Planetary science

Venus might never have been habitable

James F. Kasting & Chester E. Harman

A sophisticated climate model suggests that liquid-water oceans never formed on Venus, and that some planets outside the Solar System that were thought to be habitable might not be. **See p.276**

Today, Earth's sister planet Venus is more like a distant relative than a sibling. Its atmosphere is thick with carbon dioxide, its surface is hot enough to melt lead, and any water that it once had is gone – except for a tiny amount that remains as vapour in its atmosphere. But some scientists have argued that Venus might once have been habitable. On page 276, Turbet *et al.*[1] report a climate model that suggests the steam atmosphere produced during Venus's formation never condensed on the planet's surface to create oceans. Instead, water vapour was transported to Venus's night side (the hemisphere facing away from the Sun), where it cooled and condensed to form clouds that warmed the surface by absorbing and re-emitting the planet's outgoing infrared radiation. If the authors are correct, Venus was always a hellhole.

A different research group has argued that the thick cloud cover over Venus's sunlit hemisphere could have reflected most of the incident sunlight and kept the climate cool and liquid water stable for billions of years[2,3]. These scientists used a 3D climate model developed by NASA's Goddard Institute for Space Studies (GISS), and assumed that the planet was spinning slowly early in its history, as it does today, and had substantial liquid water on its surface. Such predictions led to suggestions that life could have evolved on Venus's surface and later taken refuge in its clouds[4]. This claim might have been supported by reported spectroscopic evidence of the gas phosphine in the planet's atmosphere[5], but this has now been convincingly refuted[6].

How could two experienced climate-modelling groups reach such different conclusions about the effects of clouds on the evolution of Venus's climate? Scientists familiar with these models know that clouds have long been a problem for modellers of Earth's climate. Parallel simulations based on ensembles of 20 or more climate models for the Intergovernmental Panel on Climate Change yield answers of 2.5–4 °C for the increase in Earth's surface temperature if atmospheric concentrations of carbon dioxide were to double[7] – compared with 1.5–4.5 °C in previous assessments. Most of the uncertainty comes from the modelling of clouds and the fact that they can either warm or cool a planet's climate.

However, in the case of Venus, the cause of the difference seems to be much simpler: the authors of the previous studies[2,3] assumed that liquid water was initially present on Venus's surface, whereas Turbet *et al.* assumed that all of the planet's water was originally present in the form of vapour in the atmosphere. Water vapour absorbs radiation at both visible and near-infrared wavelengths, at which much of the incoming solar energy is concentrated. Therefore, the presence of so much water vapour high in Venus's atmosphere causes the atmosphere to warm, creating winds that blow the vapour to the planet's night side.

The idea that Venus might have started out with a steam atmosphere is not new; it was proposed in 2013 by researchers using a relatively simple, one-dimensional climate model[8]. This model is attractive because it predicts that Venus's surface remains molten as the water is lost by photodissociation (a process in which sunlight breaks the water into hydrogen and oxygen), providing a sink for the oxygen left behind when the hydrogen escapes into space. Turbet and colleagues' work shows that similar behaviour is observed in a sophisticated 3D climate model.

That said, the new model makes a surprising prediction that was previously missed. In the 1D model[8], the steam atmosphere condenses for a planet that forms at Earth's distance from the Sun. Given that the Sun was about 70% of its present brightness when Earth formed[9],

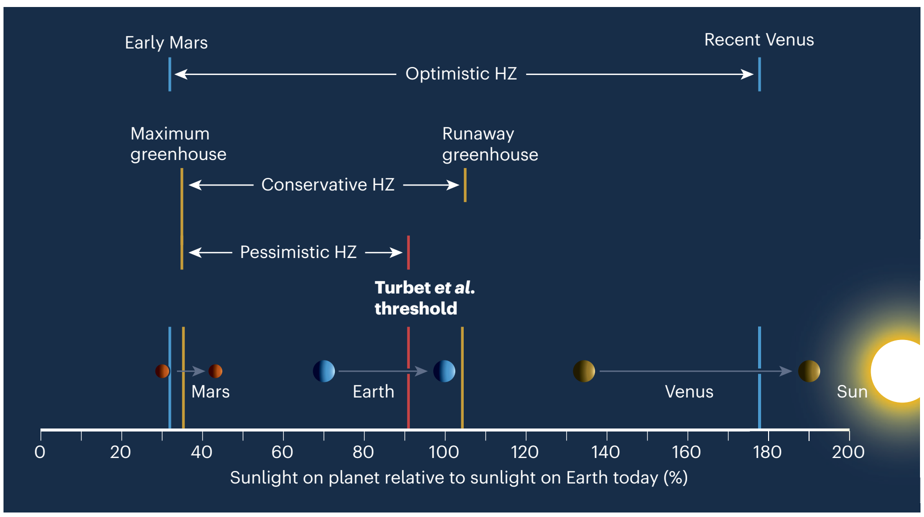

Figure 1 | Evolution of the habitable zone around the Sun. Brightening of the Sun has caused the habitable zone (HZ) – the region where liquid water can exist on a planet's surface – to move outwards over time. As a consequence, when the HZ is shown on a solar-flux scale (as it is here), the positions of the planets on this scale look as if they have moved inwards with time. The optimistic HZ is defined empirically, and stretches from early Mars to recent Venus. The conservative HZ is defined by climate modelling[13], and spans planets ranging from those with a runaway greenhouse effect to ones with a maximum greenhouse effect. Turbet *et al.*[1] calculated a limit that cuts off the innermost part of the conservative HZ, based on models showing that planets forming there never have oceans. However, given that a planet (such as Earth) that migrates into this part long after it forms can still be habitable, the associated HZ might be called the pessimistic HZ. (Data from ref. 13.)

the amount of sunlight hitting our planet at that time was roughly 70% of the amount received today. The new model shares this feature; however, Turbet *et al.* show that if the Sun had been just a little brighter when Earth formed – about 92% of its present luminosity – our planet's steam atmosphere would never have condensed. Instead, Earth would have become similar to Venus, and we would not be around to tell the story.

This finding also has implications for exoplanets – planets around stars other than the Sun. Exoplanets that orbit near the inner edge of the conventional habitable zone, where liquid water can exist on a planet's surface, might not actually be habitable (Fig. 1). Indeed, Turbet and colleagues' theory could be tested by building direct-imaging space telescopes that can observe such planets and take spectra of their atmospheres[10,11].

Another way to test this hypothesis would be to measure the composition of Venus's surface. The planet has highly deformed regions called tesserae that exhibit high infrared emissivity (the effectiveness of emitting energy as thermal radiation). The surface composition of these tesserae is thought to be felsic – that is, the rock is rich in silica and poor in iron – similar to continental rocks on Earth[12]. On our planet, such rocks form by metamorphic processes (in which minerals change form without melting) that occur in the presence of liquid water. If the tesserae turn out instead to be basaltic, like normal sea floor on Earth, liquid water would not have been needed to generate them, further supporting Turbet and colleagues' hypothesis.

The VERITAS mission – part of NASA's Discovery Program – will attempt to analyse the composition of the tesserae and other parts of Venus's surface from orbit using infrared spectroscopy. But definitive measurements might require a lander that can survive the harsh conditions on the surface. This technological challenge is comparable in difficulty to that of imaging exoplanets, and is a worthy goal for future Venus explorations.

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Diet

Seafood assessed for global human nutrition

Lotte Lauritzen

What role might seafood have in boosting human health in diets of the future? A modelling study that assesses how a rise in seafood intake by 2030 might affect human populations worldwide offers a way to begin to answer this. **See p.315**

An adequate and sustainable supply and intake of nutritious food is essential to tackle major global health issues such as dietary deficiencies. Seafood, which in this context includes fish, shellfish and marine mammals, is rich in micronutrients (such as vitamin A, iron, vitamin B_{12} and calcium) needed to combat the most common such deficiencies. Seafood is also the dominant source of marine omega-3 fatty acids, which have many health-promoting effects. On page 315, Golden *et al.*[1] present ambitious research that puts seafood centre stage.

Golden and colleagues' project is part of an initiative that aims to build healthy and sustainable aquatic food systems (see go.nature.com/3tnulm8). The authors carried out modelling analyses to assess the potential benefits on a global scale that increased seafood availability would have on the lowering of micronutrient deficiencies and the boosting of cardiovascular health. They modelled how much seafood production could increase by 2030, using a hypothetical scenario of production reaching the upper limit predicted by the Food and Agriculture Organization of the United Nations (FAO).

The authors' simulation arrived at an 8% gain in seafood supply worldwide by 2030, relative to the simulated production in a status quo scenario extrapolated from current trends. This hypothetical figure might not be particularly interesting in itself, but its value is in providing a good estimate as the basis for the authors' subsequent analyses of health benefits. These analyses are extremely complex, depend on the available data and involve many modelling steps that are based on assumptions that have a potential influence on the results.

It is difficult to get accurate dietary information, even with the typical standard methods used to determine the food intake of individuals, and such methods are not applicable in a worldwide study. So, as with similar global-scale studies, Golden *et al.* used national supply data, and presupposed a close link between food supply and consumption in the national population. The authors estimated the overall food consumption by following models used by the FAO and the Organisation for Economic Co-operation and Development to simulate food supplies on the basis of price and availability. Estimates of dietary intake derived by this method will obviously have limitations in accuracy, and the modelling assumptions might also introduce biases. Moreover, cultural differences between nations would probably affect how a hypothetical increase in seafood production would alter future dietary behaviours in a given national population. Also, people in affluent countries might not necessarily eat more seafood if supply increased, considering that the current intake is low in many countries in which seafood is readily available.

Making assumptions about future patterns of seafood export and import is also tricky. From their modelling results, the authors found that the top three global seafood exporters – Vietnam, China and Norway[2] – would show large increases in their national seafood supply. This is counter-intuitive, because countries that already export most of their production would be expected to expand their export market rather than their national supply if production was upgraded. This is especially so for Norway, which already has one of the highest national seafood intakes in the world[2]. It is therefore necessary to take into account the assumptions made in modelling studies that have multiple layers of analysis, especially universal assumptions in a global