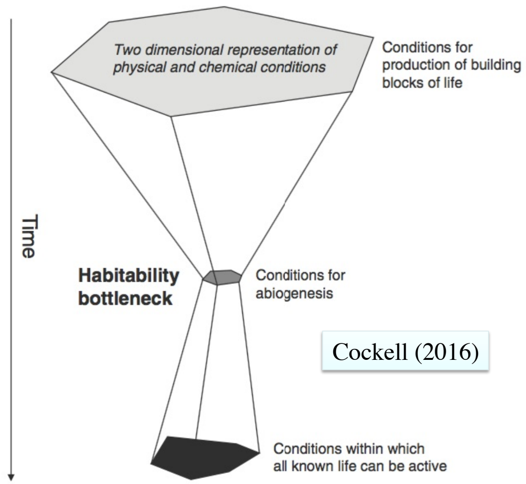
Life in the Universe (1)

Planets and Astrobiology (2018-2019)
G. Vladilo

Conditions for the existence of life in habitable environments

The conditions for prebiotic chemistry (top of the figure), for the emergence of life (middle) and for habitability (bottom) are generally different

The conditions for the emergence of life represent a sort of "bottleneck" for the effective presence of life in an astronomical body



Cockell (2016)

Conditions for abiogenesis and habitability

The emergence of life from the abiotic world (abiogenesis) requires specific physico-chemical conditions

In general, the conditions for abiogenesis will be different from the conditions of habitability

- A habitable planet will host life only if the conditions for abiogenesis were present at some stage of its history
- *Understanding the conditions of abiogenesis is essential to find plausible candidates in the quest for life in the universe*

The study of the conditions for abiogenesis is still in its early stages

- We need to explore plausible sequences of prebiotic steps leading to the emergence of life
- The physico-chemical requirements may change at different stages of the chemical pathways that lead to the emergence of life

Continuous habitability

Based on the example of the Earth,
life evolution takes some billon years to produce advanced forms of life

To understand if life can evolve in a distant planet,
we need to define the concept of "continuous habitability",
i.e. the persistence of habitable conditions for long periods of time,
comparable to the time scale of evolution of terrestrial life (~10^9 yr)

Continuous habitability is influenced by:

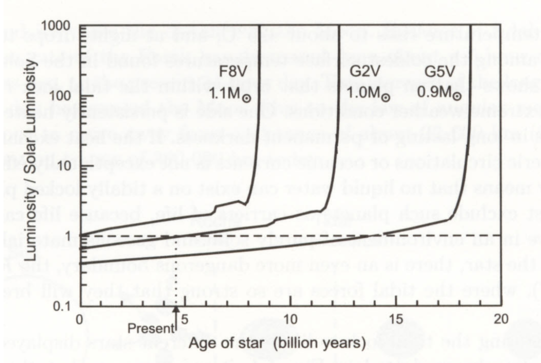
1) evolution of the stellar luminosity
2) evolution of the orbital parameters
3) mechanisms of climate stabilization
4) feedbacks between life and the environment

Evolution of the stellar luminosity

The evolution of the stellar luminosity shifts the location of the circumstellar habitable zone in planetary systems

–The shift is gradual during the main sequence stage of hydrogen burning, but is sudden at later stages of stellar evolution

–The type of evolution depends on the spectral type of the host star

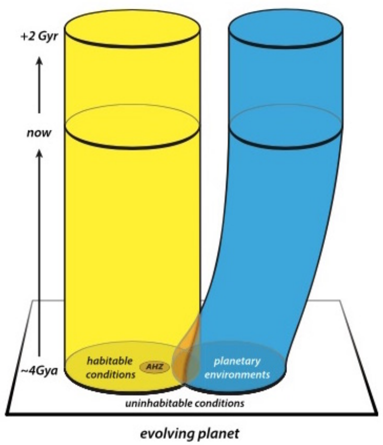


Evolution of planetary conditions without life

A planet that has the conditions for habitability, but not those for the emergence of life, will evolve under the effects of abiotic climate feedbacks

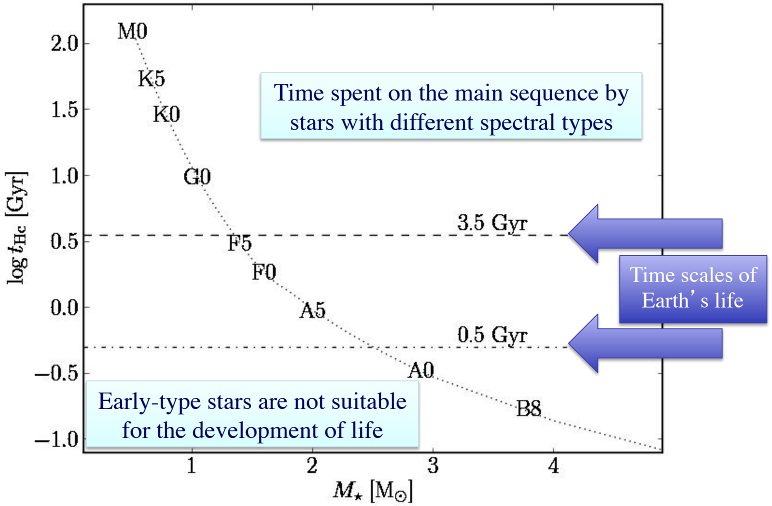
Examples of abiotic evolution: stellar luminosity, orbital parameters, and abiotic climate feedbacks (e.g.: ice-albedo, temperature-water vapour, inorganic CO_2 cycle, etc…)

If positive abiotic feedbacks are dominant, the planet will loose the requierements of habitability in the course of its evolution



Chopra and Lineweaver (2016)

Continuous habitability and spectral type of the host star



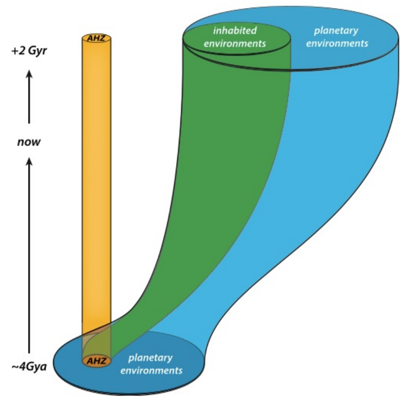
Impact of life on habitable environments

Inhabited environments (green) are a subset of planetary environments (blue); both can change with time

The abiogenic habitable zone (AHZ) conditions are narrower than the conditions to which life can later adapt

Through its management of the greenhouse and its partitioning of reductants and oxidants, the activity of life increases the range of inhabited environments (Nisbet et al., 2007)

The activity of life may provide a "Gaian regulation" of the planetary conditions



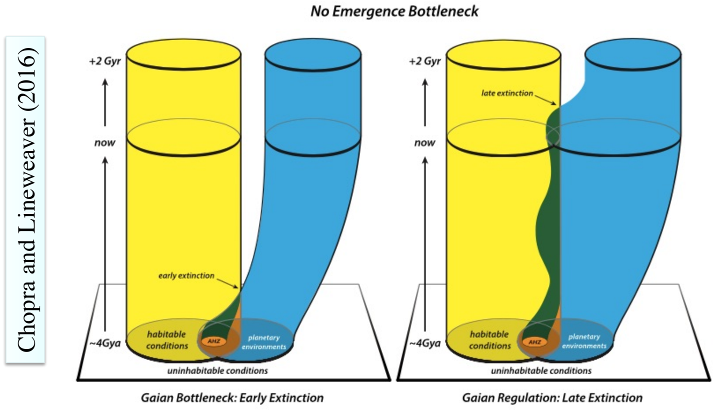
Chopra and Lineweaver (2016)

Gaian regulation of habitability conditions

might help to explain the long-term persistence of habitability conditions on Earth

Two possible scenarios of biotic habitability evolution
(Chopra & Lineweaver 2016)

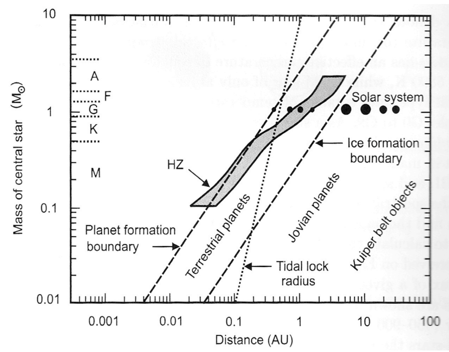
Left: life is unable to evolve rapidly enough to control runaway positive feedbacks.
Right: in rare cases, Gaian regulation evolves fast enough to keep at least part of the planet habitable for billions of years; this could be the case of the Earth



Search for habitable exoplanets

Influence of the spectral type of the central star

The spectral type of the host star affects the habitability in at least two ways:
1) location of the habitable zone
2) permanence time in the main-sequence



Exoplanets and astrobiology

- In exoplanets we cannot perform the close-by observations or sample analysis that can be done in the Solar System
  - Astrobiological studies of exoplanets are focused on habitability and search for biosignatures
- Habitability

  The habitability of exoplanets can be assessed with climate models

  Exoplanetary climate models are constrained by the stellar, orbital and planetary data obtained from remote observations

  The focus is on the surface habitability

  Sub-surface life, if any, would hardly generate biosignatures detectable with remote observations
- Search for biosignatures

  Biosignatures can be searched in the spectra of exoplanetary atmospheres

A simple relationship between stellar parameters and distance of the habitable zone
(does not take into account variations of albedo and greenhouse effect)

$$\boxed{\sigma T_p^{\,4} = \tfrac{1}{4}\, S_* \,(1-A)}$$

$$S_* \equiv L_*/(4\pi d^2) \qquad\qquad S_* = \frac{R_*^2}{d^2}\,\sigma T_*^4$$

$$(1-A)\,\frac{R_*^2}{4\,d^2}\,T_*^4 = T_\mathrm{p}^4$$

Assuming
$A \sim$ const
$d = a$

$$T_\mathrm{p} \propto \left(\frac{R_*}{a}\right)^{\frac{1}{2}} T_*$$

Assuming T_p constant, optimal for life, the distance a of the habitable zone increases linearly with the stellar radius and quadratically with the effective temperature

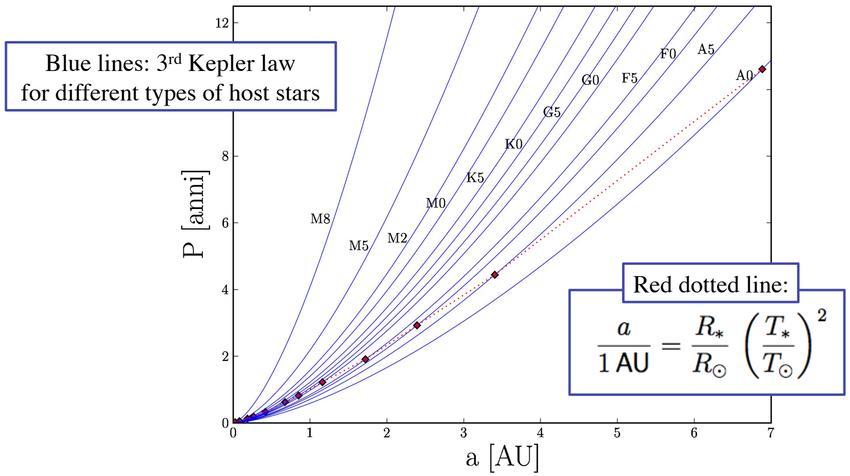
$$\frac{a}{1\,\mathrm{AU}} = \frac{R_*}{R_\odot}\left(\frac{T_*}{T_\odot}\right)^2$$

Detection of habitable planets: observational issues

The habitable zone becomes more distant in <u>early type stars</u>

Because of the 3rd Kepler law, the orbital periods will become larger

The temporal baseline for detecting habitable planets will become longer



<u>Habitable</u> planets with the <u>*Doppler method*</u>

- Advantages of M-type stars with the Doppler method

  The semi-amplitude of the radial velocity curves scales as

  $$K \sim (a\, M_*)^{-1/2}$$

  where a is the semi-major axis, M_* the stellar mass

  <u>The advantage of a smaller stellar mass combines with the advantage of the smaller distance of the habitable zone</u>

  For a given planetary mass, the Doppler signal of a planet in the HZ of an M-type star is ~ 3-30 times stronger than the signal of planet in the HZ of a solar-type star

Detection of habitable planets: observational issues

- The temporal baseline of observations required for detecting habitable exoplanets does not represent a serious problem

  Planets in the HZ of <u>late-type stars</u> can be detected in short time scales

  Planets in the HZ of <u>early-type stars</u> require several years of observations, but are less interesting for astrobiology because the fast evolution of the stellar luminosity limits the continuous habitability

  Planets in the HZ of <u>early-type stars</u> could be detected with the "direct imaging" on observational time scales much shorter than the orbital period

- There are several types of observational bias that affect the detection of habitable planets

  The bias depend on the observational technique used to detect the planet

<u>Habitable</u> planets with the <u>*transit method*</u>

- Geometrical probability of detecting a planet with the transit method

  $$\mathcal{P}_{\mathrm{tr}} \simeq 4.65 \times 10^{-3}\, \frac{R_*\,[R_\odot]}{a\,[\mathrm{AU}]}$$

  The geometrical probability increases with decreasing semi-major axis

  Since habitable planets around late-type stars are located at small semi-major axis, <u>*also the geometrical probability is higher in late-type stars*</u>

  This can also be seen combining the above relation with the relation previously derived, between planetary and stellar parameters

$$T_{\mathrm{p}} \propto \left(\frac{R_*}{a}\right)^{\frac{1}{2}} T_* \qquad\qquad \mathcal{P}_{\mathrm{tr}} \sim (T_{\mathrm{p}}/T_*)^2$$

Habitable planets with the *transit method*

- Transit depth of the minimum of the light curve

$$\Delta F = \frac{F - F_{\rm tr}}{F} = \left(\frac{R_{\rm p}}{R_*}\right)^2$$

The strongest signal is given by giant planets around stars of small radii

For a given planet size, the detection is easier in stars of small size

Since late-type stars on the main sequence have smaller radii than early-type stars, the transit signal tends to be more intense in low-mass stars

Habitability around M-type stars

The detection of habitable planets
with the most efficient detections methods (Doppler and transit)
is severely biased in favour of planets around low-mass stars

However, the habitability around M-type stars faces several problems

Potential problems of habitability around M-type stars

- The vicinity to the star may lead to a synchronization of the planet orbital period with the planet rotation period ("tidal locking")
  - The distance from the star at which the planet becomes tidally locked after a time t scales as

    $r \propto (P_{\rm o}\, t\,/Q)^{1/6}\, M_*^{1/3}$

    where $P_{\rm o}$ is the initial rotation period, Q is a planetary dissipation factor and M_* the stellar mass

    for t=10^9 yr and $P_{\rm o}$=0.5 d, typical values of r are lower than ~0.3 AU
- Tidal locking has heavy implications on the planetary climate
  - Only one hemisphere is constantly illuminated
  - In absence of atmospheric transport, the planet would be habitable only in a narrow circle between the dark and illuminated side
  - In presence of atmospheric transport, the planet would be characterized by a very strong circulation between the two sides

Potential problems of habitability around M-type stars

- The intense stellar activity, characteristic of late-type stars, may limit the habitability
  - in low-mass stars the stellar activity is more intense and long-lasting than in solar-type stars
  - strong stellar winds, one of the effects of stellar activity, tend to erode planetary atmospheres
  - high-energy charged particles accelerated by stellar magnetic fields will induce a high dose of ionizing radiation on the planet surface

- A strong planetary magnetic field and a thick atmosphere are required to mitigate these effects
- The thick atmosphere would also mitigate the temperature gradients between the illuminated and dark hemispheres, but would be characterized by very strong surface winds

Potential problems of habitability around M-type stars

- Planets in the habitable zone of M-type stars could be dry
  - Simulations of planetary formation in late-type stars predict that planets in the habitable zone of M-type stars would accrete dry planetesimals
  - The accreted planets would be dry, unless volatiles are adquired from distant wet planetesimals driven to the inner regions of the planetary system as a result of a dynamical instability

- None of the above problems completely prevents the habitability around M-type stars
  - For instance, tidal locking could drive a 3:2 spin-orbit resonance (rather than 1:1 resonance), as in the case of Mercury; in this case all the planetary surface would be illuminated during each orbit

Terrestrial-type exoplanets in the habitable zone

Most of them orbit low-mass stars

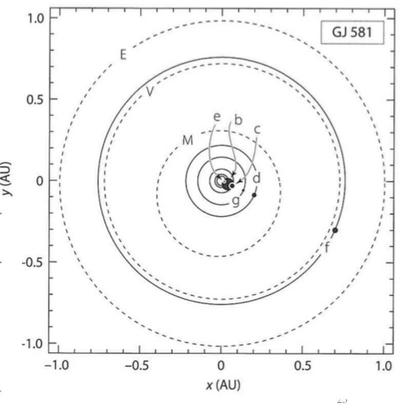
- Examples of planets discovered with the Doppler method

Planetary system around the M3V star GJ 581 (at 6.3 pc from the sun)

- Planets c and d lie close to the inner and outer edge of the classic habitable zone, respectively
- Planet g, apparently confirmed after years of debate, lies well inside the habitable zone

Vogt et al. (2010)

Planet	$M_P \sin i$ ($M_\oplus$)	a (AU)	P (d)
e	1.7	0.028	3.15
b	15.6	0.041	5.37
c	5.6	0.073	12.92
g	3.1	0.146	36.56
d	5.6	0.218	66.87
f	7.0	0.758	433



Search for habitable exoplanets

- Basic search criteria (in light of present-day observational limitations)
  - Insolation compatible with "habitable zone"

    Calculated from stellar luminosity and orbital parameters

    This criterion by itself guarantees the existence of an energy source sufficient to drive photosynthesis (the energy requirements for photosynthesis are extremely low)
  - Terrestrial type

    $M \lesssim 10\ M_{\rm Earth}$ or $R \lesssim 2\ R_{\rm Earth}$

    Planets with larger mass/size adquire an extended atmosphere, yielding a non-habitable situation (similar to that of giant planets)
- Focus on surface (rather than subsurface) habitability
  - Surface habitability has the highest chance of producing atmospheric biosignatures
- Presence of water is assumed
  - at the moment hard to test experimentally

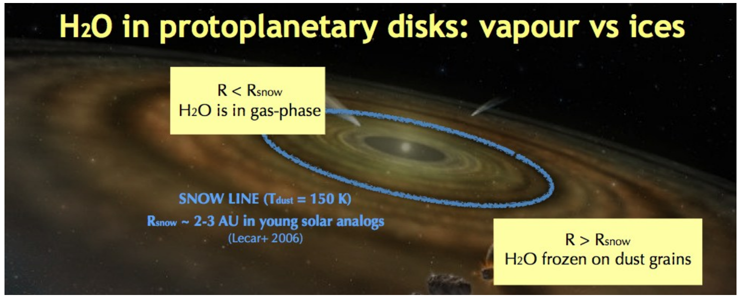
Water delivery on planets in the habitable zone

At the present time it is not clear if the planets in the HZ have been able to adquire water at the stage of planetary formation

Important progress in this field will be done by studying the location of the "ice line" in protoplanetary disks

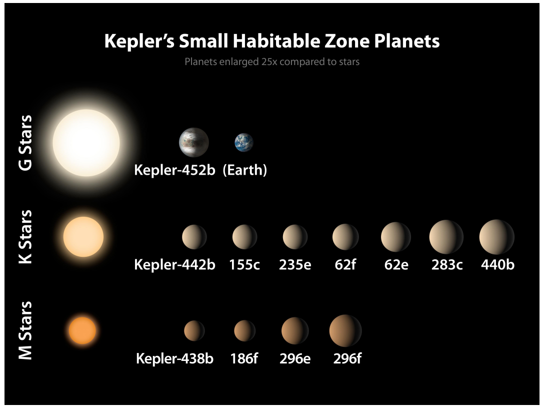
This type of observation can be performed with high angular resolution observations in the mm and sub-mm spectral bands

With instruments such as ALMA <u>we are starting to probe directly the the pathways for delivery of ices and chemicals on the planets</u>



Terrestrial-type exoplanets in the habitable zone discovered with the transit method

- A number of planets in the classic habitable zone have been discovered with the transit method
- Habitable planets start to be discovered around solar-type stars and not just around M-type stars



The Trappist-1 planetary system

Gillon et al. (2018)