What makes a planet habitable?
How to detect planets?
Radial velocity

Doppler Shift due to Stellar Wobble

![Graph showing radial velocity data with a sine wave fit and residuals](image)
Transits

Planet moves in front of star

-> star gets dimmer

- Planet size
- Planet orbit
- Large atmosphere?
Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans?
- Rotation period
- Weather patterns
- Planetary environment:
  - Planets + dust
Coronagraphs
Spectral signatures of plants: “Red edge”
Fig. 7.—Earth’s observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 $\mu$m) and the data presented in Paper I (0.5–0.8 $\mu$m). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006
A few examples

• 51 Peg b [RV]: Hot Jupiter, first discovery (*)
• HD209458 b [RV + transit]: Hot Jupiter, 3.5 day period, 0.045 AU, 0.69 MJ, 35% larger in diameter, atmosphere blown by star (Na, H, C, O, CO2, H2O, CH4 detected), powerful storms
• Gl 581 b,c,d,e [RV]: habitable planets? Only 20 light year away, 4 planets. Gl 581 e (closest to star) is only 1.9 Earth Mass. Gl 581 b is Neptune-mass. Gl 581 c is a super-Earth (>5 Me) at the inner edge of the habitable zone, probably with a Venus-like greenhouse effect. 581 d is a super-Earth (~10 Me), potentially habitable, probably giant ocean. Stellar irradiance is slightly less than Mars, but thicker atmosphere.
• GJ1214 b [transit + RV]: 6.5 Me, 2.7 Re, 1.6 day period. Low density, large fraction of gas or water (could be an ocean planet, 75% water, 25% rock)
• Corot 7-b [transit + RV]: 1.7 Earth radius, 4.8 Earth mass, 20 hr period. Rocky planet with less iron and/or more water. Tidally locked: night side is cold, day side very hot (possibly lava).
• OGLE-2005-BLG-390L b [microlensing]: ~5.5 Me, at 2.6 AU from a red dwarf. Very cold world (like Pluto)
• HR8799 [imaging]: planetary system, 24 to 68 AU, giant planets, ~10 MJ each
• Beta Pictoris b [imaging]: young planet caught just after formation, Saturn-like orbit, 8MJ, 8 AU (*)
• Fomalhaut b [imaging]: mysterious object, too bright to be just a planet: large disk (*)
• (*): naked-eye star
HR 8799 planets imaged by Keck
Life on other planets?
When is a planet habitable?

- Too many collisions in the first few 100 Myr
- Stellar activity decreases with time -> challenge for life around young stars
- Stars get brighter with time -> HZ moves out!

We have ~400 Myr left before CO2 cycle fails to regulate Earth’s temperature

- Magnetic field is a good thing, but WILL “freeze away” with time
Water...

Mars & Venus lost their oceans

H$_2$O $\rightarrow$ Hydrogen + Oxygen

Oxygen oxydizes rocks (Mars is red),
Hydrogen escapes in space

Why not Earth ??? Right size, right spot.

$\sim$2 billion years ago Oxygen concentration went up (bacteria) $\rightarrow$ recaptures Hydrogen, stops H$_2$O loss.
Carbon cycle regulates temperature on Earth

• Production:
  Volcanos & direct emission from Earth’s crust (~0.5 Gt/yr)
  Humans burning fossil fuels (~6 Gt/yr)

• Removal (depletion in 10 000 yrs for atmosphere, 500 000 yrs for atm+oceans):
  Silicate wehathering
  Carbonate deposition
  Burial of organic matter
What kind of life?

- On Earth, bacteria got an early start and ruled Earth for the first 2 billion yrs.
- Bacteria live in many environments (extremophiles).
- Complex life started with unlikely merging of Bacteria + Archaea -> Eukaryote.
- Complex life may be rare event...
How much time needed to have complex life?

Life on Earth does not evolve at a constant pace

BIG jumps forward:

~2 Gy ago: Eukaryotes appear

560 Myr ago: Cambrian explosion
But also...

“Snowball Earth” episodes 2.3 Myr and 790 to 630 Myr ago

Several mass extinctions since Cambrian explosion

(large impact, massive volcanic eruption...)
Solar system rocky planets
Conclusions

COMPLEX life, AS WE KNOW IT requires special conditions on planet

simple life forms (bacteria / Archaea) might be much more common

BUT many many “suitable” planets in our galaxy, and many many galaxies... (Drake equation)

Within next decades, we will finally be able to probe for life on exoplanets not too different from Earth