Chapter 4
Search for habitable environments, biomarkers
and life outside the Earth
Search for habitable environments and life in the Solar System
Examples of non-habitable planets

- **Venus**
  
  $T_s = 735$ K
  
  $p_s = 92 \times 10^5$ Pa

  Venus has probably undergone a “runaway greenhouse effect” in the early stages of its history.
Non-habitable planets

- **Jupiter**
  Some of the atmospheric layers have pressure and temperature in the intervals $10^5 \text{ Pa} < p < 10^7 \text{ Pa}$ and $300 < T < 500 \text{ K}$

  In principle, these ranges allow for the presence of liquid water in such atmospheric layers

  The conditions for life to adapt in such environment are very restrictive

  Hypothetical forms of life should stay suspended in those layers

Even if some authors did investigate the potential habitability of such atmospheric layers (Sagan & Salpeter 1976), giant planets are never considered among candidate habitable planets
Mars

- Surface habitability
- At present time the Mars surface is not habitable
  - The surface is slightly below the triple point of water
  - $T_s = 210 \text{ K}$
  - $P_s \sim 600 \text{ Pa} ~ (\sim 6 \text{ mbar})$

- In layers below the surface we expect a gradient of pressure and temperature
  - At some proper depth, this could yield conditions suitable for liquid water to exist
Search for water in Mars

- Evidence of water in present-day Mars
  
  Even if the bulk of the polar caps is constituted by CO$_2$ ice, the North polar cap must also contain a fraction H$_2$O
  
  in order to explain why such polar cap is able to persist, to some extent, during the Mars summer, when CO$_2$ sublimates into the atmosphere
Search for water in Mars

- Evidence of water in present-day Mars
  - Traces of recent erosion at the border of craters
    - Interpreted as transient outflows of water in liquid phase ("gullies")
Search for water in Mars

- Evidence of water in present-day Mars
  
  Space probes are collecting evidence on the presence of underground water ice.
  
  The distribution of hydrogen below the ground, inferred from the data collected from the probe “Mars Odyssey”, suggests the existence of a layer of water ice at a depth of about one meter.

  Blue areas: maximum concentration

[Image of Mars surface with color-coded hydrogen distribution]
Tentative evidence of methane in present-day Mars

- Recent claims of detection of CH$_4$ outgassing on Mars
  By means of high resolution infrared spectroscopy from Earth
  Methane emissions seem to have a local and seasonal character
  Villanueva et al. (2009)

- If confirmed, these observations would suggest the presence of some form of underground chemical activity
  possibly of geochemical origin, but methane-producing biochemical processes are well-known on Earth
Mars habitability in the past

- Several independent evidence suggests that Mars was habitable in the past.
  These evidences are particularly important in astrobiology, because of the possibility that life might have developed on Mars.

- Among the different evidences we mention:
  - Statistics of impact craters
  - Geomorphological evidence
  - Martian meteorites collected on Earth
Mars habitability in the past

- Evidence for the presence of a thick atmosphere in the past
  - Statistics of the diameters of impact craters
  - Deficit of small size ancient craters with respect to recent craters
  - The presence of a past atmosphere may have caused this deficit by means of:
    - Fusion of small size meteoroids due to friction during the crossing of the atmosphere
    - Erosion of the shallowest craters by means of atmospheric weathering
Mars habitability in the past

- Evidence for the presence of liquid water in the past
  
  Geomorphological evidence
  
  For instance, network of valleys similar to those excavated by terrestrial rivers
Mars habitability in the past

- Evidence for the presence of liquid water in the past
  
  Some meteorites, classified as SNC, of martian origin, recovered in Antarctica, suggest that liquid water was present on Mars in past epochs.
  
  ALH 84001, found in 1984.
Mars habitability in the past

- In light of the “faint young sun paradox”, the requirement for a primordial CO$_2$-rich atmosphere is more compelling for Mars than the Earth.
- An intense, early volcanic activity may have generated large amounts of atmospheric CO$_2$.
  The greenhouse effect would have provided a temperature sufficiently high for water being in the liquid phase in an atmosphere of higher pressure than today.
Early searches for life on Mars

Viking experiments (1976) searched for traces of biological activity from the analysis of samples collected in a few martian landing sites.

Three different experiments were carried out and analysed *in situ*, searching for evidence of biochemical processes.

The results of one of the three experiments were consistent with the presence of biochemical activity; however, this signal is believed to be a “false positive” since it was not confirmed by the other two experiments.
Searches for life on Mars

The ambiguous results of the Viking experiments teach us how difficult is to reveal the presence of life, even when we can analyse samples. The analysis of samples in situ is less accurate than the analysis that could be performed in laboratories on Earth, but bringing the sample back to Earth would increase dramatically the cost of the mission.

The results of the Viking experiments do not exclude that life might exist in other locations on Mars. Active biological processes might take place in underground layers at a proper depth, where the temperature and pressure gradients would allow liquid water to be present.
Searches for life on Mars

- **Searches for life in the past history of Mars**

  The analysis of the meteorite ALH 84001 revealed microstructures with morphology suggestive of a biological origin. Carbonate globules with an age of 3.9 Ga have been found in the interior. However, the sizes of those structures, between 20 and 100 nm, are too small with respect to the smallest sizes of the living cells that we know.
Europe

- One of the 4 major moons of Jupiter
  - The second one in order of distance
- Europes’ surface is not habitable
  \[<T_s> = 103\ \text{K},\ p_s=10^{-6}\ \text{Pa}\]
- In spite of this fact, Europe is one of the most interesting astronomical bodies in the Solar System from the point of view of astrobiology
Europe has been the target of several space missions

- The most detailed observations have been obtained by the “Galileo” probe
  Launched in 1989, the probe made several “flybyes” around Europe in 1997

- The surface of Europe is made of H$_2$O ice
  The surface morphology, with relatively few impact craters, suggests that the surface is constantly being reshaped
  Different types of shallow structures can be seen on the surface
    Their presence is emphasized by differences in albedo
Europe

- A water ocean is believed to exist below the external ice layer.
  The thickness of the layer is not known; likely to be between a few km and some tens of km.
- The evidence for liquid water is indirect, but quite convincing.
  - The fractures in the ice shield hint at presence of liquid water under the surface.
  - Magnetometric measurements performed by the Galileo probe indicate the presence of an internal layer with electrical conductivity similar to that of salty water (Khurana et al. 1998).
  - Internal sources of energy are expected to exist at large depths; the heating would melt the ice from below.
Europe

- **Internal heating**
  - The heat would be produced by tidal interactions with Jupiter; the strong effects of vulcanism found in the first moon of Jupiter (Io), indicate that also on Europe tidal effects could produce internal heating

- **Internal structure**
  The mean density, $\rho=3.0 \text{ g cm}^{-3}$, is similar to the value typical of silicates
  Below the layers of solid and liquid water, the interior must be rocky
Habitability of Europe’s interior

• The presence of liquid water below the surface makes Europe the main candidate for studies of habitability outside the “circumstellar habitable zone” (which is instead referred to the surface habitability)
• It is plausible that “hydrothermal vents”, similar to those found at the bottom of the Earth’s oceans, may exist at the bottom of Europe’s ocean
• In this case, all the main ingredients of habitability would be present:
  Liquid water, energy sources, protection from ionizing radiations
Motivations to search for life on Europe
Connection with studies in Antarctica

The fact that Earth’s termophilic organisms found around hydrothermal vents are close to the root of the phylogenetic tree (relatively close to the origin of life), adds an additional element of interest to the search for life in Europe.

The existence of terrestrial cryophilic organisms and the searches for life in Antarctic subglacial lakes are motivated by the similarity with Europe’s conditions; the scientific results that might be found in Antarctica and the technological development required to carry out this type of research are all relevant for Europes’ astrobiological studies.
Searches for biomarkers on Europe’s surface

- The icy surface of Europe shows reddish streaks due to different compounds, such as sulfate salts and sulfuric acid.
  Their presence may be related to outgassing from Io, but also to an exchange of material between the surface and the subsurface layers, down to the liquid layers.

- The chemical pathways able to lead to the formation of such chemical compounds are currently investigated to search for evidence of biochemical activity, if any.
  In terrestrial life, sulfur can be produced biologically, in which case the isotopic ratio $^{32}\text{S}/^{34}\text{S}$ tends to be higher than the corresponding non-biological ratio.

- Future space missions on Europe are considering the possibility of measuring the sulfur isotopic ratio on Europe’s surface, searching for evidence of a biological origin.
Titan

- Largest satellite of Saturn
  - Radius 40% of Earth’s radius
  - Non habitable surface:
    - $<T_s>$=94 K
    - $p_s=1.47 \times 10^5$ Pa
- Main observations from space missions
  - NASA Pioneer 11, Voyager 1 and 2 between 1979 and 1982
  - Mission NASA/ESA Cassini-Huygens, since 2004
    - Close up maps obtained by Cassini
    - Landing of the Huygens probe in 2005
Titan’s atmosphere

The most abundant molecule is $\text{N}_2$, as in the Earth’s atmosphere

The highest atmospheric layers are characterized by a *haze of tholin*

Organic compounds obtained from the processing of simple organic molecules
photo-dissociated and photo-ionized
Titan’s surface

- The surface pressure is comparable to that of the Earth (50% larger)
  \[ p_s = 1.47 \times 10^5 \text{ Pa} \]
- What makes particularly interesting Titan is the presence of large amounts of organic molecules in liquid phase, forming surface lakes of hydrocarbons
  - Mainly methane (CH\textsubscript{4}) and ethane (C\textsubscript{2}H\textsubscript{6})
    - The lakes have been discovered by the Cassini probe and, with higher detail, in the landing site of the Huygens module
Titan as a laboratory of astrobiology

- The presence of large quantities of organic material makes it possible the formation of complex organic molecules on Titan.
  Laboratory simulations of Titan’s atmosphere have shown the possibility of formation of prebiotic material, including aminoacids and nucleic acids.
  Horst et al. (2010)

- Titan is an ideal laboratory to understand whether a biochemistry based on a liquid different from water, such as methane and ethane, can be possible.
  However, methane and ethane molecules are not polar.
  Some authors have considered the possibility that non polar liquids may give rise to some type of alternative biochemistry, but this possibility is controversial.

- Liquid water might exist in undergound layers in Titan.
  There are no direct evidences, but the expert agree that this possibility is plausible; in this case, the exchanges between the organic material and the liquid water may yield extremely interesting astrobiological conditions in the subsurface layers.
Enceladus

- Small satellite of Saturn
  - The surface is icy
  - Some of its features are interesting in astrobiology: jets of icy particles and water vapour are being ejected from the South pole
    - This activity suggests the presence of an internal energy source of geophysical character; the water vapour shows evidence of simple organic compounds
      McKay et al. (2008, AsBio, 8, 909)
Future missions of astrobiological interest towards Jupiter and Saturn

For reasons of budget, missions to Jupiter/Europe are preferred over missions to Saturn/Titan
Different projects have been considered, in collaboration between NASA and ESA, but some have been discontinued due to the high costs
The ESA project currently under consideration is called

*Jupiter Icy Moon Explorer (JUICE)*

and it is mostly motivated by astrobiological research on Europe
Search for habitable environments and biomarkers in extrasolar planets (exoplanets)
Exoplanets and astrobiology

- In exoplanets we cannot apply the detailed techniques of astrobiological research used in the Solar System (e.g. sample analysis)
  - In this case we focus on studies of habitability and search for biomarkers

- **Habitability**
  The habitability of exoplanets can be assessed from the study of the orbits, of the central star and of the planetary properties
  Here we focus on surface habitability

- **Search for biomarkers**
  Biomarkers can be searched in the spectra of exoplanet atmospheres
Search for habitable exoplanets

In spite of the large number of exoplanets discovered so far (http://exoplanet.eu - http://exoplanets.org), the number of habitable exoplanets is still quite small

We briefly review the observational limitations of this type of search
Relation between stellar parameters and distance of the habitable zone (HZ)

\[ \sigma T_p^4 = \frac{1}{4} S_*(1-A) \]

\[ S_* \equiv \frac{L_*}{(4\pi d^2)} \]

\[ S_* = \frac{R_*^2}{d^2} \sigma T_*^4 \]

Assuming \( A \sim \text{const} \),
\[ d = a \]

\[ (1 - A) \frac{R_*^2}{4d^2} T_*^4 = T_p^4 \]

\[ T_p \propto \left( \frac{R_*}{a} \right)^{\frac{1}{2}} T_* \]

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.

\[ \frac{a}{1\text{AU}} = \frac{R_*}{R_\odot} \left( \frac{T_*}{T_\odot} \right)^2 \]
Detection of habitable planets: observational issues

The habitable zone becomes more distant in early type stars

Because of the III Kepler law, the orbital periods will become larger

The temporal baseline for detecting habitable planets will become longer for early type stars
The temporal baseline of observations for detecting habitable exoplanets does not represent a serious problem. Planets in the HZ of late-type stars can be detected in short time scales. Planets in the HZ of early-type stars require several years of observations, but these planets are less interesting from the point of view of astrobiology, because of the relatively fast evolution of the stellar luminosity, which limits the continuous habitability (required for life to evolve into complex forms). Planets in the HZ of early-type stars can 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.
Detection of habitable exoplanets with the “direct imaging” method

The direct imaging technique favours the discovery of planets with large angular separation from their central star

\[ \theta = \arctan \left( \frac{a}{D} \right) \]

Planets at large semi-major axis, \( a \), and small distances from the observer, \( D \), will be detected more easily

The bias of the semimajor axis, \( a \), favours the detection of planets that tend to be too distant from the HZ; less critical for early-type stars

The bias of the stellar distance, \( D \), favours nearby stars and, in practice, low-mass stars because they are more numerous in a distance-limited volume; as a result, detection of planets around M-type stars will be favoured
Detection of habitable exoplanets with the “direct imaging” method

In order of increasing difficulty, the roadmap for detection of exoplanets with the “direct imaging” method is:

- young giant planets (strongest IR emission), old giant planets, neptunes,
- rocky planets far from the HZ and, eventually, rocky planets in the HZ

The last category is the most interesting one for astrobiology, but the most difficult to achieve: none of the observational projects currently foreseen will be able to detected rocky planets in the HZ with imaging

Space interferometry in the infrared spectral band, with coronagraphic instruments, will be required to achieve this goal in the future
Detecting **habitable** planets with the *Doppler method*

For circular orbits, the semi-amplitude $K$ is given by

$$K = (2\pi G/P)^{1/3} M_p \sin i / (M_*+M_p)^{2/3}$$
Table I
Radial Velocity Signals of the Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>$M_p$ (M$_J$)</th>
<th>R (AU)</th>
<th>P (years)</th>
<th>$\Theta_*$ at 10 pc (mas)</th>
<th>$V_*$ (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>1.74E-4</td>
<td>0.387</td>
<td>0.241</td>
<td>6.4E-6</td>
<td>0.008</td>
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<tr>
<td>Venus</td>
<td>2.56E-3</td>
<td>0.723</td>
<td>0.615</td>
<td>1.8E-4</td>
<td>0.086</td>
</tr>
<tr>
<td>Earth</td>
<td>3.15E-3</td>
<td>1.000</td>
<td>1.000</td>
<td>3.0E-4</td>
<td>0.089</td>
</tr>
<tr>
<td>Mars</td>
<td>3.38E-4</td>
<td>1.524</td>
<td>1.881</td>
<td>4.9E-5</td>
<td>0.008</td>
</tr>
<tr>
<td>Jupiter</td>
<td>1.0</td>
<td>5.203</td>
<td>11.86</td>
<td>0.497</td>
<td>12.4</td>
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<tr>
<td>Saturn</td>
<td>0.299</td>
<td>9.54</td>
<td>29.46</td>
<td>0.273</td>
<td>2.75</td>
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<tr>
<td>Uranus</td>
<td>0.046</td>
<td>19.18</td>
<td>84.01</td>
<td>0.084</td>
<td>0.297</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.054</td>
<td>30.06</td>
<td>164.8</td>
<td>0.156</td>
<td>0.281</td>
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<tr>
<td>Pluto</td>
<td>6.3E-6</td>
<td>39.44</td>
<td>247.7</td>
<td>2.4E-5</td>
<td>3E-5</td>
</tr>
</tbody>
</table>
Detecting **habitable** planets with the *Doppler method*

- Advantages of M-type stars with the Doppler method

  The semi-amplitude of the radial velocity curves scales as

  \[ K \sim (a M_\star)^{-1/2} \]

  where \( a \) is the semi-major axis, \( M_\star \) the stellar mass

  The advantage of a smaller stellar mass combines with the advantage of the smaller distance of the habitable zone

  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
Detecting habitable planets with the *Doppler method*

Also the Doppler method is sensitive to the distance from the observer, \( D \).

The flux of stellar photons scales as \( D^{-2} \).

The signal-to-noise ratio of the spectrum scales with the square root of the number of photons, and therefore scales as \( D^{-1} \).

For a given observing time and stellar type, the measurements of stellar radial velocities will be more accurate in nearby stars.

Also in this case, the high density of low-mass stars favours the detection of planets around M-type stars (however, one should also take into account that early-type stars are brighter).
Detection of habitable planets with the *transit method*
Detection of **habitable** planets with the **transit method**

- Transit depth of the minimum of the light curve

\[ \Delta F = \frac{F - F_{tr}}{F} = \left( \frac{R_p}{R_*} \right)^2 \]

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

For a given planet size, the detection will be easier, in terms of signal-to-noise ratio, in front of stars of small size

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

However, at a given stellar distance, the signal-to-noise ratio of the spectrum will be higher for early-type stars
Detection of habitable planets with the transit method

- Geometrical probability of detecting a planet with the transit method

\[ P_{\text{tr}} \approx 4.65 \times 10^{-3} \frac{R_* [R_\odot]}{a [\text{AU}]} \]

The probability is low and requires surveys of many thousands of stars to discover transits.

The geometrical probability increases with the inverse of the semi-major axis.

Since habitable planets around late-type stars are located at small semi-major axis, also the geometrical probability will become higher in late-type stars.

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

\[ T_p \propto \left( \frac{R_*}{a} \right)^{1/2} T_* \]

\[ P_{\text{tr}} \sim \left( \frac{T_p}{T_*} \right)^2 \]
Potential problems of habitable planets around M-type stars

- M-type stars are strongly favoured for detection of exoplanets in the HZ

- However, the effective habitability around these type of stars is under debate, because of the following potential problems:
  - The intense stellar activity, characteristic of late-type stars, may give problems of “space weather”
    - e.g., effects on the planet of high-energy particles emitted by the star
  - The vicinity to the star may lead to a synchronization of the planet orbital period with the planet rotation period (“tidal locking”)
    - this has heavy implications on the planetary climate
  - The different spectral distribution of M-type stars with respect to solar-type stars may give a lower efficiency of photosynthesis

- Probably, none of these problems completely prevent the habitability
Search for **rocky habitable planets**

By combining the observational data obtained with the Doppler and transit methods, we can measure masses and radii of exoplanets. In this way we can study their mean density and internal composition.

Most exoplanets discovered so far are gaseous ($\rho < 1 \text{ g cm}^{-3}$), but we are starting to discover rocky ones ($\rho > 3 \text{ g cm}^{-3}$)
List of “super-Earths” (May 2012)

<table>
<thead>
<tr>
<th>Name</th>
<th>a</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 1461 b</td>
<td>0.0635 AU</td>
<td>7.63 M(earth)</td>
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<tr>
<td>HD 7924 b</td>
<td>0.0566 AU</td>
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<td>HD 20794 b</td>
<td>0.1207 AU</td>
<td>2.70 M(earth)</td>
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<tr>
<td>HD 20794 c</td>
<td>0.2036 AU</td>
<td>2.36 M(earth)</td>
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<tr>
<td>HD 20794 d</td>
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<td>0.0801 AU</td>
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<td>HD 40307 b</td>
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<td>CoRoT-7 b</td>
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<td>55 Cnc e</td>
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<td>GJ 581 e</td>
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<td>GJ 876 d</td>
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<td>5.86 M(earth)</td>
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</tbody>
</table>

“Super-Earths” : M < 10 M(earth)

Best candidates habitable planets, in lack of Earth-mass planets

At largers masses, the planet could become a gaseous giant in the course of planetary formation

However, super-Earths could also have an icy core
One of the most interesting planetary systems discovered in the past years, as far as the habitability is concerned, is the system around the star Gl581, with a few planets close to the habitable zone (HZ)

By applying models of planetary climate one can understand the limits of habitability of such planets for different sets of planetary conditions
Habitability of Gl 581d

By using an Earth-like climate model, the planet is completely frozen.

To make the planet habitable we need a very strong greenhouse atmosphere. Our calculations suggest that a pressure of CO$_2$ of at least 8 bar is required — more than three orders of magnitude than the Earth’s $p$(CO$_2$).

If the pressure is so high, the model predicts a very uniform surface temperature, not affected by seasonal and latitudinal variations.
### Kepler-22b (Borucki et al. 2012)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective temperature, (T_{\text{eff}}) (K)</td>
<td>5518 ± 44</td>
</tr>
<tr>
<td>Surface gravity, (\log g) (cgs)</td>
<td>4.44 ± 0.06</td>
</tr>
<tr>
<td>Metallicity, [Fe/H]</td>
<td>−0.29 ± 0.06</td>
</tr>
<tr>
<td>Projected rotation (v \sin i) (km s(^{-1}))</td>
<td>0.6 ± 1.0</td>
</tr>
<tr>
<td>Density, (g \text{ cm}^{-3})</td>
<td>1.458 ± 0.030</td>
</tr>
<tr>
<td>Mass, (M_{\odot})</td>
<td>0.979 ± 0.020</td>
</tr>
<tr>
<td>Radius, (R_{\odot})</td>
<td>0.79 ± 0.04</td>
</tr>
<tr>
<td>Luminosity, (L_{\odot})</td>
<td>11.664</td>
</tr>
<tr>
<td>\textit{Kepler} magnitude (mag)</td>
<td>Not determined</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>190</td>
</tr>
<tr>
<td>Distance (pc)</td>
<td>289.8623 ± 0.0016/−0.0020</td>
</tr>
<tr>
<td>Orbital period, (P) (days)</td>
<td>66.6983 ± 0.0023</td>
</tr>
<tr>
<td>Scaled semimajor axis, (a/R_{\odot})</td>
<td>186.4 ± 1.1/−1.6</td>
</tr>
<tr>
<td>Scaled planet radius, (R_p/R_{\odot})</td>
<td>0.0222 ± 0.0012/−0.0011</td>
</tr>
<tr>
<td>Impact parameter, (b) (eccentric orbit)</td>
<td>0.768 ± 0.132/−0.078</td>
</tr>
<tr>
<td>Orbital inclination, (i) (deg)</td>
<td>89.764 ± 0.025/−0.042</td>
</tr>
<tr>
<td>Transit duration, (\Delta) (hr)</td>
<td>7.415 ± 0.067/−0.078</td>
</tr>
<tr>
<td>Radius, (R_{\oplus})</td>
<td>2.38 ± 0.13</td>
</tr>
<tr>
<td>Mass, (M_{\oplus}), (1(\sigma), 2(\sigma), and 3(\sigma) upper limits)</td>
<td>36, 82, 124</td>
</tr>
<tr>
<td>Orbital semimajor axis, (a) (AU)</td>
<td>0.849 ± 0.018/−0.017</td>
</tr>
<tr>
<td>Equilibrium temperature, (T_{\text{eq}}) (K)</td>
<td>262</td>
</tr>
</tbody>
</table>

**Stellar spectral distribution not too different from solar**

**Planet lies beyond tidal lock distance and has \(R=2.38\,R_{\oplus}\)**

... but the mass is still not “weighted” with accuracy...
Effects of gravity and pressure on the climate and habitability of exoplanets

Vertical mass column of the atmosphere: $p/g$
Effects of gravity on the Outgoing Longwave Radiation (OLR)
Effects of gravity on the top-of-atmosphere (TOA) albedo

\[ p = 1.0 \text{ bar} \quad a_s = 0.3 \quad Z = 60^\circ \]

![Graph showing the effects of gravity on TOA albedo.](image)

- \( g/g_\oplus = 2.0 \)
- \( g/g_\oplus = 1.0 \)
- \( g/g_\oplus = 0.5 \)

(b)
Effects of gravity and pressure on the mean global temperature
Effects of gravity and pressure on the mean global temperature

![Graph showing the effects of gravity and pressure on the mean global temperature for Kepler-62e. The graph plots temperature ($T_m$ in °C) against pressure ($p$ in bar) with different values of gravity ($g$) relative to Earth ($g_\oplus$). The legend indicates the values: $g/g_\oplus=0.5$, $g/g_\oplus=1.0$, and $g/g_\oplus=2.0$. The graph shows a range of temperatures for each value of gravity, indicating the impact on the mean global temperature.](image)
Searches for biomarkers
Observations of planetary atmospheres

Primary transit
Transmission spectrum of the planetary atmosphere

Secondary transit
Thermal radiation of the planet
Planetary albedo
Absorption spectroscopy of planetary atmospheres

- The atmospheric absorption signal scales with the scale-height of the atmosphere, $h$, and the planet radius, $R_p$
- Gaseous giants give the strongest signal; already detected
  - e.g. Tinetti et al. (2007)
- Earth-like atmospheres are beyond detection limit even for the most advanced instrumental projects currently scheduled
- Atmospheres of super-Earths may be feasible with next generation instrumentation
- Detection bias favours stars with smaller radii

\[ \delta I \sim \frac{2h R_p}{R_*^2} \]
Absorption spectroscopy of planetary atmospheres

- Atmospheric absorption spectroscopy with primary transits: molecular detections in gaseous giant planets

$H_2O, CH_4, CO_2, CO$
Biomarkers in the spectra of planetary atmospheres

Oxygen is considered one of the most promising biomarkers.

In absence of a biosphere, oxygen tends to oxydate rocks and to decrease its atmospheric concentration.

The history of Earth’s atmospheric oxygen reveals the fundamental role of biology.
What do we hope to detect in planetary atmospheres?
Examples: spectra of the Earth’s atmosphere observed from space

Reflection spectrum in the visible/near IR

IR emission spectrum
Direct imaging studies of planetary atmospheres
Example of multiple planetary system: HR 8799bcd (Marois et al. 2008)
IR imaging of nearby, young stars
(young stars → young planets → IR emitters)
Direct imaging studies of planetary atmospheres: detection of molecular absorption

Fig. 2. K-band spectrum of HR 8799c (black) at the full resolution of OSIRIS ($\lambda/\lambda \Delta \lambda \sim 4000$). Both lines and continuum are shown, and the spectral features most relevant to objects of this mass are highlighted. For clarity, uncertainties are shown separately in red. The best-fitting model spectrum is shown in green. A clear drop from CO is detected, along with features typical of the CO bandhead at $\lambda > 2.29 \mu$m. The slight increase in the spectrum at the red end is attributed to residual speckle effects after the attenuation algorithm. Again, broad features from CH$_4$ are not easily detected. Spectral data are provided in database S1 (15).