Habitable worlds: Can we discriminate them from their atmospheric composition?

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Image credit Hanno Rein
The search for exoplanets has often been driven by the goal to discover life in the Universe...
We know today that planets are ubiquitous... 

There are at least as many planets as stars

Cassan et al, 2012; Batalha et al., 2015
Huge diversity

3700+ planets, 2700 planetary systems known in our galaxy
Most of them are small

Earth
Super-Earths
Small-Neptunes
Saturns
Jupiters

Small is trendy!
Some of them might be habitable

Potentially Habitable Exoplanets

Ranked by the Earth Similarity Index (ESI)

- [0.85] Proxima Cen b
- [0.85] TRAPPIST-1 e
- [0.84] GJ 667 C c
- [0.84] Kepler-442 b
- [0.80] GJ 667 C f
- [0.77] Kepler-1229 b
- [0.73] TRAPPIST-1 f
- [0.68] LHS 1140 b
- [0.68] Kaptflyn b
- [0.67] Kepler-62 f
- [0.61] Kepler-186 f
- [0.60] GJ 667 C e
- [0.60] TRAPPIST-1 g

Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI measures similarity to Earth size and insolation. Planet candidates indicated with asterisks.

K2-18B: 'SUPER-EARTH' THAT COULD HOST ALIEN LIFE IS DISCOVERED

06/12/2017, 16:49 | K2-18b: 'Super-Earth' that could host alien life is discovered | The Independent

It also has a neighbour...

DAVE MACLEAN IN NEW YORK
Wednesday 6 December 2017 10:18 GMT

A little-known planet 111 light years away could be a 'scaled-up version of Earth' which is able to host alien life, according to new research.

The distant exoplanet is known as K2-18b and has been described as being a potential 'Super-Earth' - a large rocky planet with the potential to support life.

It orbits within its star's habitable zone, which means there's a chance it could hold liquid water on its surface, which is a key component for the possibility of life as we know it.
Planet atmosphere

Formation
Impacts
Clouds
Star radiation
Escape
Volcanoes
Life
Habitable planets?

Transiting temperate super-Earths orbiting cool stars best chance to study habitable planets in a foreseeable future.
Worlds around cool stars

Can live survive to flares, effects of tidal-locking, red-shifted photons from star?

Anglada Escudé et al, 2016; Gillon et al., 2017;
Image Credit: ESO/M. Kommesser
Habitable planets?

Figure 2. Simulated JWST observations of the TRAPPIST-1 planets, assuming 30, 60 and 90 transits are observed. Fits to the synthetic observations are shown for each case in blue (coldest equilibrium temperature) and red (hottest equilibrium temperature). For TRAPPIST 1b, at least 60 transits would be required with each instrument for O3 to be detected, but for 1c and 1d, 30 is sufficient.

From Barstow et al. (2015, 2016). The photon noise is calculated using the following equation:

\[ n_\lambda = \frac{I_\lambda \pi (r_\star / D_\star)^2 (\lambda / hc)(\lambda / R) A_{\text{eff}} Q \eta t}{(1)} \]

where \( n_\lambda \) is the number of photons received for a given wavelength \( \lambda \), \( I_\lambda \) is the spectral radiance of the stellar signal, \( r_\star \) is the stellar radius, \( D_\star \) is the distance to the star, \( h \) and \( c \) are the Planck constant and speed of light, \( R \) is the spectral resolving power, \( A_{\text{eff}} \) is the telescope effective area, \( Q \) is the detector quantum efficiency, \( \eta \) is the throughput and \( t \) is the exposure time. The effective exposure time is taken to be the transit duration from Table 1, assuming an 80 per cent duty cycle, and therefore planets with shorter transit durations will have noisier spectra. Values for all instrument parameters are identical to those used by Barstow et al. (2015, 2016), and system specific values are as discussed elsewhere in this work.

Noise added to the synthetic spectra is random and white – no correlated noise is included. To calculate the noise on the stellar radiance \( I_\lambda \), we take the square root of the number of photons and then invert the above equation. The noise on the transit depth is given by \( \sqrt{2 \times \sigma_{I_\lambda} / I_\lambda} \).

RESULTS

We present simulated spectra assuming 30, 60 and 90 transits of each instrument (NIRSpec and MIRI), with spectral fits from retrievals based on the extreme equilibrium temperatures for each planet (coldest blue, hottest red; Fig. 2). Retrieved properties are the O3 volume mixing ratio (VMR), planetary radius at the solid surface (90 bar pressure level), and H2O and CO2 VMRs. The H2O and CO2 VMRs do not deviate far from the prior and we conclude that the retrieval is relatively insensitive to these properties. We present the retrieval results for radius offset and O3 VMR in Fig. 3. Here, the radius offset quoted is at 1 bar to facilitate easy comparison with the true value. The retrieved radius compensates for temperature deviations from the true value, as it is smaller for the higher temperature retrievals and larger for the lower temperature ones. As well as just increasing the size of the planet, increasing the radius also increases the scaleheight as the gravity is slightly reduced.

The a priori abundance of O3 is set to be \( 10^{-8} \times \) the present-day Earth value. This value is low enough such that no O3 features are visible at all in the spectrum. We then retrieve a scaling factor on the present-day Earth profile starting from this prior assumption. Our results show that O3, if present in quantities similar to present-day Earth, would be detectable on all TRAPPIST-1 planets if at least 60 transits are obtained with both NIRSpec and MIRI.

TRAPPIST-1d is the most likely of the three planets to be Earth-like. O3 can be detected for 30 transits each of NIRSpec and MIRI, regardless of the temperature profile used in the retrieval. CO2 features can also be seen at shorter wavelengths, with the 4.3 \( \mu m \)
James Lovelock

« The history of a planet can not be disentangled from the evolution of the organisms living on that planet »

Biosignature

« The presence of chemically based life on a planet would change the composition of its atmosphere away from the abiological steady state. The change would be recognizable even at astronomical distances. »

Chemical disequilibrium: is it a robust biosignature?

Below 1500K atmospheres are likely to be in disequilibrium!

Venot et al., 2015
ARIEL
A chemical census of exoplanet atmospheres
ARIEL – key facts

- 1-m telescope, spectroscopy from VIS to IR
- Satellite in orbit around L2
- Chemical census of ~1000 exoplanets (rocky + gaseous), primarily warm & hot
- Simultaneous coverage 0.5-7.8 micron
- Payload consortium: 11 ESA countries
INSTANT & SHORT-TERM VARIABILITY: 55 CNC e

(NON)-EQUILIBRIUM CHEMISTRY? ATMOSPHERIC CIRCULATION? CLOUD PATTERN?

ARIEL phase-curve spectra, chemical composition & thermal profile

Planet orbiting around the star
CHEMICAL DIVERSITY

CORRELATION WITH ANY OTHER KEY PARAMETERS?

Is this plot true? Where are the transitions?

Forget & Leconte, 2013
IS ELEMENTAL COMPOSITION CORRELATED …

…TO EXOPLANET PROVENANCE OR STELLAR METALLICITY?

C/O retrieved from ARIEL observations
Some thoughts to conclude

- The search for exoplanets has been driven by the goal to discover life in the Universe.
- We know today there are billions of worlds out there, and small planets are the most numerous... so there is hope!
- Basic planetary and orbital parameters suggest the Solar System is not the paradigm of planetary system in the galaxy.
- Our definition of biosignature did not change from the seventies.
- Although Lovelock’s recipe to search for chemical disequilibrium as sign of life is still valid, there are issues.
- The chemistry of planets colder than 1500 K is expected to be increasingly driven by disequilibrium processes, are we able to recognize life?
Some thoughts to conclude

Recipe for the next decade:

- Complete a chemical census of NON-habitable planets probing the parameter space of planet temperature, mass, stellar metallicity, stellar type (ARIEL mission)

- Use the opportunity to observe planets in the habitable zone of cool stars (JWST)

- Is Lovelock’s recipe of biosignature still useful?

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