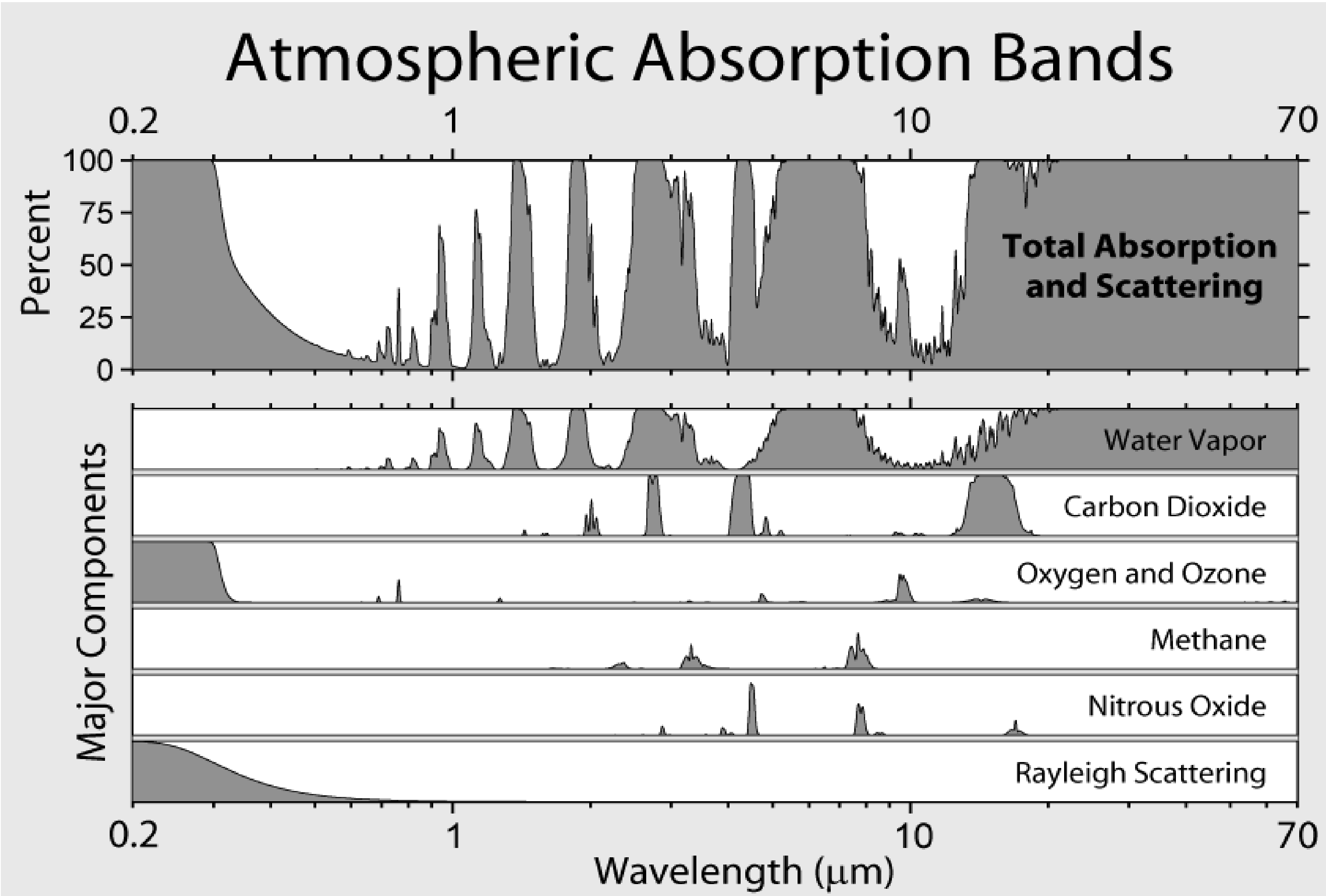
- regulates the amount of atmospheric CO_2
- removed by silicate weathering
  - → bound to carbonate rocks
  - → subducted to high T, P (plate tectonics)
  - → unbound again
- added by volcanic activity

negative feedback due to the dependence of the weathering rate on T_S (liquid water):

T_S rises → CO_2 concentration falls
T_S falls → CO_2 concentration rises

→ stabilization of the climate

(in humans would not interact...)


Atmospheric Absorption Bands
0.2
1
10
70
100
75
50
25
0
Percent
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (µm)