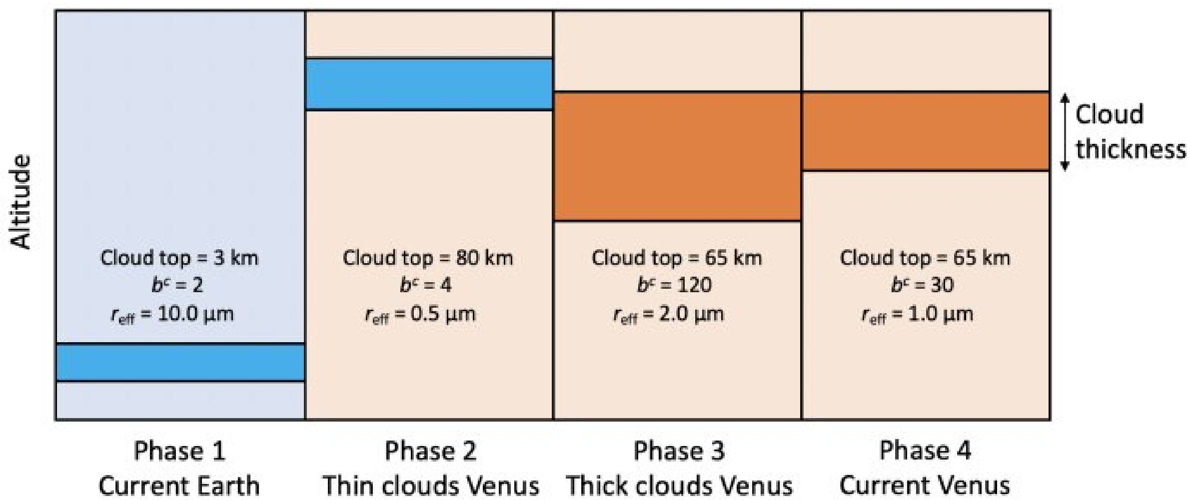
How can we know if we're looking at habitable exo-Earths or hellish exo-Venuses?

February 3 2023, by Evan Gough



This figure from the study shows four evolutionary phases of the model planets. reff is the radius of the atmospheric particles, and bc is the optical thickness of the clouds. In Phases 1 and 2, the clouds consist of liquid water droplets, and in Phases 3 and 4, of liquid sulfuric acid solution droplets. Credit: Mahapatra et al. 2023.

The differences between Earth and Venus are obvious to us. One is radiant with life and adorned with glittering seas, and the other is a scorching, glowering hellhole, its volcanic surface shrouded by thick clouds and visible only with radar. But the difference wasn't always clear. In fact, we used to call Venus Earth's sister planet.

Can astronomers tell exo-Earths and exo-Venuses apart from a great distance?

There are lots of terrestrial planets in the habitable zones of distant suns. Sometimes they're described as "Earth-like" just for being rocky and at the right distance from the star. But with scant information on their atmospheres and climates and with almost no information on other things like plate tectonics, can they really be accurately described as Earth-like? Could they just as easily be super-heated exo-Venuses?

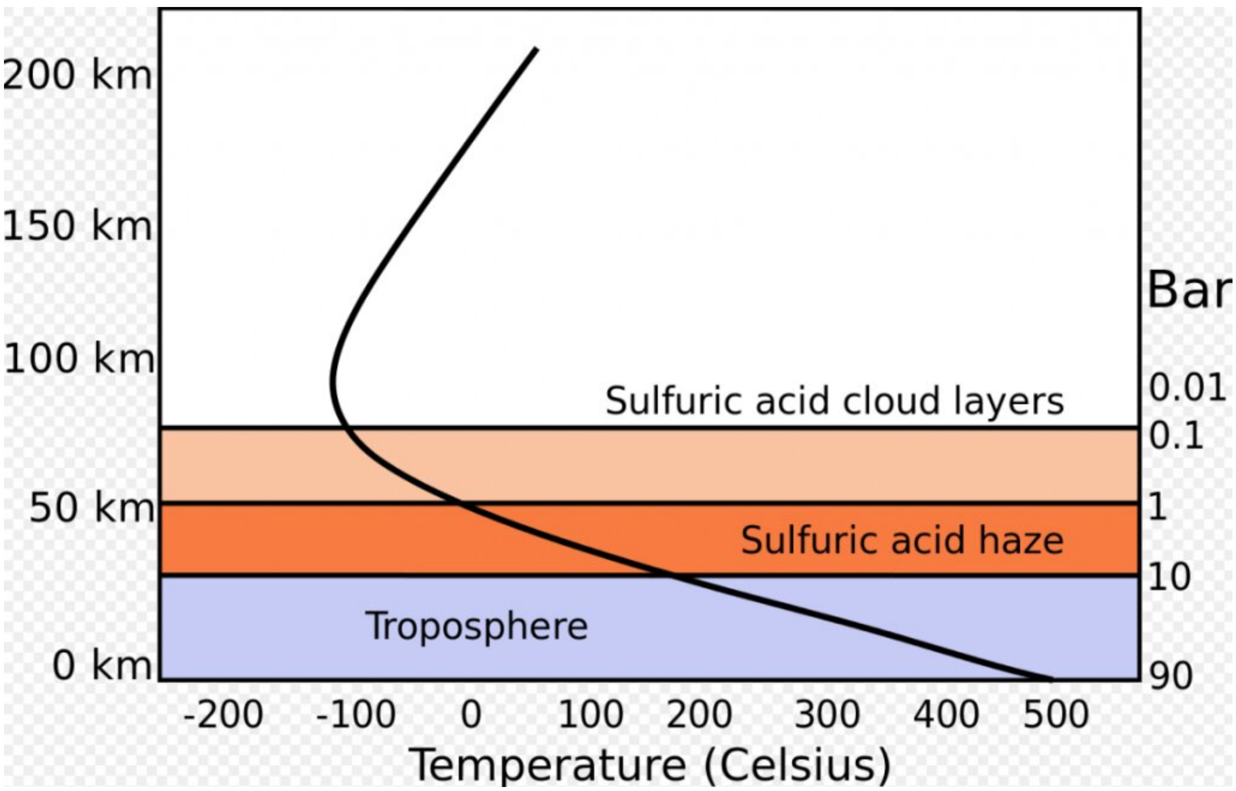
Polarimetry could help us determine which exoplanets are more like Earth and which are more like Venus.

Polarimetry is the measurement of polarized light that's been affected by material that it passes through, reflects off, or is refracted or diffracted by. Polarimetry is also the interpretation of the measurements. A new paper models the polarization of starlight that is reflected by different types of exoplanet atmospheres based on the evolution of Venus' atmosphere since its formation. The authors wanted to know if polarimetry could distinguish between Earth-like exoplanets and Venus-like exoplanets.

The paper "From exo-Earths to exo-Venuses—Flux and Polarization Signatures of Reflected Light" is published on the *arXiv* preprint server. The lead author is Gourav Mahapatra, an Atmospheric Physicist at the Netherlands Institute for Space Research.

Comparisons between Venus and Earth are instructive cases in planetary science. They're both the same age, they're about the same size, they're both rocky planets formed from the same materials, and they both have significant atmospheres. But astronomers are curious about habitability. And when it comes to habitability, the pair of planets are vastly different. Earth sings with the chorus of life while Venus is mute.

Scientists know that Earth's and Venus' atmospheres have both changed a lot over time. When astronomers study exoplanets searching for Earth-like planets, they can't know what phase of evolution they're in, so they need to model atmospheres at different stages of evolution. Since exo-Venuses can masquerade as exo-Earths, they need a method to tell the two apart.



This image shows the elevation and temperature of Venus' atmospheric layers. Credit: By Alexparent – Reproduction in SVG of en.wikipedia.org/wiki/File:Venusatmosphere2.GIF, Public Domain, commons.wikimedia.org/w/index.php?curid=6432901

Venus might've started out with a thin, Earth-like atmosphere. It may have had an ocean, too. But the planet suffered a runaway greenhouse effect. That drove the water into the atmosphere, creating an atmosphere enriched with water vapor. That took time, and the researchers modeled Venus' atmosphere in four different stages, mimicking what they might see when they find terrestrial exoplanets.

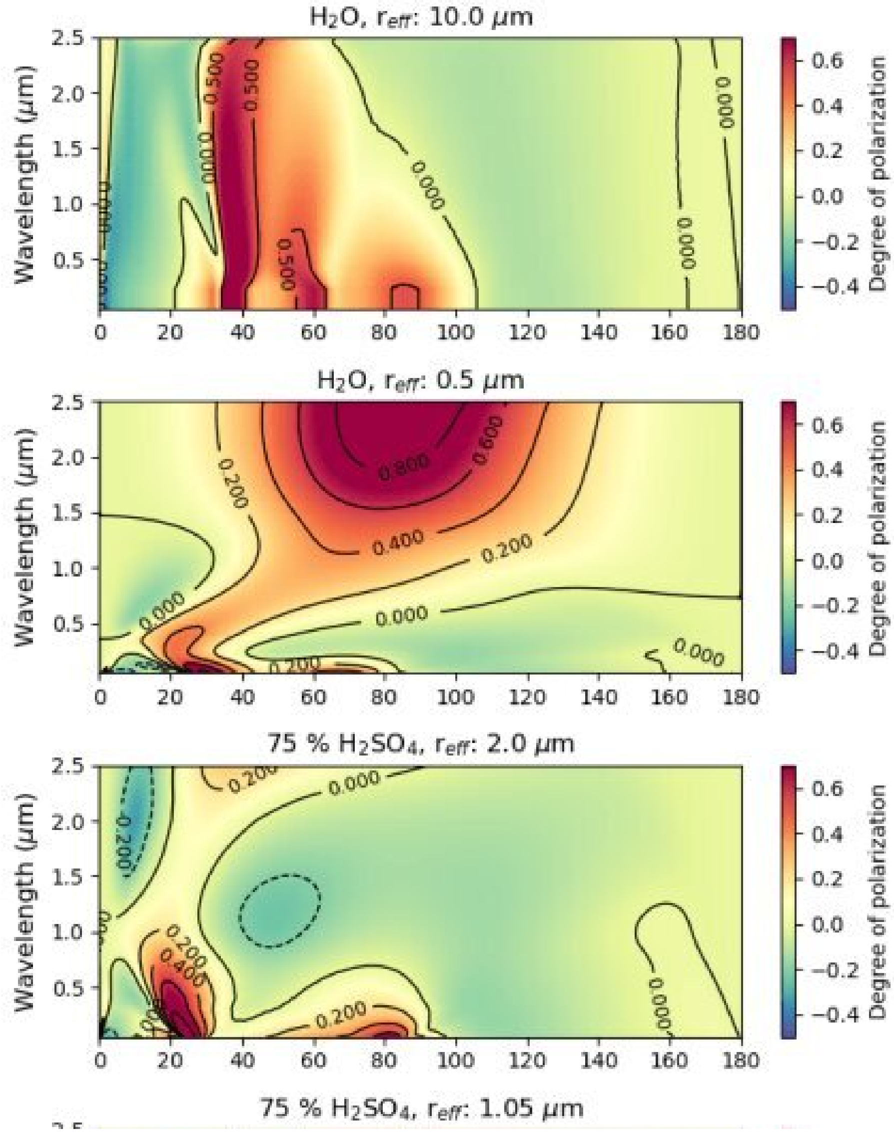
The researchers computed both the flux and the polarization of light for atmospheres from different evolutionary stages of Venus' atmosphere. They varied atmospheric compositions from pure water to ones containing sulfuric acid, a signature gas in Venus' thick modern atmosphere. They wanted to find out how strong the polarization difference is vs. the flux. If the polarization varied measurably, they were on to something.

In Phase 1, the atmosphere matches Earth's current atmosphere, aside from oxygen. Oxygen doesn't affect the results much, so the amount of oxygen in an exoplanet's atmosphere wouldn't be critical to polarimetry.

In Phase 2, the atmosphere is much more Venus-like and consists of almost pure CO_2 gas. It has relatively thin liquid water clouds with bc = 4, and with the cloud tops at 80 km. For this phase, the team used reff of 0.5 µm, which is smaller than the present-day value. The atmosphere was so hot that strong condensation couldn't take place, preventing particles from growing larger.

In Phase 3, the clouds are thick sulphuric-acid solution clouds. The bc = 120, and the cloud tops are at 65 km because the atmosphere is cool enough to allow condensation and/or coalescence of saturated vapor over a large altitude range.

In Phase 4, the clouds are much like present-day Venus' clouds. The clouds aren't as thick with a bc = 30, and the cloud tops are at 65 km.



This figure from the research shows some of the results. The top panel is earliest Venus atmosphere, and the bottom panel is the current Venus atmosphere. Overall, the results show that early Venus shows more polarization than modern Venus. The types of atmospheric particles and their sizes work with phase angle to determine the degree of polarization. Credit: Mahapatra et al. 2023.

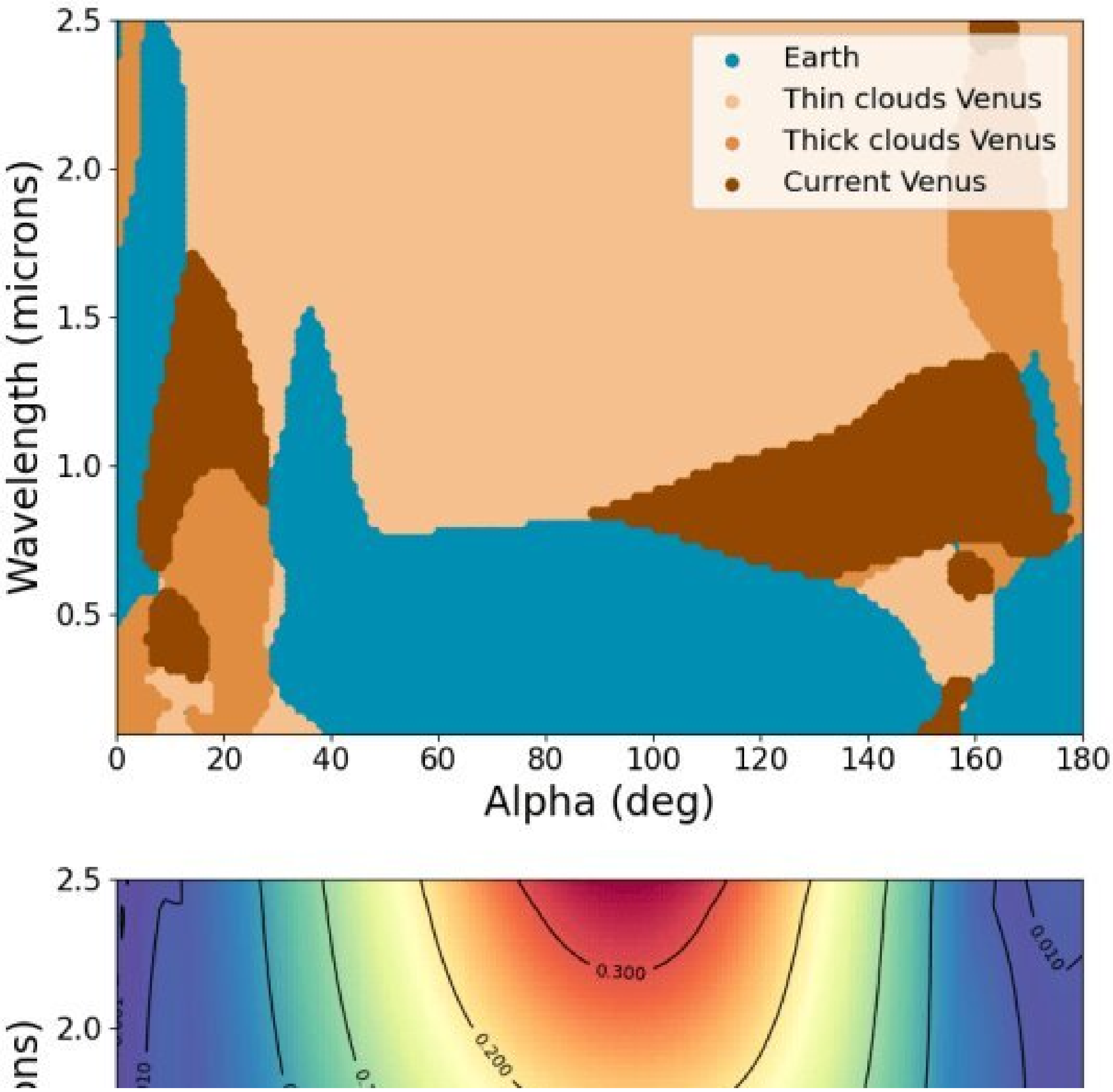
Since the researchers were looking at polarized light, the planetary phase angle is critical to their results. The phase angle is the angle between the light incident onto an observed object and the light reflected from the object. In this case, it's the angle between us (observer,) the exo-star, and the exoplanet.

In their paper, the researchers use a model planet in the Alpha Centauri system to help explain their work.

So what did they find?

"The degree of polarization of the reflected starlight shows larger variations with the planetary phase angle and wavelength than the total flux," they write. In visible light, the largest degree of polarization is for Earth-like atmospheres containing water vapor clouds. That's partly because of Rayleigh scattering.

At NIR wavelengths, "a Venus-like CO_2 atmosphere and thin water clouds shows the most prominent polarization features due to Rayleigh-like scattering by the small cloud droplets," the authors write.



Top: The planet models that yield the largest absolute degree of polarization over all phase angles and wavelengths: Phase 1 -‘ Current Earth’ (blue); Phase 2 -‘ Thin clouds Venus’ (light orange); Phase 3 ‘ Thick clouds Venus’ (dark orange); and Phase 4 -‘ Current Venus’ (brown). Bottom: The maximum values of degree of polarization of the four model planets. Credit: Mahapatra et al. 2023.

A problem astronomers face when studying exoplanet atmospheres is that they can't control the phase angle of their observations. The orientation of a planet's orbit determines that, and it changes over time.

To account for that, the researchers combined all their modeling data into one image that shows which planetary models have the largest absolute degree of polarization.

The researchers have modeled Venus in four evolutionary stages and shown how the polarity changes with atmospheric composition, particle size, and phase angle. So it seems that polarimetry can play a larger role in exoplanet studies. It's already an important tool in astronomy and is used to study black holes, planet-forming disks around stars, hidden galactic nuclei, and other astronomical objects.

Astronomers have a lot of polarimeters at their disposal. The SPHERE instrument on the VLT and the HARPS instrument at La Silla both have polarimeters, as do many other telescopes. The problem is, while we can model polarity changes in exoplanets, that doesn't mean they're so prominent that we can detect them from a great distance.

"Current polarimeters appear to be incapable to distinguish between the possible evolutionary phases of spatially unresolved terrestrial exo-planets," the authors write. Our current polarimeters aren't up to the task. "A telescope/instrument capable of achieving planet-star contrasts lower than 10^9 should be able to observe the large variation of the planet's resolved degree of polarization as a function of its phase angle and thus be able to discern an exo-Earth from an exo-Venus based on its clouds' unique polarization signatures."

Polarimetry is becoming a more powerful tool in astronomy. The upcoming ELT will be the world's most powerful optical light telescope for the foreseeable future. Its powerful EPICS instrument might be able to do the job, and so will future space telescopes. "Further, instruments such as EPICS on ELT and concepts for instruments on future space observatories such as HabEx and LUVOIR hold the promise for attaining contrasts of about 10^{10}," the authors write.

The Thirty Meter Telescope's proposed Planetary Systems Imager could also do the job. But it's a second-generation instrument and won't be available at first light.

Even though current polarimetric instruments might not be powerful enough yet, the authors believe that polarimetry will be able to tell the difference between truly Earth-like planets and Venus-like planets. We just need polarimeters with extreme contrasts.

"Reaching such extreme contrasts would make it possible to directly detect terrestrial-type planets and to use polarimetry to differentiate between exo-Earths and exo-Venuses."

More information: Gourav Mahapatra et al, From exo-Earths to exo-Venuses—Flux and Polarization Signatures of Reflected Light, *arXiv* (2023). DOI: 10.48550/arxiv.2301.11314

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