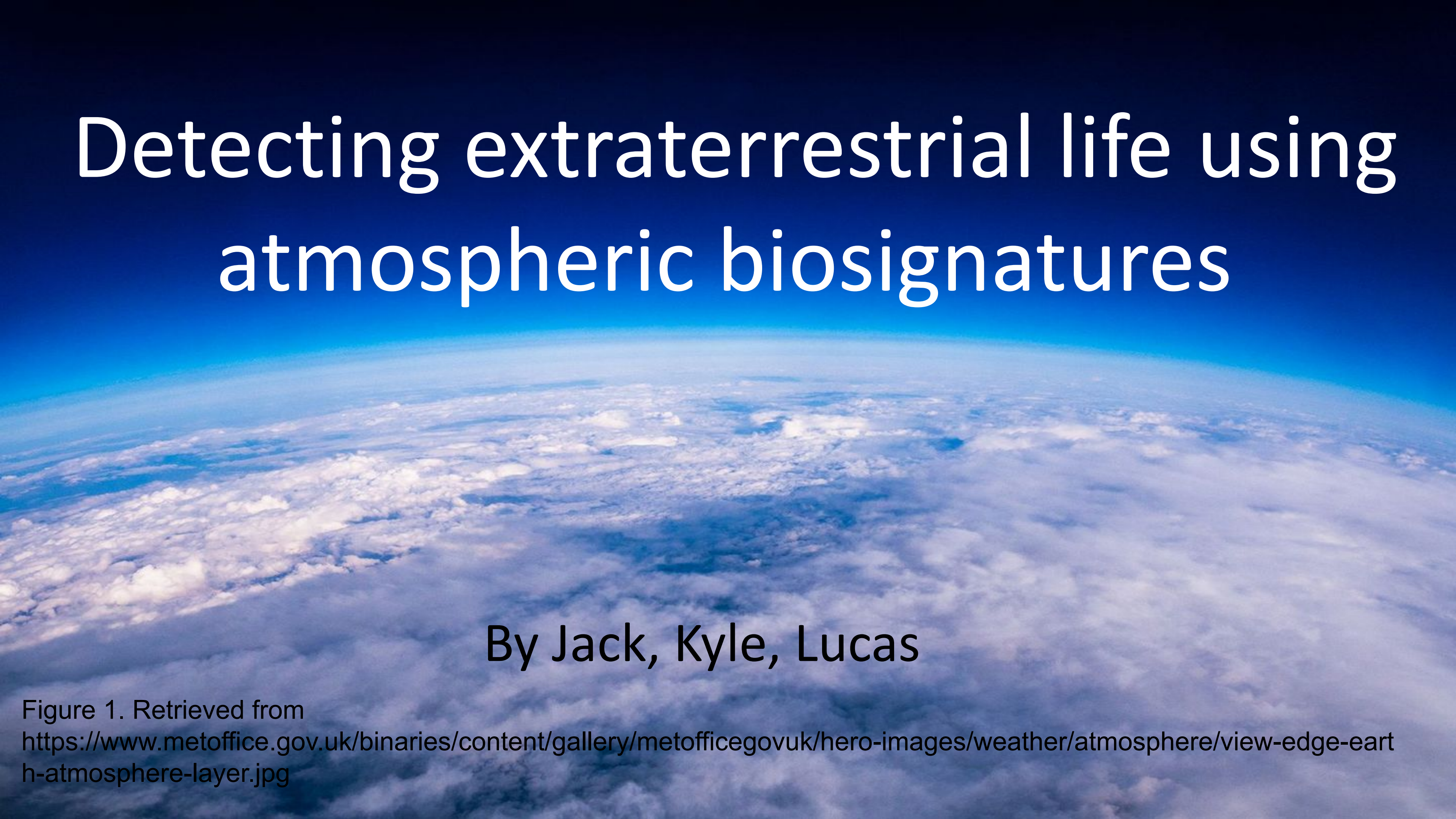
Detecting extraterrestrial life using atmospheric biosignatures



By Jack, Kyle, Lucas

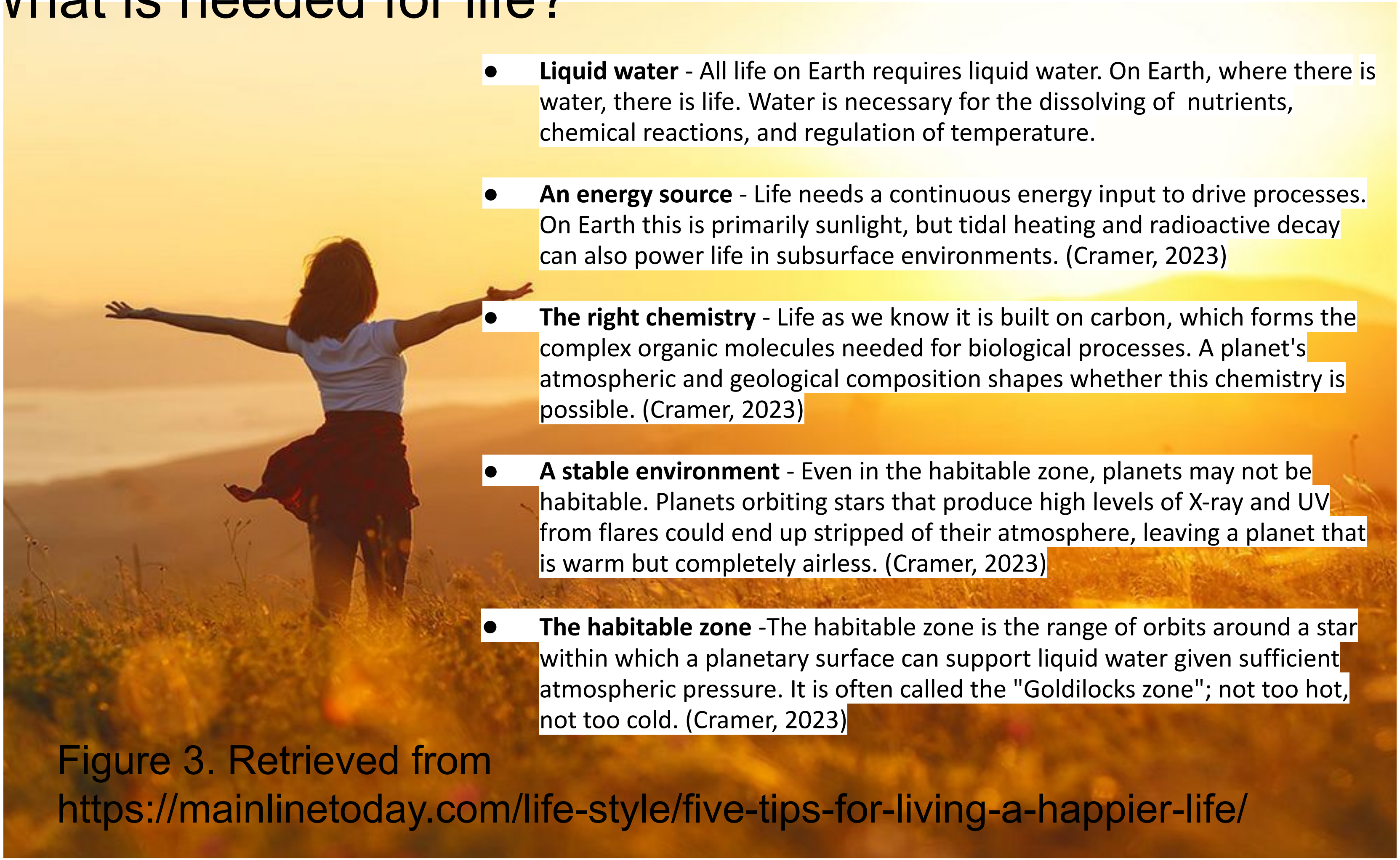
Figure 1. Retrieved from https://www.metoffice.gov.uk/binaries/content/gallery/metofficegovuk/hero-images/weather/atmosphere/view-edge-earth-atmosphere-layer.jpg

Overview

- What is required for life to exist?
- What are Atmospheric Biosignatures?
- How are we able to observe them
  -Techniques used
  -Satellites/ Technology used
- Which planets have shown the most promise?
- What comes next/holistic view on the topic
  -Complementary techniques used in addition to biochemistry

Figure 2. Retrieved from https://hycean.group.cam.ac.uk/wp-content/uploads/2025/04/biosignatures-banner.png

What is needed for life?



- **Liquid water** - All life on Earth requires liquid water. On Earth, where there is water, there is life. Water is necessary for the dissolving of nutrients, chemical reactions, and regulation of temperature.

- **An energy source** - Life needs a continuous energy input to drive processes. On Earth this is primarily sunlight, but tidal heating and radioactive decay can also power life in subsurface environments. (Cramer, 2023)

- **The right chemistry** - Life as we know it is built on carbon, which forms the complex organic molecules needed for biological processes. A planet's atmospheric and geological composition shapes whether this chemistry is possible. (Cramer, 2023)

- **A stable environment** - Even in the habitable zone, planets may not be habitable. Planets orbiting stars that produce high levels of X-ray and UV from flares could end up stripped of their atmosphere, leaving a planet that is warm but completely airless. (Cramer, 2023)

- **The habitable zone** -The habitable zone is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure. It is often called the "Goldilocks zone"; not too hot, not too cold. (Cramer, 2023)

Figure 3. Retrieved from https://mainlinetoday.com/life-style/five-tips-for-living-a-happier-life/

What is a Biosignature?

- A biosignature is any measurable property that provides scientific evidence of past or present life.

  -It is piece of evidence that says life probably occurred here

- Atmospheric biosignatures are gases or combinations of gases in a planet's atmosphere that are produced by living organisms and accumulate to detectable levels. (Schwieterman, et al. 2018)

- Over billions of years, the processes of life on a planet would result in a mixture of chemicals unlike anything that could form in ordinary chemical equilibrium. (Lemonick, 2025)

- The key challenge: distinguishing a true biological signal from an abiotic (non-living) one.

Key Biosignature Gases: Oxygen (O2) and Ozone (O3)

- Oxygen makes up 20% of Earth's atmosphere - it is sustained by oxygenic photosynthesis. (Seager et al., 2025)
- An extraterrestrial civilization with advanced telescopic technology observing Earth could interpret O2's high concentration as a strong indicator of life.
- Oxygen alone is not a definitive biosignature
- Oxygen can be created abiotically via the dissociation of Sulfur Dioxide (SO2), photolysis of Carbon Dioxide (CO2), and a reaction of water with silicate minerals (Meadows et al., 2018)
- Ozone (O3) acts as a proxy for oxygen and has strong spectral features that make it easier to detect remotely.

Figure 4. Retrieved from https://media.tenor.com/sU0FFiB6XTcAAAAM/pepper-plant-growing.gif

$$S + O_2 \rightarrow SO_2$$

Figure 5. Retrieved from https://i.ytimg.com/vi/bY9EClvwG1w/hq720.jpg?sqp=-oaymwEhCK4FEIIDSFryq4qpAxMIARUAAAAAGAElAADIQj0AgKJD&rs=AOn4CLCqe5IHl2cHmhyJzB3CXM27N_dYOg

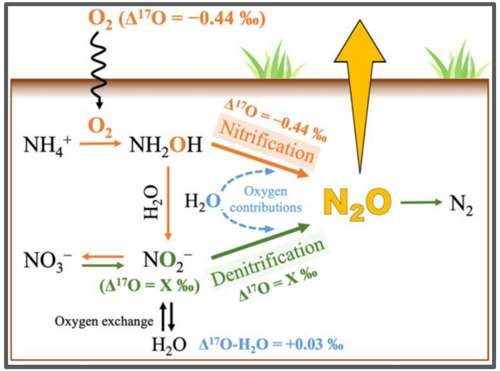
Key Biosignature Gases: Methane, Nitrous Oxide, and DMS

- Biosignatures such as methane (CH4), nitrous oxide (N2O), and chloromethane (CH3Cl) are easier to identify under low UV conditions

  -Exoplanets orbiting cooler stars or Exoplanets with atmospheric shielding may show clearer anomalies with the above molecules rather than O2 or O3 (Cowing, 2025)

- On Earth, dimethyl sulfide (DMS) and dimethyl disulfide (DMDS) are only produced by microbial life, typically marine phytoplankton.

  -Its short atmospheric lifespan makes it a strong biosignature, if detected on another planet, something alive would have to be producing it continuously. (Lemonick, 2025)



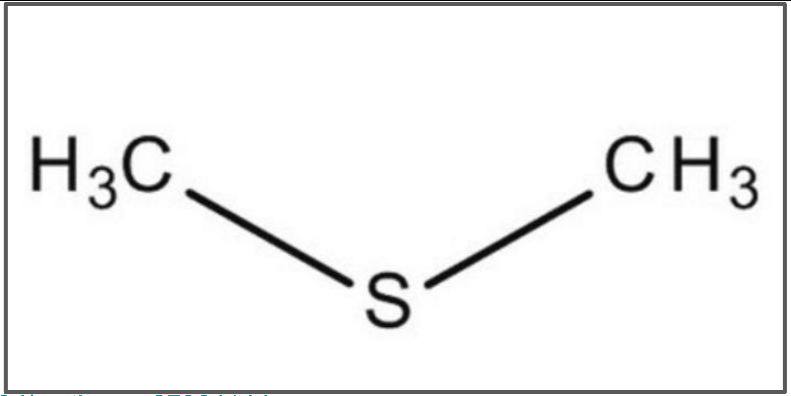


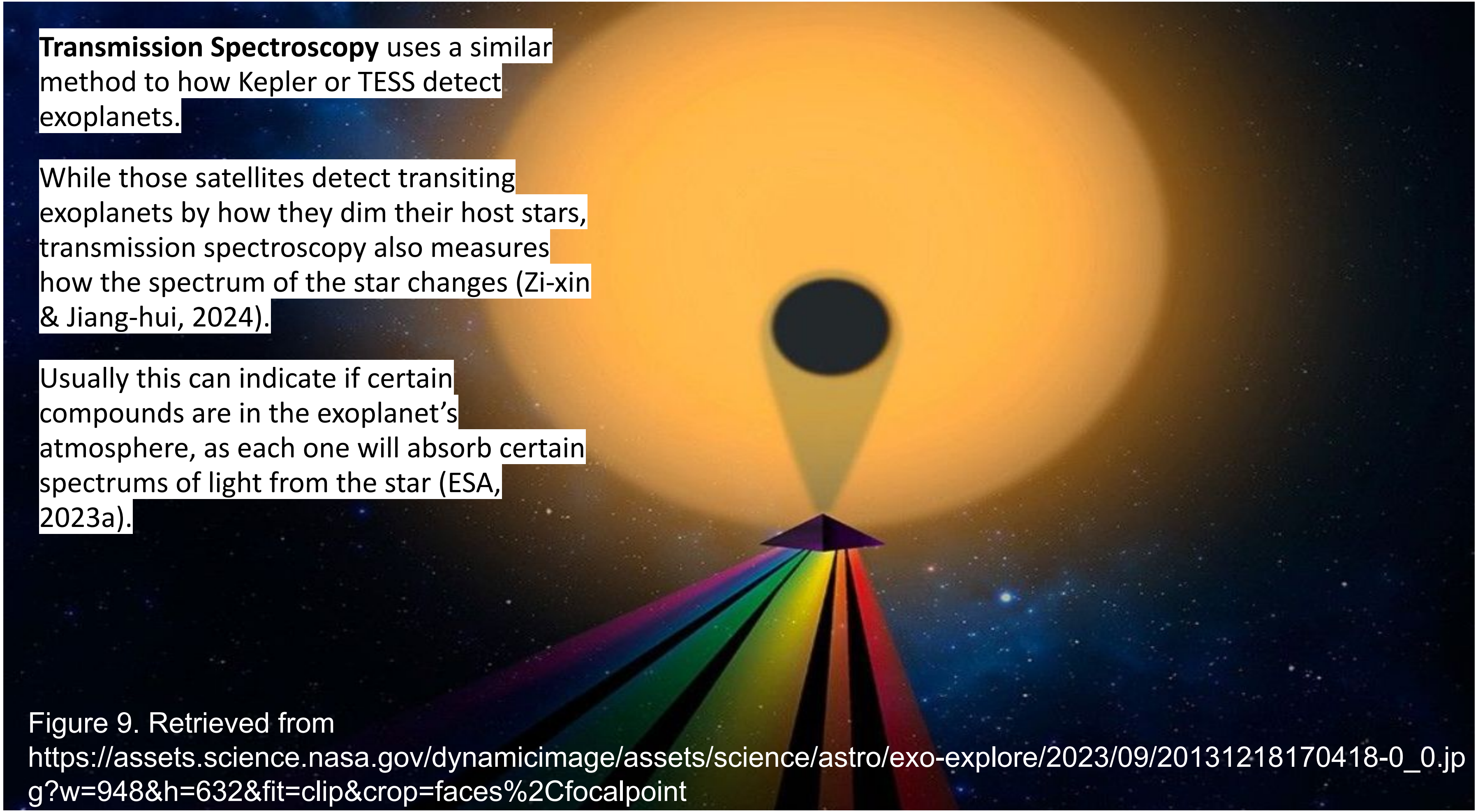
Figure 6. Retrieved from https://i.natgeofe.com/n/8feba573-7c65-44c3-97cd-c1660331286d/methane_2736414.jpg
Figure 7. Retrieved from https://bg.copernicus.org/articles/22/4333/2025/bg-22-4333-2025-avatar-web.png
Figure 8. Retrieved from https://structuresearch.merck-chemicals.com/cgi-bin/getStructureImage.pl?owner=MDA&unit=CHEM&product=820833

What techniques are used to “see” Biosignatures

- To see atmospheric biosignatures around exoplanets, spectroscopy is used, which is when light passing through an exoplanets atmosphere is analyzed to see what portion of the spectrum is missing. This helps indicate what compounds are present (NASA, 2024b).

- Every molecule has a unique spectral emission or absorption, which can be used to identify the compounds present in the atmosphere.

- If the exoplanet passes in front of its sun, methods like transmission spectroscopy or eclipse spectroscopy are usable, otherwise more versatile methods like phase curves or high contrast imaging have to be used (Fujii et al., 2018).



Transmission Spectroscopy uses a similar method to how Kepler or TESS detect exoplanets.

While those satellites detect transiting exoplanets by how they dim their host stars, transmission spectroscopy also measures how the spectrum of the star changes (Zi-xin & Jiang-hui, 2024).

Usually this can indicate if certain compounds are in the exoplanet's atmosphere, as each one will absorb certain spectrums of light from the star (ESA, 2023a).

Figure 9. Retrieved from https://assets.science.nasa.gov/dynamicimage/assets/science/astro/exo-explore/2023/09/20131218170418-0_0.jpg?w=948&h=632&fit=clip&crop=faces%2Cfocalpoint

Eclipse Spectroscopy, Phase Curves

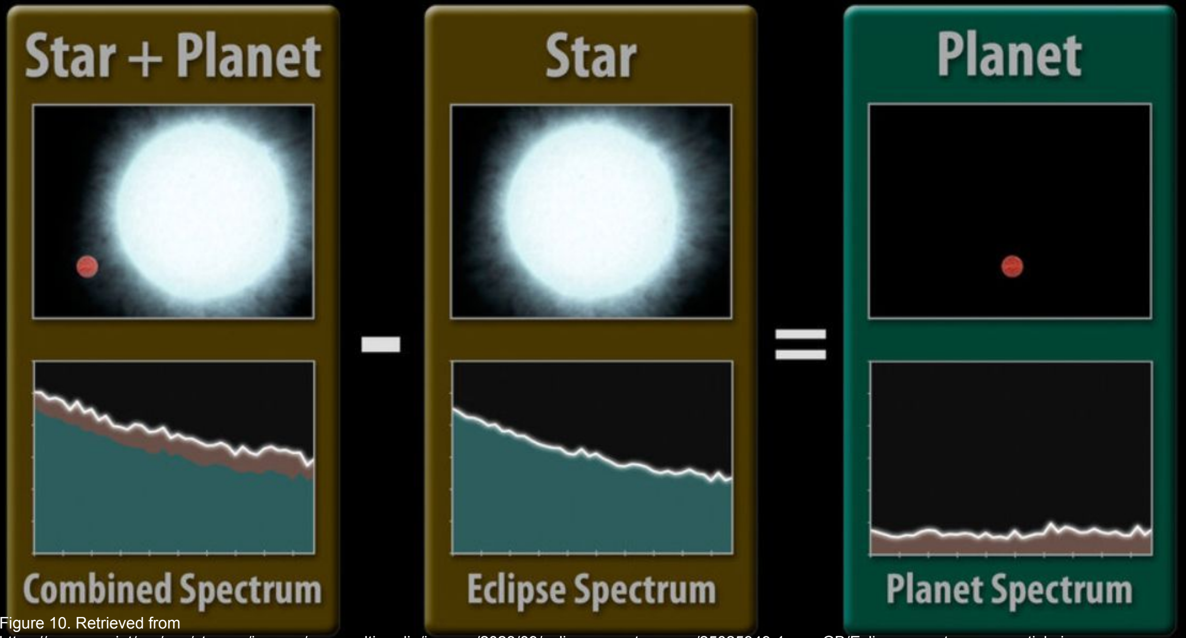


Figure 10. Retrieved from https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2023/09/eclipse_spectroscopy/25025949-1-eng-GB/Eclipse_spectroscopy_article.jpg

- Eclipse Spectroscopy works by comparing the light received from a star while an exoplanet is transiting in front of it, with the light received when the exoplanet is completely obscured by the star (ESA, 2023b).
- This allows for the spectrum of the star to be subtracted from the combined spectrum of the star and the exoplanet, to get the spectrum of just the exoplanet (ESA, 2023b).

- Phase curves work by studying the light reflected by an exoplanet during different phases of its orbit. This can allow for spectroscopy of an exoplanet even if it does not transit in front of its star, but not as effectively (ESA, 2019).
- However, it is best used to track how heat is distributed in an atmosphere, and is a weaker option for spectroscopy overall.(Fujii et al., 2018)

High Contrast Imaging(HCI) / Direct Imaging

Direct Imaging involves directly imaging an exoplanet. Usually this requires blocking the light of the exoplanet’s host star, as otherwise the glare would blind the telescope.(Fujii et al., 2018)

The two possible approaches for blocking a star’s light are coronagraphs and starshades.

Coronagraphs are directly attached to a space telescope, while starshades are separate objects that can be tens of thousands of kilometers away from the telescope, and are maneuvered around to block specific stars.(Fujii et al., 2018)

Direct imaging is capable of doing spectroscopy on exoplanets that do not transit in front of their host star.(Fujii et al., 2018)

It can also be augmented with Doppler Spectroscopy, which uses the redshifting and blueshifting of the planet as it orbits to help distinguish it from background noise (Zi-xin & Jiang-hui, 2024).

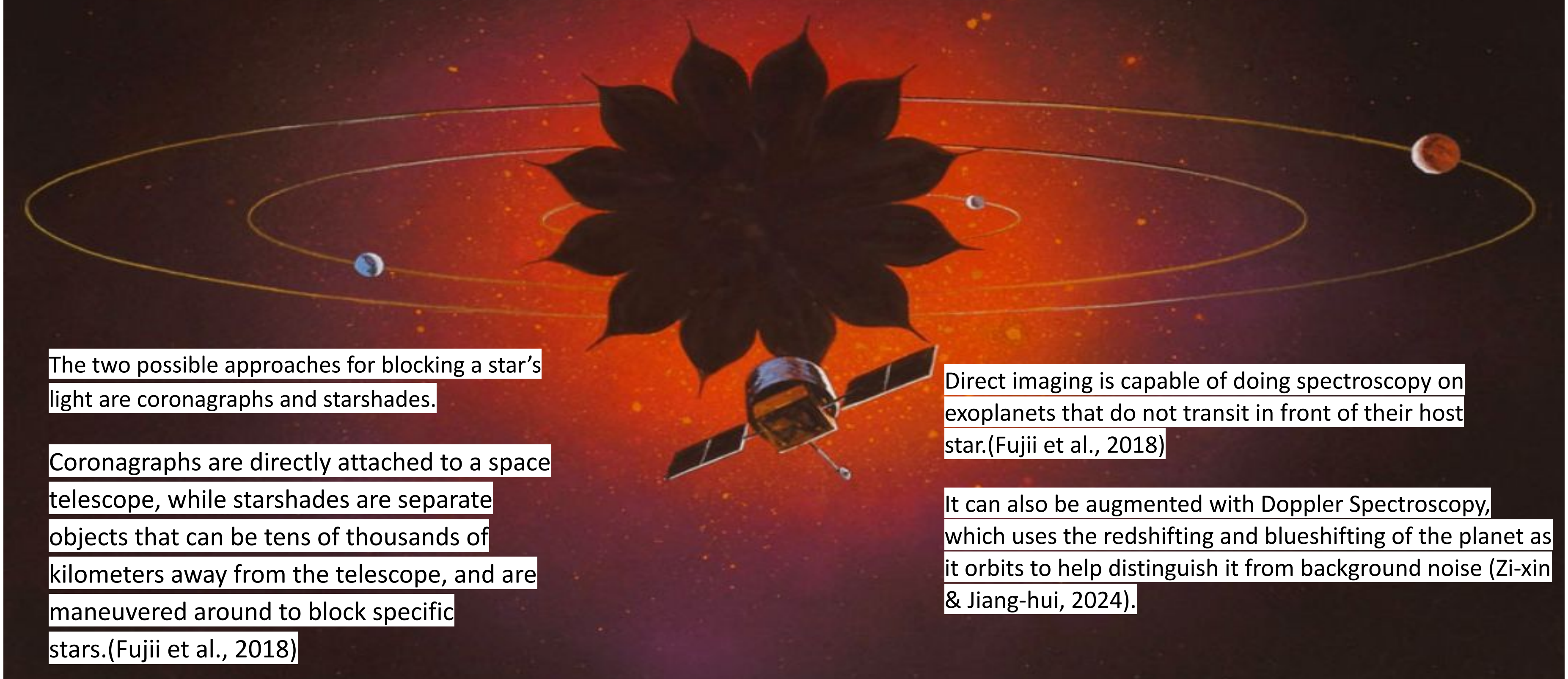


Figure 11.Retrieved from https://microdevices.jpl.nasa.gov/capabilities/optical-components/starshade/images/hero-starshade-concept-b.jpg

What can we currently detect?

- Currently, the James Webb Space Telescope (JWST) is our best tool for researching the atmospheres of exoplanets.
- It is unable to do spectroscopy on earth-like planets around stars similar to ours, but it can on earth-like planets around M class dwarf stars (Zi-xin & Jiang-hui, 2024).
- It can do spectroscopy on Sub-Neptunes in general.
- Better satellites are needed.

Figure 12. Retrieved from https://www.newscientist.com/definition/james-webb-space-telescope-jwst/

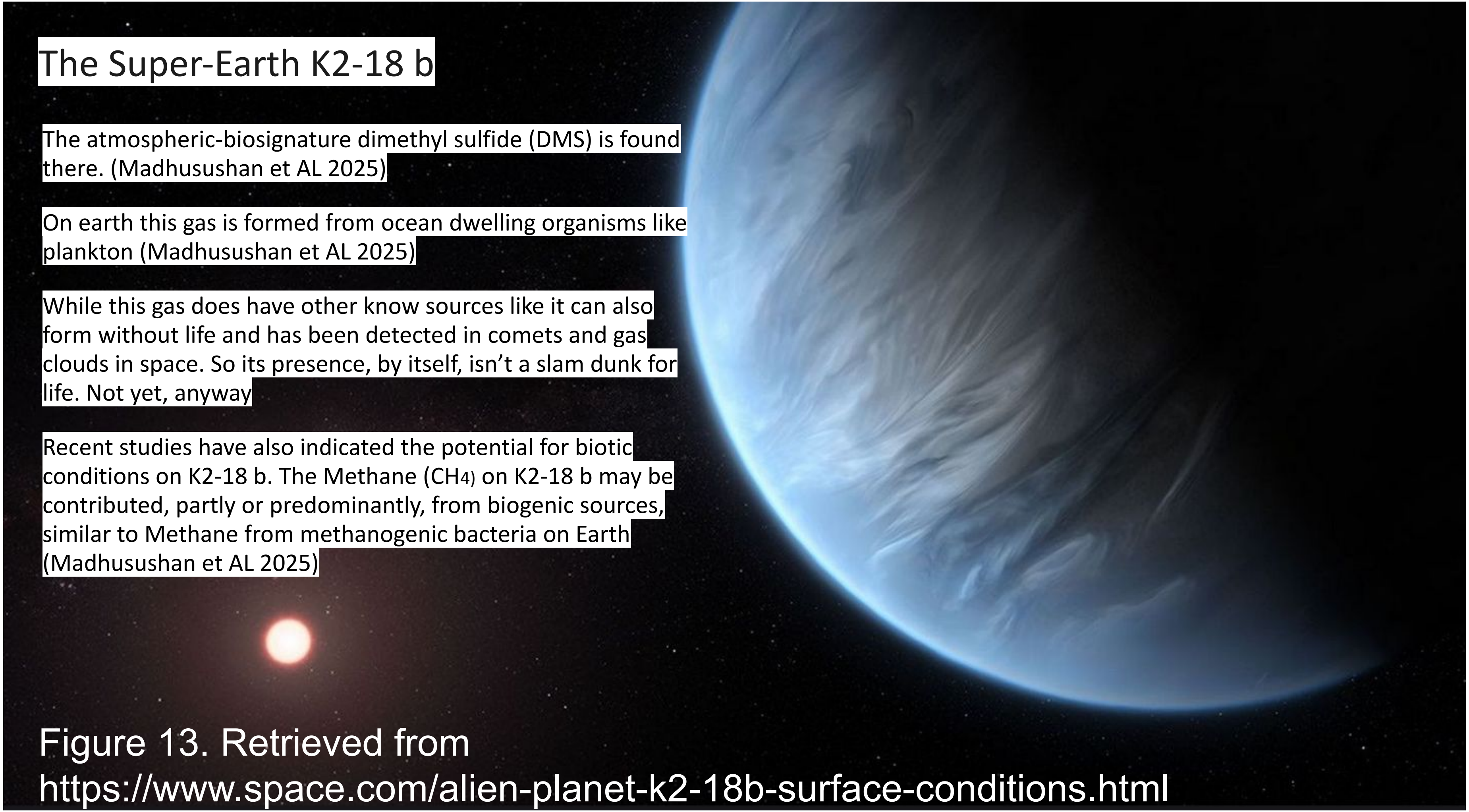
Future missions

Several missions are planned which will enhance our ability to see atmospheric biosignatures:

- Roman: Will do Direct Imaging using the first high contrast coronagraph in space (Zi-xin & Jiang-hui, 2024), will have a field of view 100 times the power of Hubble, and will launch by 2027 (NASA, 2026a).
- Habitable Worlds Observatory: Will do Direct Imaging, and is the next telescope NASA plans to launch after Roman (NASA, 2026b).
- Plato: An ESA telescope scheduled to launch in 2026(ESA, n.d.-a). Will use 26 cameras to help filter out noise (ESA, n.d.-b).
- Ariel: An ESA telescope scheduled to launch in 2031 (ESA, n.d.-c). Will do transit and eclipse spectroscopy, and phase curves, but not direct imaging (ESA, n.d.-d).
- ELTs(GMT, E-ELT/ELT, TMT): A class of telescopes under construction called Extremely Large Telescopes include the Grand Magellan Telescope, the Extremely Large Telescope, and the Thirty Meter Telescope (Fujii et al., 2018).

What are some Promising planets

- The search for life on far exoplanets is in its infancy
- The JWST is one of our best tools at detecting atmospheric biosignatures, but it was not built for this purpose
- As of now, our most promising prospects include: Super Earth K2-18b, LHS 1140b, and Proxima Centauri b



The Super-Earth K2-18 b

The atmospheric-biosignature dimethyl sulfide (DMS) is found there. (Madhusushan et AL 2025)

On earth this gas is formed from ocean dwelling organisms like plankton (Madhusushan et AL 2025)

While this gas does have other know sources like it can also form without life and has been detected in comets and gas clouds in space. So its presence, by itself, isn’t a slam dunk for life. Not yet, anyway

Recent studies have also indicated the potential for biotic conditions on K2-18 b. The Methane (CH_4) on K2-18 b may be contributed, partly or predominantly, from biogenic sources, similar to Methane from methanogenic bacteria on Earth (Madhusushan et AL 2025)

Figure 13. Retrieved from https://www.space.com/alien-planet-k2-18b-surface-conditions.html

LHS 1140b

- LHS 1140b orbits a quiet red dwarf 48 light-years away and is widely regarded as one of the most promising habitable-zone candidates currently known.
- At 1.73 times Earth's radius, estimates suggest that 10 to 20% of its mass may be composed of water (Cadieux et AL, 2024)
- Studies on the planet have shown it to have a “high mean molecular weight atmosphere”, possibly composed of Nitrogen, water vapour and, Carbon Dioxide (Cadieux et AL, 2024)
- Models predict it to have a 20 degrees celsius surface temperature

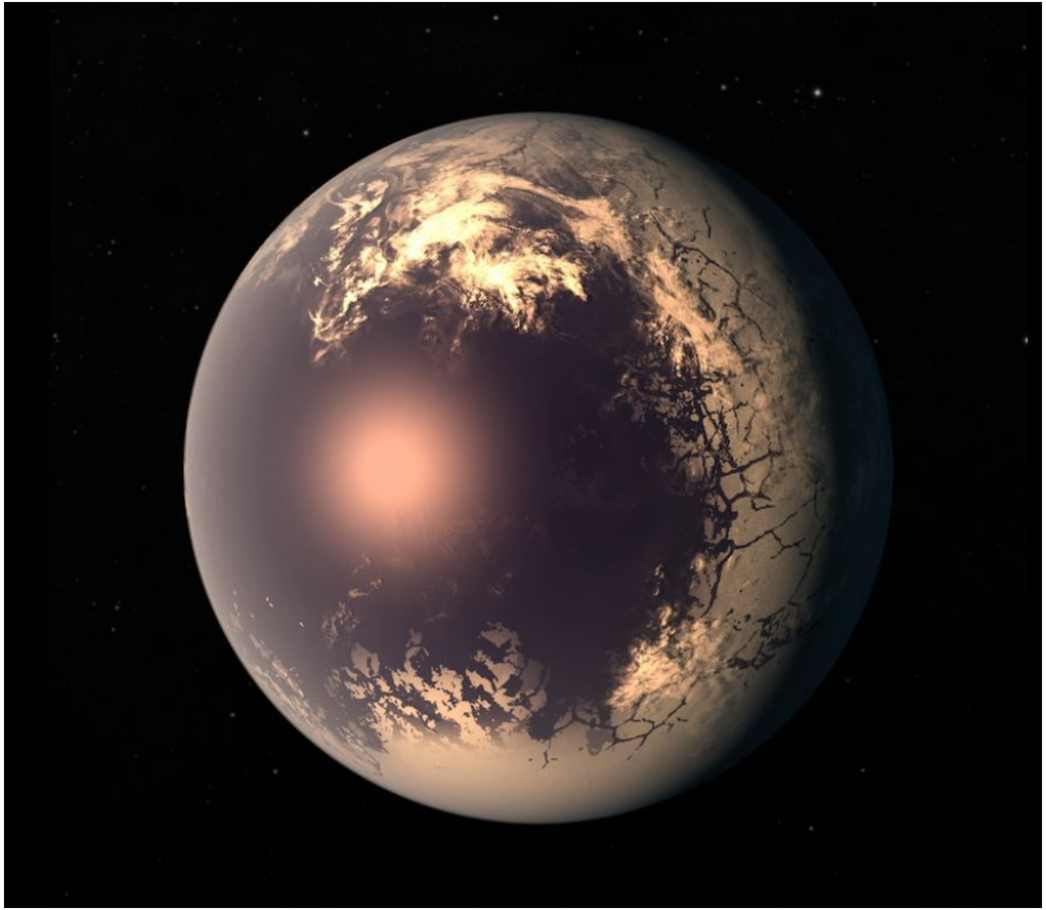


Figure 14. Retrieved from https://earthsky.org/upl/2024/07/TRAPPIST-1-f-exoplanet-eyeball-planet-artist-concept-February-22-2017.png

Proxima Centauri b

- Proxima Centauri b is the nearest known exoplanet to Earth, orbiting in the habitable zone of our closest stellar neighbor at just 4.2 light-years away (NASA,2024).

- Transmission Spectroscopy is not possible as it does not transit its star (Cowing, 2019).

- Much is still uncertain about this star, but it is a great candidate for more research

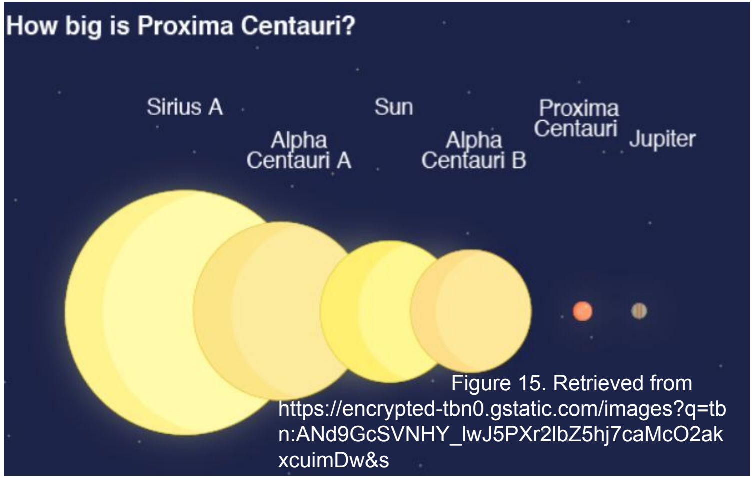


Figure 15. Retrieved from https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSVNHY_lwJ5PXr2lbZ5hj7caMcO2akxcuimDw&s

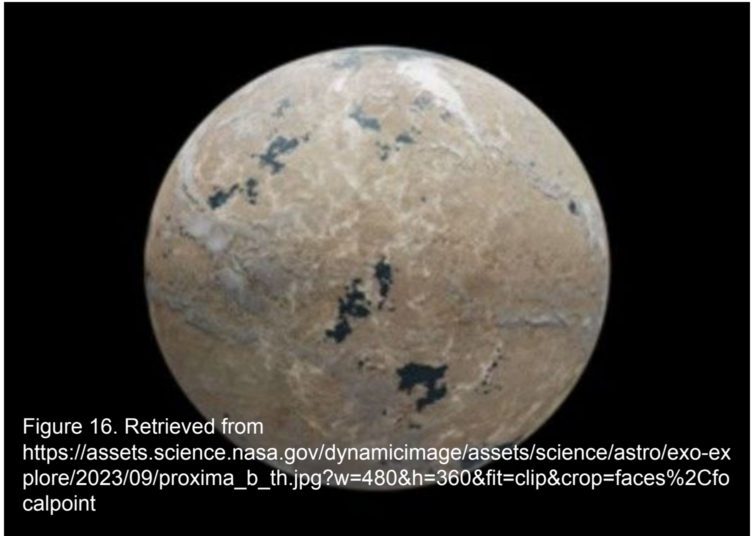


Figure 16. Retrieved from https://assets.science.nasa.gov/dynamicimage/assets/science/astro/exo-explore/2023/09/proxima_b_th.jpg?w=480&h=360&fit=clip&crop=faces%2Cfocalpoint

Difficulty detecting these signatures

- Spectroscopy and other techniques only work for certain planets. James Web spectroscopy won’t work for earth sized planets around stars similar to our sun (Seager et AL 2025)

- Hosts stars radiation can influence results

- M dwarf stars are the only temperate systems James web can observe but they present unique challenges.

  -Their stellar magnetic activity, higher than for Solar-type stars, manifests as star spots, faculae, and flares that contaminate the spectra .

  -Star spots can mimic transit transmission spectra by the star’s heterogeneity. In the case of Trappist-1, the measured star contamination dominates the signal (Seager, et AL 2025).

- Any exoplanet can host a moon that contaminates the planetary spectrum. In general, we will be unable to exclude the existence of a moon (Rein et AL 2014).

Problems with atmospheric biosignatures

- Most measurements contain intrinsic uncertainty
- There are various ways many of the atmospheric biosignatures can be created abiotically
- Interference and contamination from host stars, moons, and intergalactic dust can influence readings
- Human error
- It is difficult to detect biosignatures at this time, the technology has just been implemented and we will quickly get better

Conclusion

- We can use spectroscopy and other techniques to analyze the contents of a planet's atmosphere
- The search for life on other planets has just begun, multiple missions are planned to begin soon, aimed specifically at finding life.
- We have numerous candidates for exoplanets with life on them, more research needs to be done