

## Introduction to Astrobiology

### Chapter 4

#### Search for habitable environments, biomarkers and life outside the Earth

## The Solar System

### Search for habitable environments and life

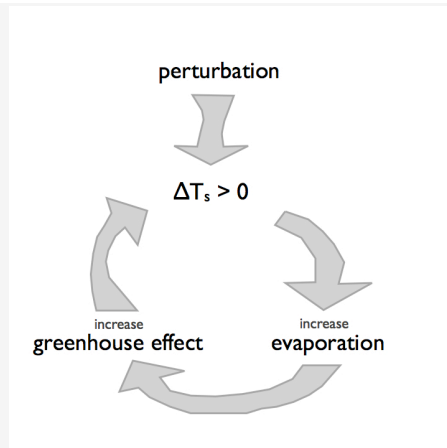
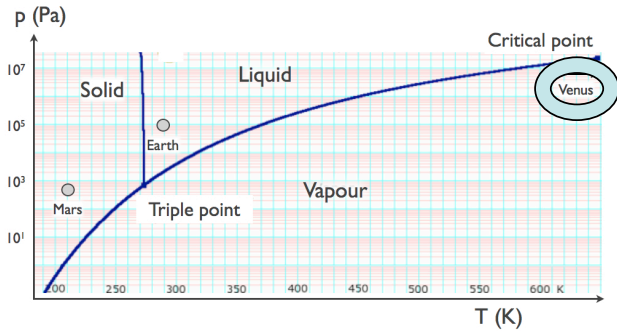
## Examples of non-habitable planets

### ➤ Venus

$$T_s = 735 \text{ K}$$

$$p_s = 92 \times 10^5 \text{ Pa}$$

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 of pressure and temperature allow water to be present in liquid phase in such atmospheric layers

The conditions for life to originate in such environment are unknown

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 not considered to be habitable

## Mars

- Surface habitability
- At present time the Mars surface is not habitable

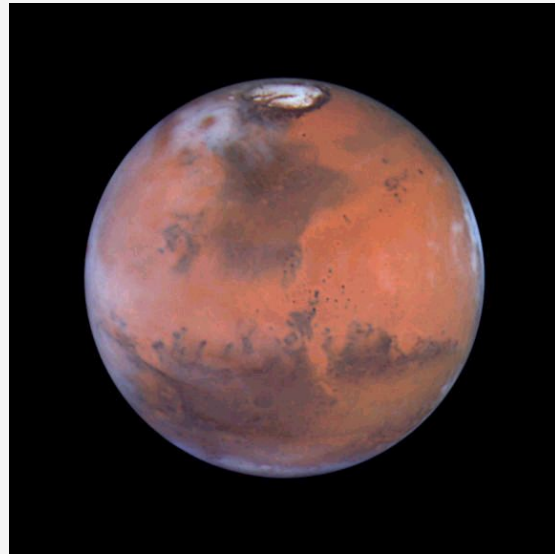
The surface is slightly below the triple point of water

$$T_s = 210 \text{ K}$$

$$P_s \sim 600 \text{ Pa } (\sim 6 \text{ mbar})$$

- In layers below the surface we expect a gradient of pressure and temperature

At some proper depth, this should yield conditions suitable for liquid water to exist

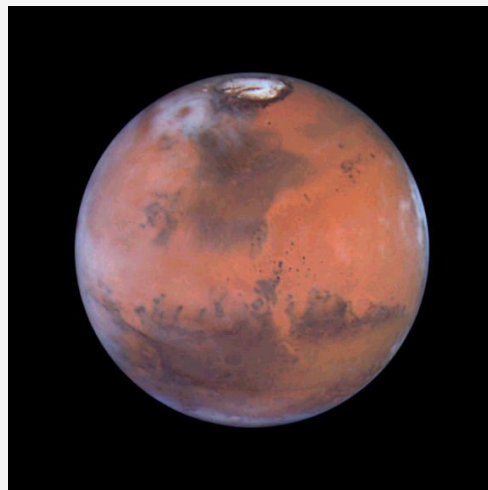


## Search for water in Mars

- Evidence of water in present-day Mars

Even if the bulk of the polar caps is constituted by  $\text{CO}_2$  ice, the North polar cap must also contain  $\text{H}_2\text{O}$

this would explain why such polar cap is able to persist, to some extent, during the Mars summer, when  $\text{CO}_2$  sublimates into the atmosphere

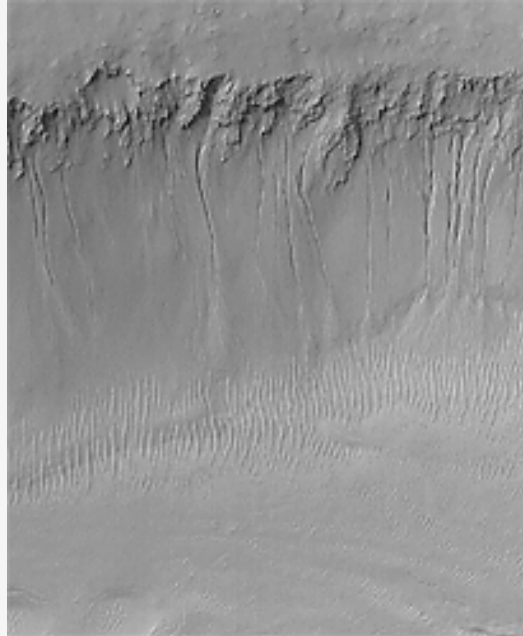


## Search for water in Mars

### ➤ 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”)



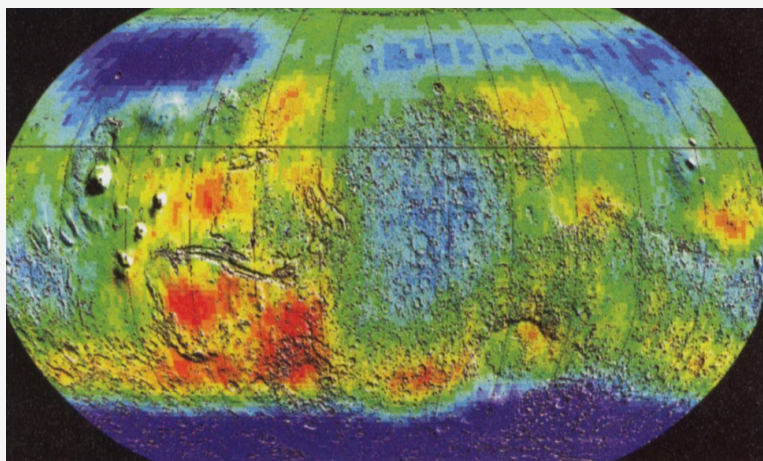
## Search for water in Mars

### ➤ 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 layer of water ice at a depth of about one meter

Blue areas: maximum concentration



## Tentative evidence of methane in present-day Mars

- Recent claims of detection of CH<sub>4</sub> outgassing on Mars

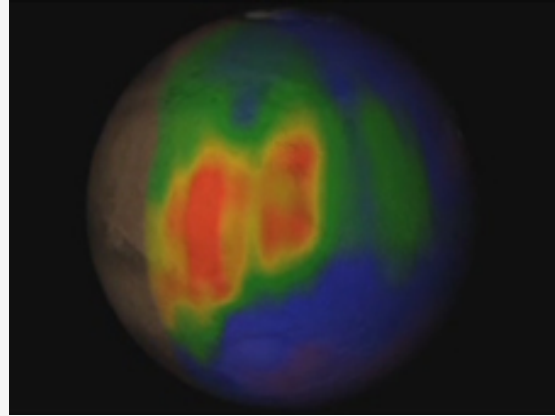
- By means of high resolution infrared spectroscopy from Earth

- 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 cannot be excluded



## 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

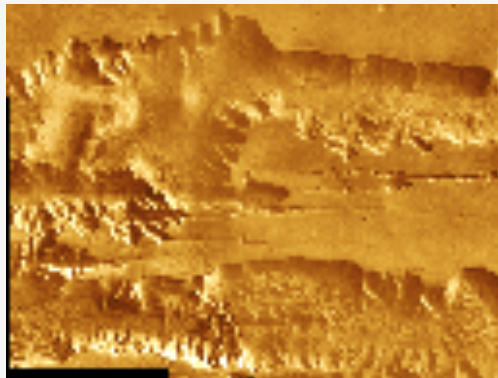
Erosion of the shallowest craters by means of atmospheric weathering

## 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

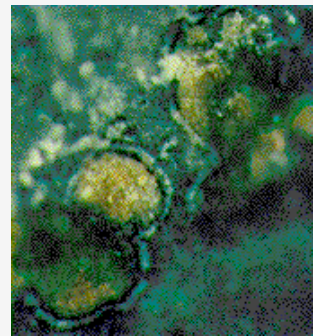


## Mars habitability in the past

### ➤ 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

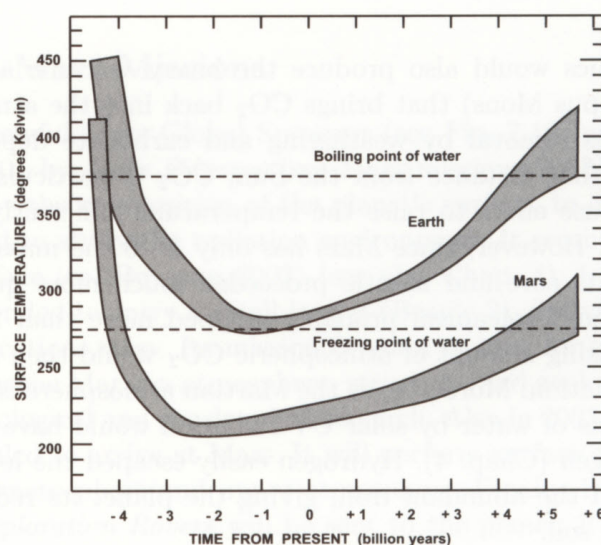


## Mars habitability in the past

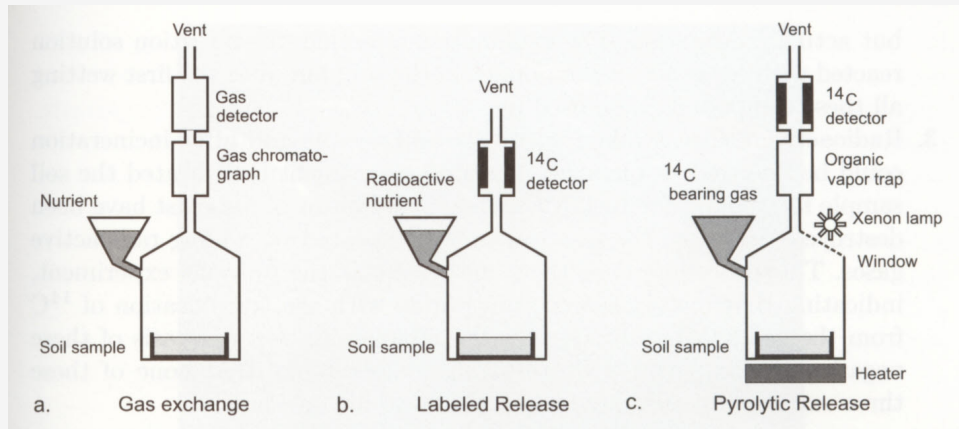
- In light of the “faint young sun paradox”, the requirement for a primordial CO<sub>2</sub>-rich atmosphere is more compelling for Mars than the Earth
- An intense, early volcanic activity may have generated large amounts of atmospheric CO<sub>2</sub>

The greenhouse effect would have provided a temperature sufficiently high for water being in the liquid phase

The atmospheric pressure should have been much higher 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

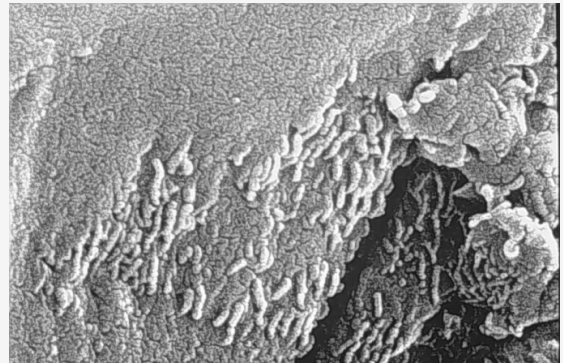
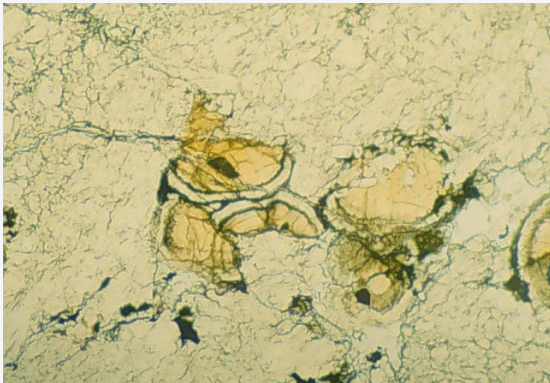
## Searches for life on Mars

### ➤ Searches for life in the past history of Mars

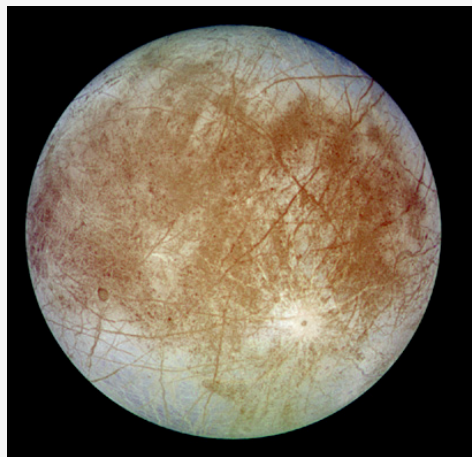
The analysis of the meteorite ALH 84001 revealed microstructures with morphology suggestive of a biological origin

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 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
  - $\langle T_s \rangle = 103 \text{ K}, p_s = 10^{-6} \text{ Pa}$
- 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

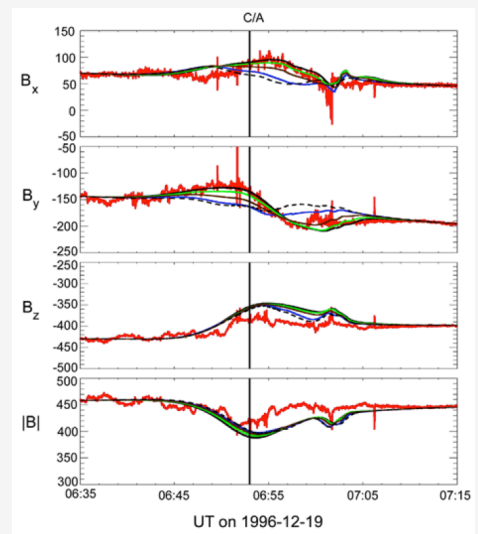
## Europe



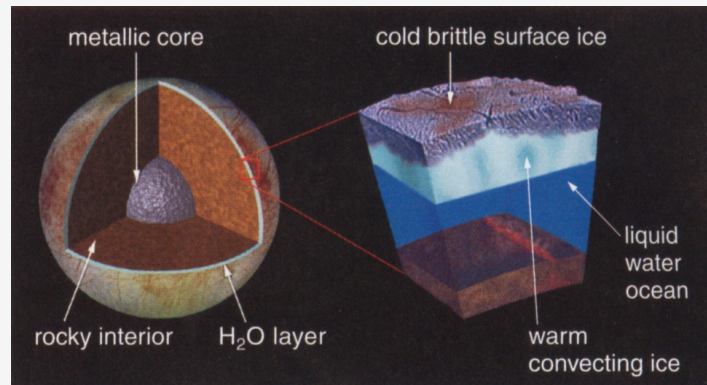
- Europe has been the target of several space missions
- The most detailed observations have been obtained by the “Galileo” probe  
Launched in 1989, the probe made several “flybys” around Europa in 1997
- The surface of Europa is made of H<sub>2</sub>O ice  
The surface morphology, with relatively few 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

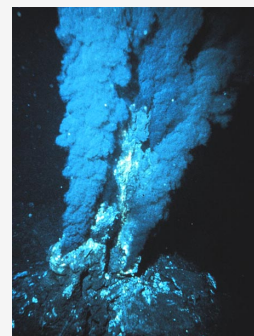
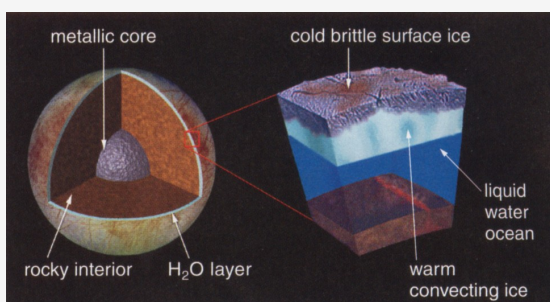
- The heat would be produced by tidal interactions with Jupiter
- The strong effects of vulcanism found in the first moon of Jupiter (Io), suggest that also on Europa tidal effects can produce internal heating

### ➤ 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

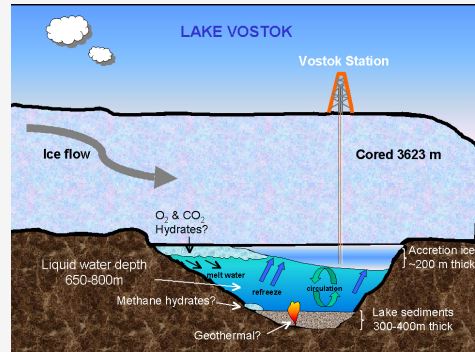
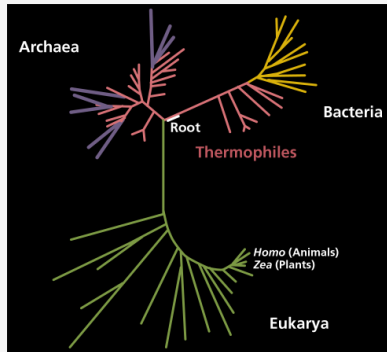
## Habitability of Europe's interior



?

- The presence of liquid water below the surface makes Europa a candidate for studies of habitability outside the “circumstellar habitable zone” (which is defined according 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 Europa'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 thermophilic 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

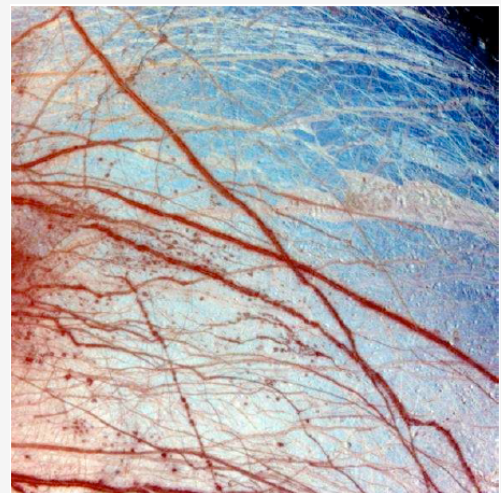
The existence of terrestrial cryophilic organisms and the searches for life in Antarctic subglacial lakes are motivated by the similarity with Europe's conditions; the scientific results that might be found in Antarctica and the technological development required to carry out this type of research are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

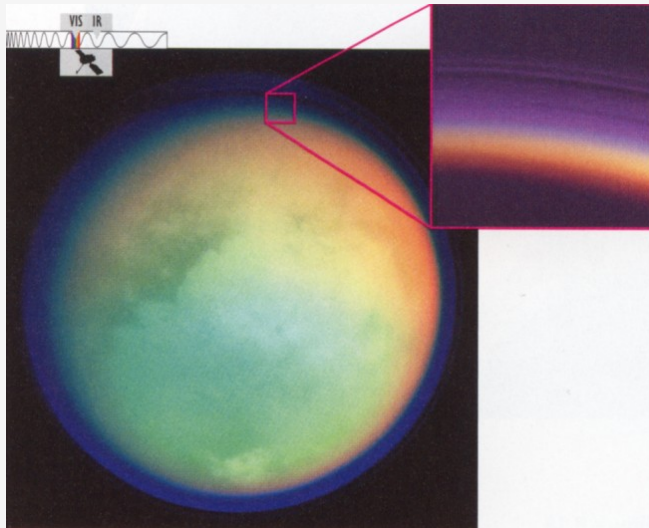
In terrestrial life, sulfur can be produced biologically, in which case the isotopic ratio  $^{32}\text{S}/^{34}\text{S}$  tends to be higher than the corresponding non-biological ratio
- Future space missions on Europe are considering the possibility of measuring the sulfur isotopic ratio on Europe's surface, searching for evidence of a biological origin



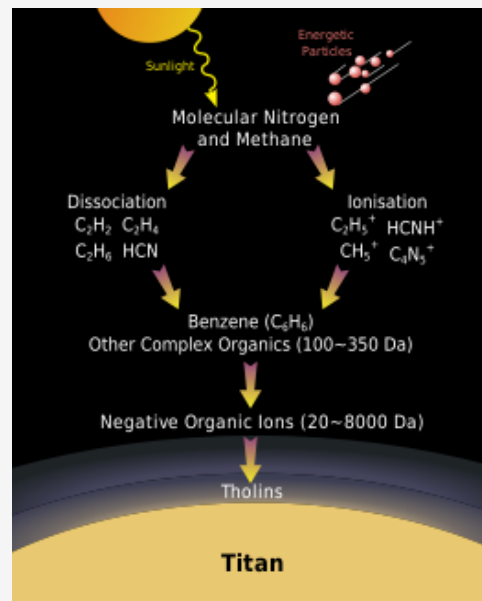
## Titan



- **Largest satellite of Saturn**
  - Radius 40% of Earth's radius
  - Non habitable surface:
  - $\langle T_s \rangle = 94 \text{ K}$      $p_s = 1.47 \cdot 10^5 \text{ Pa}$
- **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

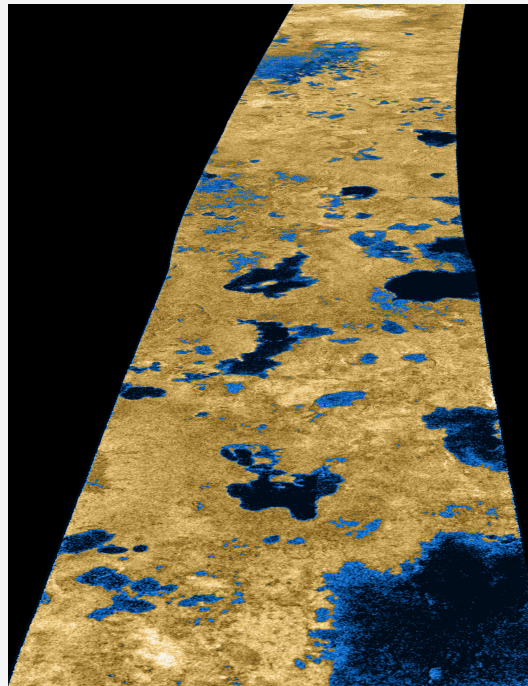
- The surface pressure is comparable to that of the Earth (50% larger)

$$p_s = 1.47 \times 10^5 \text{ Pa}$$

- What makes particularly interesting Titan is the presence of large amounts of organic molecules in liquid phase, forming surface lakes of hydrocarbons

Mainly methane ( $\text{CH}_4$ ) and ethane ( $\text{C}_2\text{H}_6$ )

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

Schulze-Makuch & Irwin (2004)

- Liquid water might exist in underground layers in Titan

There are no direct evidences, but 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

## Exoplanets

Search for habitable environments and biomarkers

### 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

With different observational methods

## 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

## Continuous habitability

Life evolution may take a few billion years to produce advanced forms of life, as in the case of the Earth

For this reason the search for habitable exoplanets is focussed on planets that can maintain a habitable climate for long periods of time ( $\sim 10^9$  yr)

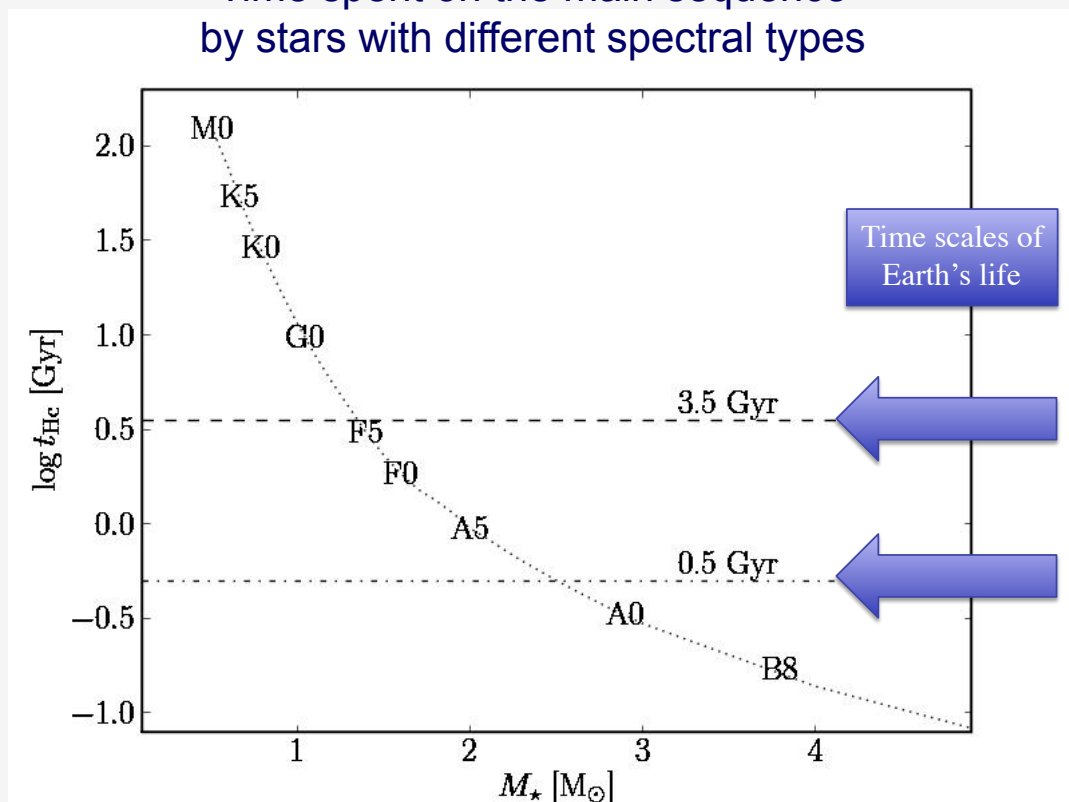
This requires:

- 1) stability of the stellar luminosity
- 2) stability of the orbital parameters
- 3) presence of a mechanism of climate stabilization

## Continuous habitability and evolution of the stellar luminosity

- The gradual increase of the stellar luminosity shifts the habitable zone during the hydrogen-burning phase
- The sudden rise of luminosity that takes place after the hydrogen burning phase produces a fast shift of the habitable zone
- The evolution of stellar luminosity constrains the type of stars that are of astrobiological interest

Time spent on the main sequence  
by stars with different spectral types



## Continuous habitability and orbital stability

- In order to have continuous habitability, the planetary orbit must be dynamically stable in the long term ( $\sim 10^9$  yr)
  - Episodes of dynamical instability are likely to be present in the early stages after the formation of planetary systems
- The dynamical stability of planetary systems can be studied with methods of numerical integration (N-body problem)
- Dynamical stability, once applied only to the Solar System, starts to be applied to extrasolar planetary systems
  - Examples of application:
    - Dynamical stability tests of orbital parameters deduced by observational methods
    - Exploration of orbital parameter space where planets not detected by observations may exist in stable orbits

Relation between stellar parameters and distance of the habitable zone (HZ)

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

$$S_* \equiv L_*/(4\pi d^2)$$

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

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

Assuming  
 $A \sim \text{const}$   
 $d = a$

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

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

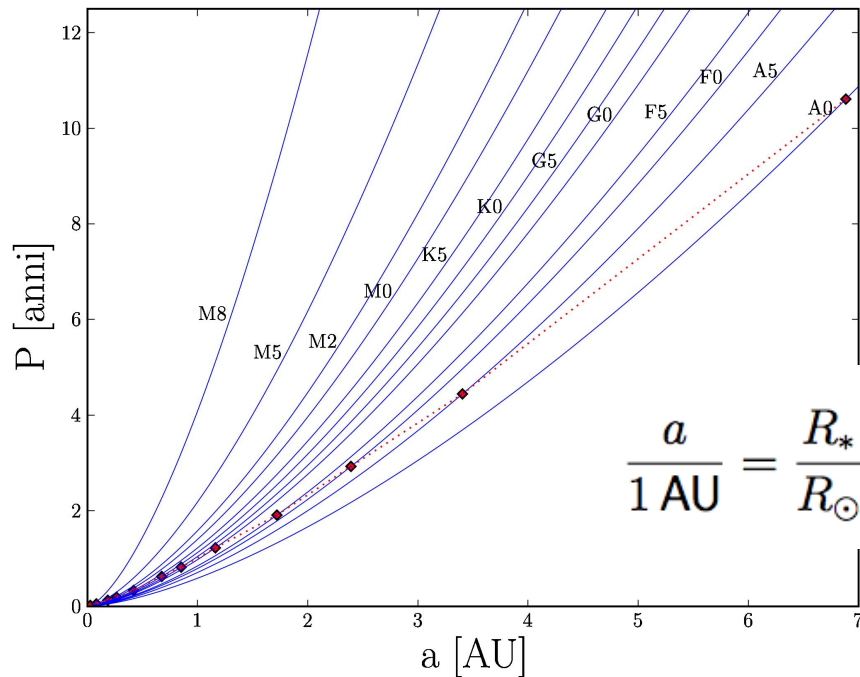
$$\frac{a}{1 \text{ AU}} = \frac{R_*}{R_\odot} \left( \frac{T_*}{T_\odot} \right)^2$$

## 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



## Detection of habitable planets: observational issues

- 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 fast evolution of the stellar luminosity, which limits the continuous habitability

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

$$\theta = \arctan (a/D)$$

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; this makes hard to detect habitable planets around M-type stars with the direct imaging method

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

Detection of habitable planets around M-type stars could be possible if the small distance from the observer compensates for the small value of the semimajor axis

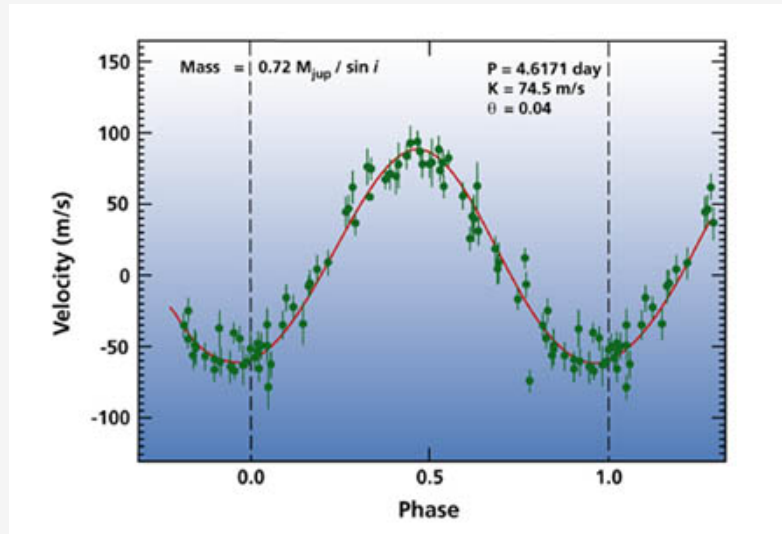
## Detection of habitable exoplanets with the “direct imaging” method

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 detect 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

$$K = (2\pi G/P)^{1/3} M_p \sin i / (M_* + M_p)^{2/3}$$

W. D. COCHRAN AND A. P. HATZES

Table I  
Radial Velocity Signals of the Planets



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

## 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

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

where  $a$  is the semi-major axis,  $M_*$  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  $\sim 3$ -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,  $D$

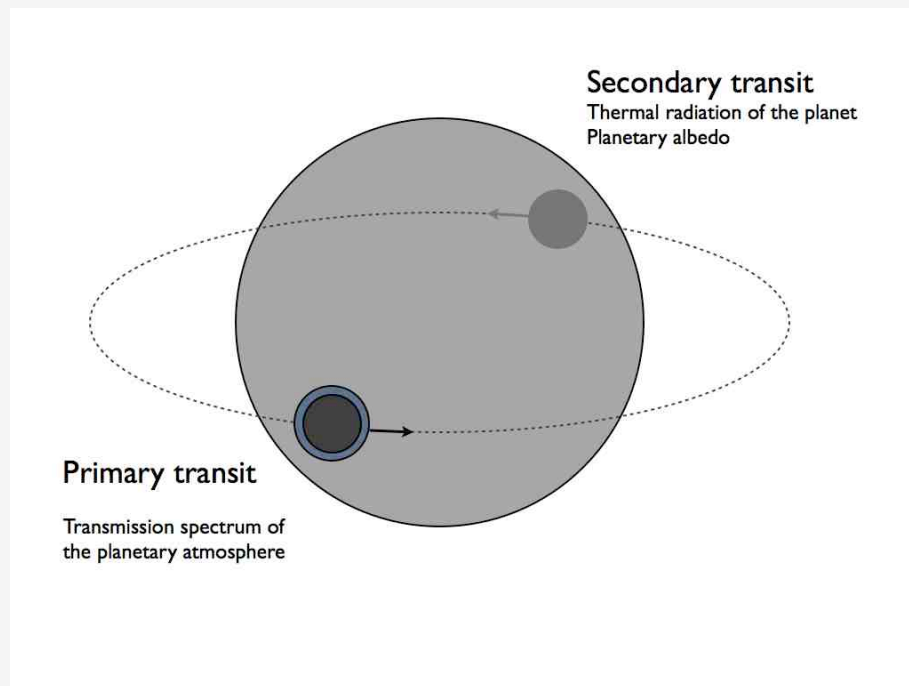
The flux of stellar photons scales as  $D^{-2}$

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 high-mass 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

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

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

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

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

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

$$\mathcal{P}_{\text{tr}} \sim (T_p/T_*)^2$$

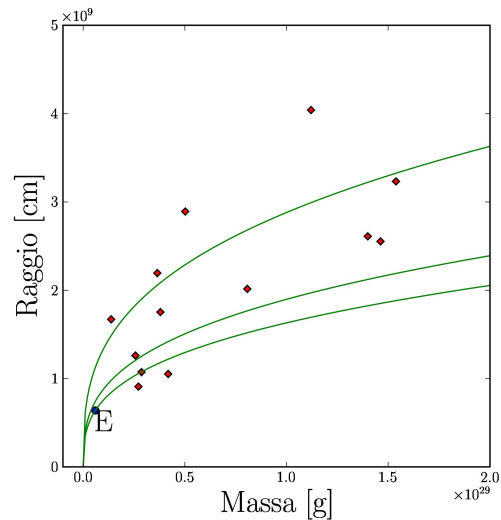
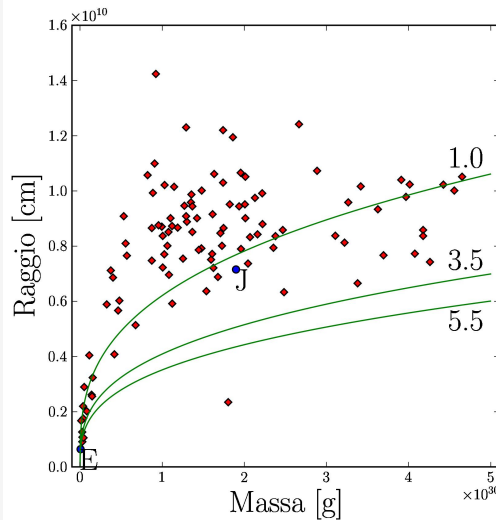
## Potential problems of habitable planets around M-type stars

- 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
  - According to some authors, planets in the habitable zone of M-type stars could be dry
  - The different spectral distribution of M-type stars with respect to solar-type stars may give a lower efficiency of photosynthesis
- 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)

|             |                       |                           |
|-------------|-----------------------|---------------------------|
| HD 1461 b   | $a=0.0635 \text{ AU}$ | $M=7.63 \text{ M(earth)}$ |
| HD 7924 b   | $a=0.0566 \text{ AU}$ | $M=9.26 \text{ M(earth)}$ |
| HD 20794 b  | $a=0.1207 \text{ AU}$ | $M=2.70 \text{ M(earth)}$ |
| HD 20794 c  | $a=0.2036 \text{ AU}$ | $M=2.36 \text{ M(earth)}$ |
| HD 20794 d  | $a=0.3498 \text{ AU}$ | $M=4.70 \text{ M(earth)}$ |
| GJ 176 b    | $a=0.0657 \text{ AU}$ | $M=8.27 \text{ M(earth)}$ |
| HD 40307 c  | $a=0.0801 \text{ AU}$ | $M=6.72 \text{ M(earth)}$ |
| HD 40307 b  | $a=0.0469 \text{ AU}$ | $M=4.10 \text{ M(earth)}$ |
| HD 40307 d  | $a=0.1324 \text{ AU}$ | $M=8.93 \text{ M(earth)}$ |
| CoRoT-7 b   | $a=0.0172 \text{ AU}$ | $M=4.95 \text{ M(earth)}$ |
| 55 Cnc e    | $a=0.0154 \text{ AU}$ | $M=7.81 \text{ M(earth)}$ |
| HD 85512 b  | $a=0.2604 \text{ AU}$ | $M=3.62 \text{ M(earth)}$ |
| GJ 3634 b   | $a=0.0287 \text{ AU}$ | $M=7.06 \text{ M(earth)}$ |
| HD 97658 b  | $a=0.0797 \text{ AU}$ | $M=6.40 \text{ M(earth)}$ |
| 61 Vir b    | $a=0.0501 \text{ AU}$ | $M=5.11 \text{ M(earth)}$ |
| GJ 581 c    | $a=0.0729 \text{ AU}$ | $M=5.33 \text{ M(earth)}$ |
| GJ 581 d    | $a=0.2177 \text{ AU}$ | $M=6.08 \text{ M(earth)}$ |
| GJ 581 e    | $a=0.0285 \text{ AU}$ | $M=1.95 \text{ M(earth)}$ |
| GJ 1214 b   | $a=0.0143 \text{ AU}$ | $M=6.47 \text{ M(earth)}$ |
| HD 156668 b | $a=0.0500 \text{ AU}$ | $M=4.15 \text{ M(earth)}$ |
| Kepler-10 b | $a=0.0168 \text{ AU}$ | $M=4.52 \text{ M(earth)}$ |
| Kepler-20 b | $a=0.0454 \text{ AU}$ | $M=8.46 \text{ M(earth)}$ |
| Kepler-20 d | $a=0.3453 \text{ AU}$ | $M=7.53 \text{ M(earth)}$ |
| HD 181433 b | $a=0.0801 \text{ AU}$ | $M=7.55 \text{ M(earth)}$ |
| Kepler-11 b | $a=0.0911 \text{ AU}$ | $M=4.30 \text{ M(earth)}$ |
| Kepler-11 d | $a=0.1542 \text{ AU}$ | $M=6.10 \text{ M(earth)}$ |
| Kepler-11 f | $a=0.2495 \text{ AU}$ | $M=2.30 \text{ M(earth)}$ |
| Kepler-11 e | $a=0.1939 \text{ AU}$ | $M=8.40 \text{ M(earth)}$ |
| Kepler-18 b | $a=0.0447 \text{ AU}$ | $M=6.88 \text{ M(earth)}$ |
| HD 215497 b | $a=0.0466 \text{ AU}$ | $M=6.63 \text{ M(earth)}$ |
| GJ 876 d    | $a=0.0208 \text{ AU}$ | $M=5.86 \text{ M(earth)}$ |

“Super-Earths” as habitable planets

“Super-Earths” :  $M < 10 \text{ M(earth)}$

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

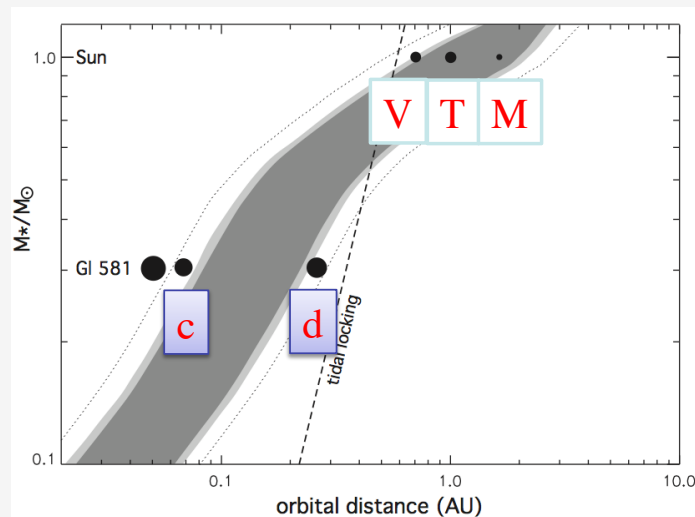
At largers masses, the planet could  
become a gaseous giant in the  
course of planetary formation

However, super-Earths could also  
have an icy core

A few examples of potentially habitable planets discovered so far

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 Gl 581, 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

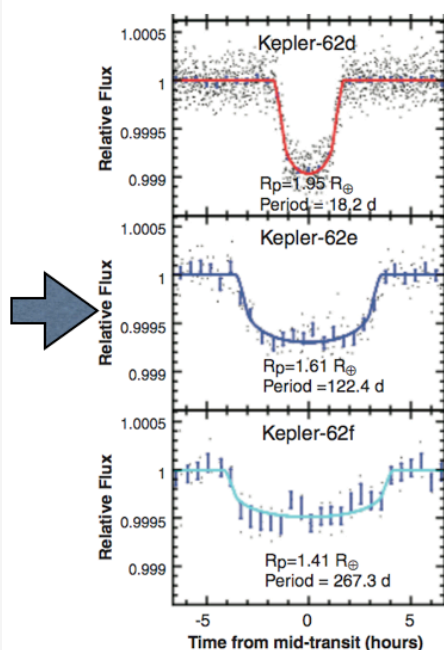


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## Kepler-62e (Borucki et al. 2013)

Central star: K2V

Spectral distribution not too different from solar

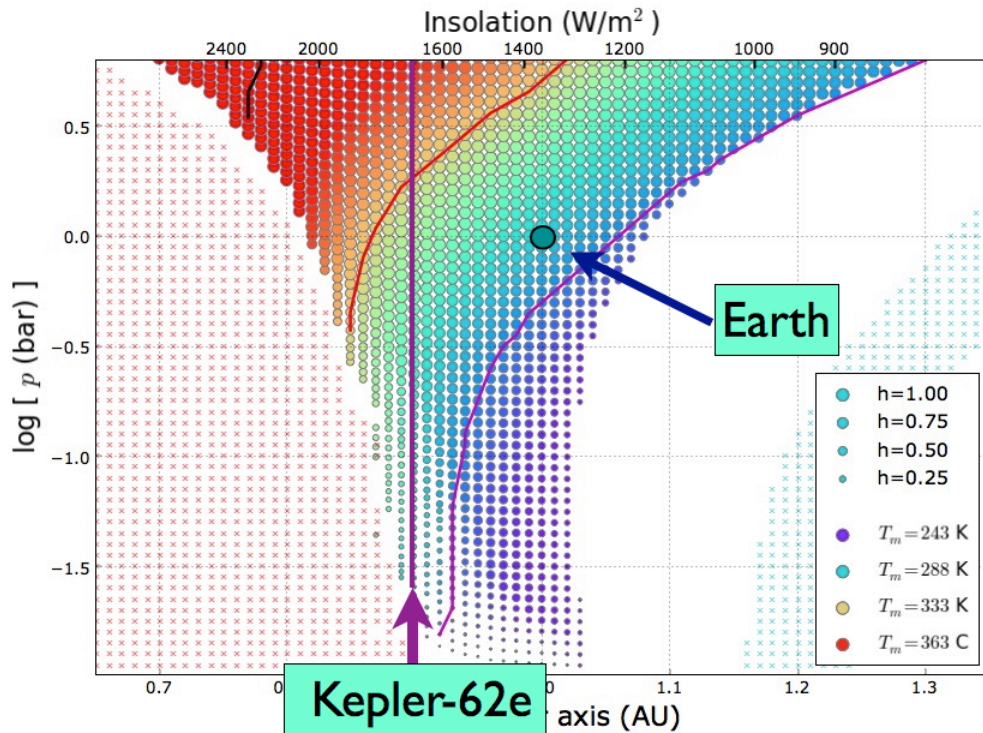


| Parameter                       | Kepler-62e            |
|---------------------------------|-----------------------|
| $T_0$ (BJD-2454900)             | $83.404 \pm 0.003$    |
| $P$ (days)                      | $122.3874 \pm 0.0008$ |
| Transit duration (hours)        | $6.92 \pm 0.16$       |
| Depth (%)                       | $0.070 \pm 0.003$     |
| $R_p/R_*$                       | $0.0232 \pm 0.0003$   |
| $a/R_*$                         | $144 \pm 4$           |
| $b$                             | $0.06 \pm 0.05$       |
| $i$                             | $89.98 \pm 0.02$      |
| $e \cos \omega$                 | $0.05 \pm 0.17$       |
| $e \sin \omega$                 | $-0.12 \pm 0.02$      |
| $a$ (AU)                        | $0.427 \pm 0.004$     |
| $R_p$ ( $R_\oplus$ )            | $1.61 \pm 0.05$       |
| Maximum mass ( $M_\oplus$ ) (9) | 36                    |
| Number of observed transits     | 8                     |
| Total SNR                       | 31                    |
| $T_{eq}$ (K)                    | $270 \pm 15$          |

Planet lies  
beyond tidal  
lock distance  
and has  
Earth-size  
 $R=1.61 R_\oplus$

The mass is unknown but there is no doubt on the planetary nature

## Habitability of Kepler-62e



Effects of the atmospheric columnar mass  
on the climate and habitability of exoplanets

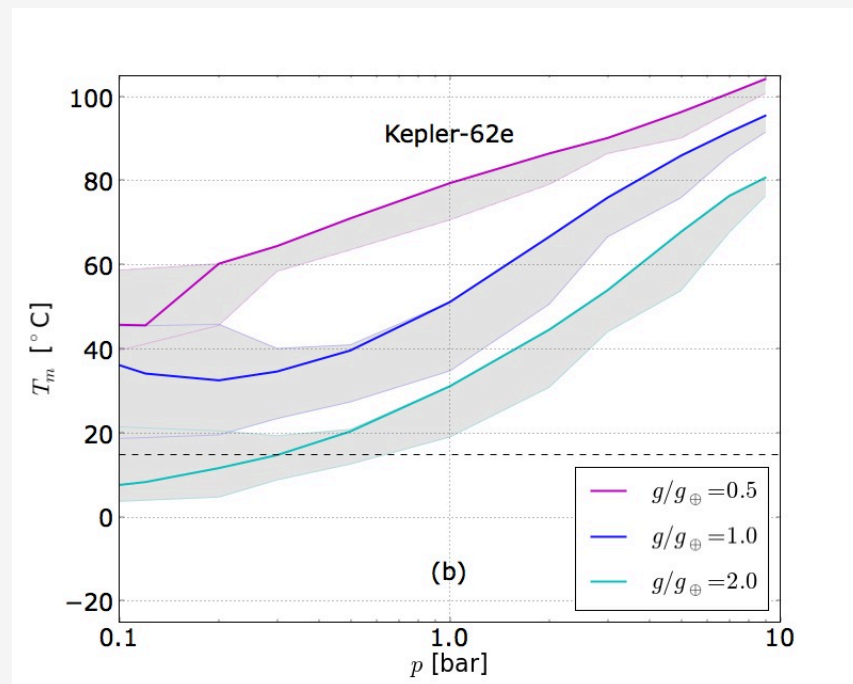
Columnar mass of the atmosphere:  $p/g$

The columnar mass affects the radiative transfer and the  
horizontal heat transport

An increase of gravity tends to cool the planet surface at a  
given value of surface pressure

The “gravity cooling” effect is particularly strong for  
planets with surface water

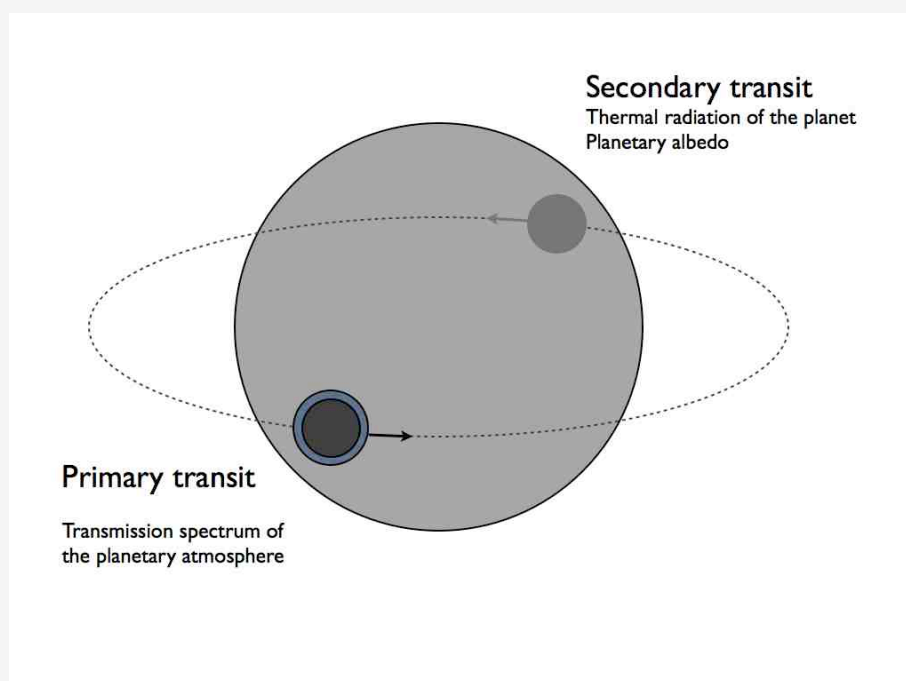
## Effects of gravity and pressure on the mean global temperature



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## Searches for biomarkers

### Observations of planetary atmospheres



## Absorption spectroscopy of planetary atmospheres

- The atmospheric absorption signal scales with the scale-height of the atmosphere,  $h$ , and the planet radius,  $R_p$
- The detection is easier in stars with smaller radii

$$\delta I \sim \frac{2 h R_p}{R_*^2}$$

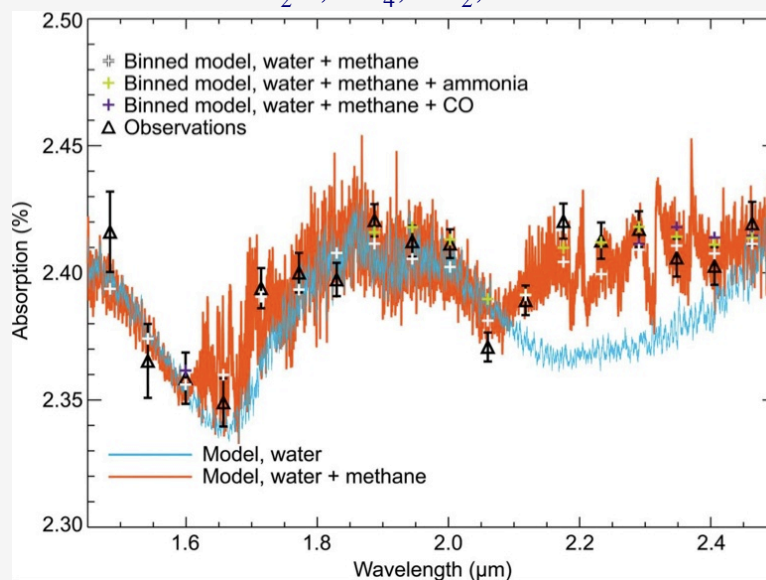
- Gaseous giants give the strongest signal; already detected
  - e.g. Tinetti et al. (2007)
- Terrestrial planet atmospheres are beyond detection limit even for the most advanced instrumental projects currently scheduled
- Atmospheres of super-Earths may be feasible with next generation instrumentation

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## Absorption spectroscopy of planetary atmospheres

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

$\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{CO}$



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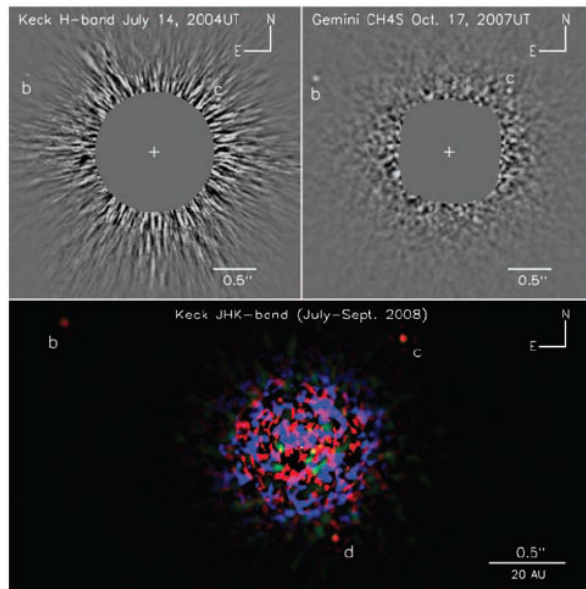
## Direct imaging studies of planetary atmospheres

Example of multiple planetary system: HR 8799bcd (Marois et al. 2008)

IR imaging of nearby, young stars

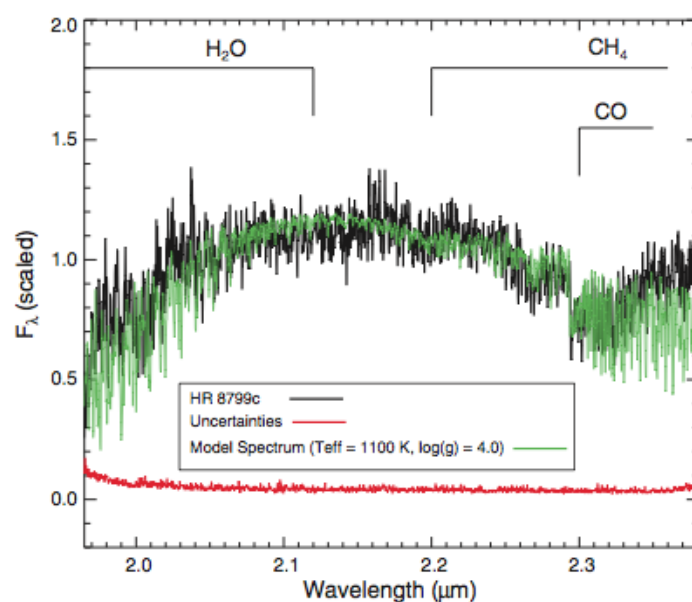
(young stars → young planets → IR emitters)

**Fig. 1.** HR 8799bcd discovery images after the light from the bright host star has been removed by ADI processing. (Upper left) A Keck image acquired in July 2004. (Upper right) Gemini discovery ADI image acquired in October 2007. Both b and c are detected at the two epochs. (Bottom) A color image of the planetary system produced by combining the J-, H-, and Ks-band images obtained at the Keck telescope in July (H) and September (J and Ks) 2008. The inner part of the H-band image has been rotated by  $1^\circ$  to compensate for the orbital motion of d between July and September. The central region is masked out in the upper images but left unmasked in the lower to clearly show the speckle noise level near d.



## Direct imaging studies of planetary atmospheres: detection of molecular absorption

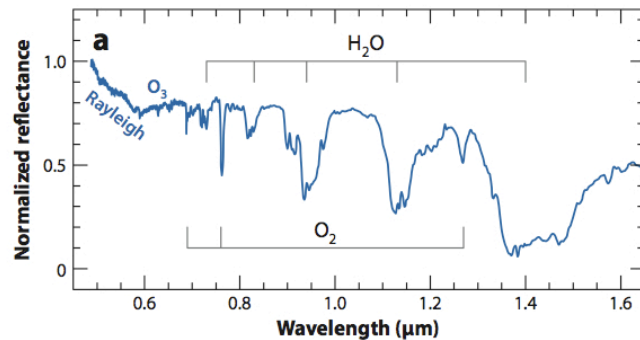
**Fig. 2.** K-band spectrum of HR 8799c (black) at the full resolution of OSIRIS ( $\lambda/\Delta\lambda \sim 4000$ ). Both lines and continuum are shown, and the spectral features most relevant to objects of this mass are highlighted. For clarity, uncertainties are shown separately in red. The best-fitting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



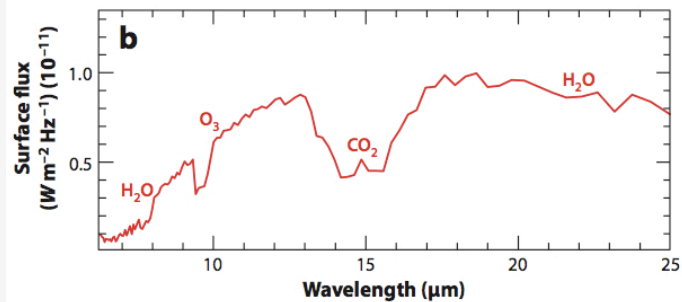
## What do we hope to detect in planetary atmospheres?

Examples: spectra of the Earth's atmosphere observed from space

Reflection spectrum  
in the visible/near IR



IR emission spectrum



## Biomarkers in the spectra of planetary atmospheres

A biomarker is a tracer of biological activity  
employed when such activity cannot be directly detected

In the context of exoplanet observations, a biomarker is a signature of  
chemical disequilibrium in the atmospheric composition,  
likely to be induced by biological activity

## Biomarkers in the spectra of planetary atmospheres

Oxygen is considered one of the most promising biomarkers

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

The history of Earth's atmospheric oxygen reveals the fundamental role of biology

