The Marvels of the Solar System

Professor Chris Lintott

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I was sitting on the kitchen doorstep enjoying some late August sunshine when the call came. The voice on the end of the phone was my old Sky at Night colleague Chris North, a cosmologist at Cardiff University, and he had news. 'Well,' he said, 'it could be Venusians'.

Chris was reporting a discovery made by a team led by his colleague Jane Greaves of the signature of a chemical called phosphine high in Venus' thick atmosphere. Phosphine is a simple molecule - a phosphorus atom with three hydrogen atoms bonded to it - but on Earth, at least, it is distinguished by the simple fact that it is only made by life. Rich deposits are found in penguin guano, where phosphine is responsible for its distinctive smell, and a signature which has been used to monitor the health of penguin colonies from space. It is a 'biomarker', a chemical whose presence, seen in a planetary atmosphere, might indicate the presence of life.

Finding phosphines anywhere in the Solar System would have been a surprise. Spotting it on Venus, a planet whose thick, sulphuric atmosphere ensures that any visitor unwise enough to step onto the surface would be boiled, crushed, and dissolved simultaneously, and where no spacecraft has survived longer than a couple of hours, was shocking. (Venera 9, the first spacecraft to land on a planetary surface, touched down 48 years ago this week, and lasted for just 53 minutes, sending back only a single image) Yet observations made with the James Clerk Maxwell Telescope in Hawai'i, and the ALMA array in Chile, both tuned to wavelengths in the microwave region of the spectrum (what astronomers call the sub-mm), seemed to show absorption at just the right wavelength to be phosphine.

Both telescopes are high above sea level, JCMT on the summit of Mauna Kea, and ALMA on a plateau in the high Atacama Desert. Such elevation is necessary to get above the water in the Earth's atmosphere - your microwave oven uses radiation at these wavelengths to excite water molecules in your food - and the observation was challenging in many other ways. Venus is a more brilliant target than these instruments, normally used for staring at light which has travelled from distant galaxies, are used to seeing, and Jane and co were attempting the equivalent of stargazing while lit by a stadium floodlight.

Few would have given them much hope or expectation of success. The idea was proof of principle, a pathfinder observation that would demonstrate how we might, one day in the future, look for alien chemistry in the atmosphere of a distant world around another star. The data sat untouched on Jane's hard drive for several years, but once processed phosphine seemed to be there. Venusian penguins -- or at least acid-resistant bacteria -- seem to populate our neighbouring planet.

Intriguingly, it's possible to get some idea from the observations as to where in the atmosphere a chemical signature is coming from. The phosphine-bearing layer is high up, in a region where the temperature and pressure are not that different from a summer's day here in the UK. Though our putative Venusians would have to deal with the sulphuric acid in the atmosphere - a feature discussed in the Sky at Night program we ended up making by chemist William Bains, who took great delight in pouring acid onto toast and, for some reason, mushy peas, to demonstrate its effect on life - they may have more hospitable conditions than a cursory look at Venus might imply.

If this is life, it has a romantic story. Venus, we think, was once a world like the Earth, perhaps with oceans but certainly with a more temperate climate, before a runaway greenhouse effect, exaggerated by it being twenty-six million miles closer to the Sun than the Earth, changed the planet forever. If life got started early in the planet's story -- as it did here on Earth, where signs of life in the first billion years of our history exist -- then one can imagine Jane's phosphine-producing beasties as the last remnants of a once glorious and diverse ecosystem, clinging on in the least hospitable part of the planet.

Unfortunately, problems quickly appeared. Other astronomers, analysing the same data, did not find the same results as Jane's team. Worse, the scrutiny revealed that the software which processes data from ALMA before it reaches observers had a problem which affected these results in particular. And an attempt to observe phosphine with SOFIA, NASA's magnificent and now mothballed flying telescope, which observed the sky from a hole cut in the fuselage of a jumbo 747, found nothing. For those not closely following the story, phosphine on Venus is a cautionary tale, an announcement made too early.

And yet. A reanalysis of data from the Pioneer Venus probes, which dropped through the thick Venusian clouds on December 9th, 1978, found in the results from their mass spectrometers - instruments capable of weighing molecules which the probe encountered - a signature at just the right height which could correspond to phosphine. New observations from JCMT (though not from ALMA, whose time allocation committee have failed to provide further time) show that the signature of phosphine persists and, crucially, changes over the course of the long Venusian day. SOFIA didn't see anything because it looked in the evening, not the morning.

So, if the phosphine is real, is it aliens? Probably not. We don't know enough about the complex chemistry of Venus's atmosphere and about the effects of what seem to be active volcanoes on the surface of the planet, plus more exotic effects like reactions driven by lightning in the planet's cloud deck to be sure that the chemical isn't being produced by non-living chemistry. New missions to the planet, from NASA and ESA, launched in the next decade, will help resolve the confusion.

There are, though, two things worth noting about the phosphine saga. One is that identifying the signature of life on another world - something astronomers are contemplating trying to do on planets around other stars with instruments like the Extremely Large Telescope which is now in development - will be wickedly hard. If we can't quickly or easily reach a definitive conclusion about signs of complex chemistry in our nearest world, how are we to disentangle spectra from fainter sources? Our knowledge of atmospheric chemistry will need improvement if we are ever to identify from afar which of the billions of planets that throng the Milky Way are homes to life.

Second, even contemplating life on Venus, of all places, completes a dramatic transformation in how we think about life within the Solar System. Back in the pre-telescopic era, it was common to believe that all the worlds of the Solar System would be inhibited; the great William Herschel, who I talked about in my first lecture, believed the surface of the Sun revealed a landscape of mountains and valleys, and would therefore naturally be home to presumably scorching solarians.

A long list of natural phenomena was once attributed to life. On Venus, a phenomenon called the Ashen Light, where mysterious glows were observed on the planet's night side, were supposed to be campfires or streetlighting enjoyed by an intelligent population thronging by the side of soda water channels.

Mars, of course, with a changing pattern of dark blotches visible on the surface, simply had to be inhabited. The ability of the same dark features to reappear after dust storms, something we now know is due to the ability of the planet's winds to shift sand around, was - in an argument made most convincingly by Ernst Öpik, Estonian astronomer and grandfather of the more familiar Lembit - was supposed to be due to the ability of vegetation to grow back.

More intelligent life was expected too - most famously during the late 19th and early 20th century, when astronomers first in Europe and then, in particular, in the well-funded observatory on Mars Hill in Flagstaff, Arizona, saw straight lines crossing the red planet, connecting many of its features. The original description of these lines, *'canalli'* in the language of an early observer, Schiaparelli, was mistranslated into English as 'canals', implying artificial creation, and as observers watched the lines grow, change and even double and triple many believed they were watching a civilisation tame their desert planet, bringing water from Mars' polar caps down to equatorial regions.

Not everyone could see the canals, and observers on this side of the Atlantic seemed in particular unable to match the observations made in the US. By the turn of the century, it had become clear from spectroscopic observations that water was not abundant on the red planet, and optimism about life overrode cold scientific fact. Though Alfred Russel Wallace in his 1907 book 'Is Mars Habitable?' demonstrated convincingly that the planet's thin atmosphere would not support liquid water on the surface, belief in at least primitive life on the Martian surface persisted right up until the period when the first space probes visited.

(Some idea of the pervasiveness of the idea of intelligent Martians can be gained by considering the Prix Gruzman, offered by the French Académie des sciences to the first to communicate with a celestial body and receive a response. When set up in 1900, Mars was excluded as it would surely be too easy; 69 years later the Académie gave what was left of the original 100,000 Francs following inflation to the Apollo 11 astronauts, on the technical basis that they'd communicated with the Earth from the Moon.)

The start of the space age, with Russian and American probes visiting Venus and Mars, ended the idea of a verdant, populous solar system. Venus was, as discussed, a hellhole, and the first images of Mars, sent back by the Mariner 4 spacecraft in 1965, showed a craterless desert planet. The Viking probes which landed on Mars in the late 1970s - and which still have a claim to have carried the most complex set of scientific instruments to reach the surface of another world - did carry an experiment designed to test for the kind of reactions one might associate with the presence of life, they found nothing convincing.

Though the missions of the 60s and 70s taught us a great deal, there was a general sense of failure. We as a species had taken our first tentative steps into the cosmos, only to find our immediate neighbourhood at least devoid of company. Following Viking, attention moved away from our rocky neighbours, and it would be nearly two decades before another probe touched down on the red planet's surface.

When it arrived in 1997, the Pathfinder rover brought a new approach. It was equipped with a tiny rover, about the size of a tea tray, which demonstrated that effective exploration could be achieved by roaming the surface, and which paved the way for grander missions to follow. These were designed to 'follow the water' - testing not directly for life, but for the conditions in which life might exist, and for the presence of CHNOPS (Carbon, Hydrogen, Oxygen, Phosphorous and Sulphur, the atomic species life's rich chemistry is built from).

Two probes in particular revolutionized our view of Mars. Twin robot geologists, Spirit and Opportunity, landed in January 2004, just after the ill-fated descent of the budget British Beagle. Bouncing to a halt on the surface in inflated balloons, their intended mission of ninety days was extended for many years. Spirit lasted until it got stuck in a sand trap in 2010, while Opportunity holds the record for the furthest journey on the surface of an extraterrestrial body, at 28 miles more than a marathon. Between them, they showed a landscape that was incontrovertibly shaped by liquid, with a mineralogy that spoke of a distant past with Mars as a wet world, one with rivers, seas, and oceans, possibly long-lived.

This Mars, flourishing in the Solar System's first billion years or so, would perhaps have been a close match to the conditions that allowed life to start on Earth. What went wrong? We are not sure, but it seems that Mars' weak magnetic field, and the weakness of the smaller planet's gravitational pull compared to Earth, have exposed its fragile atmosphere to the baneful influence of the solar wind, which has stripped it away.

Some of the water is still there, in the polar ice caps which shrink and grow with the seasons, and in what may be an enormous subsurface ice cap, detected by radar soundings taken by orbiting spacecraft. Underneath the surface, in an environment protected from harsh radiation, and where things are a little more clement, might we imagine life might cling on? We will know more when the European Franklin rover (delayed after collaboration with Russia became unthinkable) reaches Mars, or perhaps when samples now being collected by the Perseverance rover are returned to Earthly laboratories sometime in the next decade.

As on Venus, detecting anything that we can be sure is a sign of life is bound to be difficult. The Curiosity rover has detected 'burps' of methane, which must be a sign of either biological or geological activity, though the results don't match what is observed in the atmosphere from orbit. Still, hope is now higher than for many years that at least a primitive ecology may persist on Mars. Its discovery would be hugely important, particularly if it could be shown that it arose separately from life on Earth - a finding which would imply that the vast cosmos around us must surely throng with life. It also presents a problem for billionaires with an ambition for interplanetary settlement; it would be a shame to reach Mars, only to find we have brought our own bacteria and Earthly life with us, obscuring any Martian biome.

During the long hiatus in Martian exploration, Pioneer 10 and 11, and then the two Voyager probes, were exploring the outer Solar System. The close-up images of the storms of Jupiter, the wind-sculpted clouds of Saturn with the planet's marvellous rings, and our first close look at the enigmatic ice giants, Uranus and Neptune, are marvels, as much artistic statement as scientific treasure trove. From the discovery of a hexagon at the north pole of Saturn - not, incidentally, an artificial alien base - to the spectacular and long-lived storms that roll through Jupiter's atmosphere, these missions showed these worlds to be every bit as interesting as their rocky counterparts in the inner Solar System. They provide a global view which can be combined with later missions such as Juno, which swings once every couple of months just a few thousand kilometres above the cloud tops.

More unexpectedly, these missions and the Galileo and Cassini probes which followed them, orbiting Jupiter and Saturn respectively, showed that many of the moons of the giant planets are worthy of study in their own right. Early Voyager images showed that Io, the innermost of the four moons discovered by Galileo back in the 17th century, was a volcanic world. It is, in fact, the most volcanic place in the Solar System, its interior perpetually squeezed by Jupiter's gravity, warmed in the same way that a squash ball whacked repeatedly against a wall will heat up. Material ejected from Io's volcanoes is captured by Jupiter and may be responsible for the bright auroral ovals seen at Jupiter's poles.

The same gravitational squeezing affects the other Galilean moons, though it has rather different effects. Wherever one looks in the Solar System, it is possible to use the presence or absence of craters as a crude clock. A more cratered surface is an older one, and so the lack of craters on Europa, and Ganymede, is a mystery. These surfaces, made of water ice, must be regularly refreshed.

A close study of the morphology of surface features, showing long channels and iceberg-like structures carved into the ice, suggests that both moons harbour large subsurface oceans. We do not yet know how far down such oceans are - though one Hubble Space Telescope observation seems to show water venting from some sub-surface source on Europa - but we can, remarkably, say something about their composition. Studies of the surface of so-called 'chaos regions' - places where it seems material may have been welling upwards from the ocean - on Europa show sodium chloride and, just in the last few weeks in observations from the JWST, carbon dioxide. If our assumption that these come from the ocean is right, then it is salty and contains at least some carbon, necessary for life's chemistry. It is, in fact, a habitat different from the surface or atmosphere of a rocky planet, but perhaps no less suitable for life to explore.

We will learn more about these places when two missions arrive early in the next decade. NASA's Europa Clipper is due for launch next year, spending four years studying its eponymous moon starting in 2030. Meanwhile, ESA's JUICE, which will focus on Ganymede but visit Europa and the outermost Galilean moon, Calisto, as well, is already on its way. Arrival at the Jupiter system will be in 2031. Should they find that the subsurface oceans lie just a short distance under the ice, rather than beneath an ice cap hundreds of kilometres thick, both may, one day, be seen as pathfinders for a mission that will drill through the ice and swim through the ocean below.

Another world, in orbit not around Jupiter but around Saturn, provides an even more tantalising opportunity. Though it was imaged by earlier probes, no one expected the tiny icy moon Enceladus to provide the highlight of the mission for the Cassini probe, which spent seventeen years exploring the ringed planet and its family of a hundred or so attendant moons. Enceladus is small, approximately the size of the British Isles, and though its surface was notably shiny, reflecting what might be a fresh icy surface, had not attracted much attention when Cassini passed by early in its mission. Though most of the instruments on board were off, their teams planning for upcoming encounters with more promising targets, the team running the magnetometer, led by Michele Docherty of Imperial College, were using the encounter with Enceladus as a dry run.

They were interested in how Saturn's magnetic field interacted with other bodies, particularly the fascinating moon Titan. The expectation was that no change in the magnetic field would be recorded as they flew past Enceladus, but the team decided to reduce and analyse the data they received anyway. To their surprise, there was a signal - something was happening around otherwise obscure Enceladus. Intrigued, Michele and her team persuaded the Cassini project to fly closer to the moon, passing over its southern pole at an altitude of under a thousand miles. The south pole was especially intriguing; the northern part of the moon was, while still icy, cratered and presumably ancient, while the south was made of fresher material, with odd 'tiger stripes' running through its surface.

This time, Cassini flew with its eyes open. Spectacular images captured on this, and several subsequent passes show fountains of water spraying from the moon, the clearest possible evidence that inside its icy crust, there is, as in the case of the larger moons of Jupiter, an ocean. The spacecraft even passed through the evidence for Enceladus being yet another ocean moon, except this time there was no need to burrow through an icy crust to get access to the water. What is this ocean like? Has it been there a long while or is it a temporary, recent phenomenon? Answers to these questions came from subsequent passes with Cassini, though the spacecraft was never again to go as close as it did that first time.

For starters, in flying through the fountains of Enceladus, Cassini was able to measure the composition of the water. Just as in Earth's oceans, the fountains are salty. That means that somewhere, underneath Enceladus' icy crust, there is not just an ocean but also an ocean floor, a place where water is in contact with a solid, rocky surface. Given that a leading theory of how life got started on Earth places its origins at a deepsea vent, this is exciting, especially if the ocean has been there for a significant amount of time.

What happens to the water once it leaves the tiny moon? Remarkably, it now seems like the ice crystals that form as the water enters the vacuum of space contribute to Saturn's magnificent ring system, forming the tenuous 'E' ring. This, the second outermost and fuzziest of the planet's rings, was discovered in the 1960s but seems to consist of material ejected from Enceladus, and there is enough material there to ensure us that Enceladus has been spewing water into space for millions, if not billions, of years.

A long-lived ocean exists in a tiny moon of Saturn, as well as inside the icy shells of several Jovian moons. Other bodies in the outer solar system, from Neptune's moon Triton to even Pluto itself, may have a similar structure. If so, then the most common habitat for life is not a rocky surface close to the Sun, but rather a dark ocean, isolated from the rest of the Solar System by the presence of an icy roof far above the ocean floor. Is it too far-fetched to imagine not only microorganisms, the Enceladian equivalent of algae, swimming in such a place but also higher organisms? Could Enceladus harbour squid or even dolphins? How far should our imagination go?

If there is intelligence in such a world, somewhere in the Universe, there will be a life which seems strange to us. Deprived of sight of the rest of the cosmos, any such beings would be hard-pressed to conceive of our existence, on the fragile surface of a world whirling around a star. Perhaps dolphin physicists will deduce the presence of a massive body next to their world, and if a technological civilisation exists, a greater science-fiction writer than I will be needed to describe the thoughts of the first few intrepid cetacean astronauts to emerge upwards through the ice.

Less speculatively, another moon of Saturn provides possibilities for a very different kind of life. Titan, Saturn's largest moon, is the only satellite in the Solar System to complete with its nitrogen. It is dominated by nitrogen just as the Earth's is, though sprinkled with a liberal quantity of hydrocarbons. Titan remained a mystery for many years, its hazy atmosphere blocking views of the surface, but when the European Huygens probe came swinging through the clouds after hitching a ride with Cassini, it revealed a surface with river valleys, shaped by methane rain. Further observations from orbit reveal what may be permanent hydrocarbon lakes and oceans, within which complex chemistry may be occurring; odd 'magic islands' which appear and disappear may be bubbles of nitrogen gas released under pressure as the hydrocarbon seas churn. Exploration of this fascinating place will begin in earnest in 2034, when the Dragonfly 'copter begins bouncing around the surface, carrying a miniature chemical laboratory.

Dragonfly won't sample the seas directly, but an intriguing idea due to Jonathan Lunine suggests they might be a liminal space, harbouring complex repeating cycles of chemical reactions. Such cycles, which could be self-perpetuating, would be nowhere near as complex as even the simplest microorganisms on Earth but would place Titan right at the tipping point where chemistry becomes the miracle we call life.

As we look forward to a decade of exploration of the icy moons of the giant planets, Titan's rich landscape, as well as the potential of sample return from Mars, the transformation of our view of the Solar System is complete. From a disappointing wasteland, lacking friendly little green men, we now see it as a remarkably rich range of habitats. This excitement about possibilities - and why not include hydrogen-breathing whales swimming amongst the clouds of Jupiter, as Carl Sagan suggested in the 1980s - is driving our robotic exploration of the Solar System.

And yet, I can't help wondering if we are missing something. I once interviewed Steve Squyres, the visionary leader of the team behind the Spirit and Opportunity rover missions. It was something like 18 months into a planned 90-day mission, and the team were still adjusting their lives around spacecraft living on Mars. We sat on the grass on the Cambridge's backs, and a tired Steve explained that, at that stage, they had shown that water existed on ancient Mars, but - in that location at least - it seemed to have been acidic. Thinking of the potential for life, I expressed disappointment, only to be rebuked. 'If you want to study an Earth-like planet,' Steve said, 'study Earth. We go to Mars not because it's another Earth, but because it is Mars.'

In looking for life, we can miss the richness of our surroundings. I've not mentioned scorching Mercury, a world which appears to have shrunk since its formation, and which is much heavier than it should be. The asteroids, visited by craft from Dawn at Ceres and Vesta, both big enough to be worlds in their own right, to OSIRIS-ReX's recent return with samples from threatening Bennu, are proving to have a diversity all their own. Those swirling clouds in Juno's images of Jupiter are as beguiling as the sight of Saturn's rings through a telescope. From up close, the planet is simply beautiful, and the complex dance of the billions of particles which make up the rings is still teaching us physics today. Uranus and Neptune - the closest thing we have to the most common form of planet in the galaxy - are underexplored, and if Pluto was this interesting up close then what are the other worlds of the Kuiper Belt - Eris, Makemake, and many more - going to be like? The Solar System is indeed full of marvels, even if we don't have anyone to share them with.

References and Further Reading

The Sky at Night has placed some historical Solar System episodes on iPlayer for those in the UK: https://www.bbc.co.uk/iplayer/episodes/b006mk7h/the-sky-at-night

I recommend ‘Mariner to Mars’ from 1964, and ‘Unveiling Titan’ from 2005

Upcoming missions

Details of JUICE: https://www.esa.int/Science_Exploration/Space_Science/Juice

Europa Clipper: https://www.jpl.nasa.gov/missions/europa-clipper

And Dragonfly: https://dragonfly.jhuapl.edu/

Mars

I highly recommend ‘Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet’, Steve Squyres, Hachette, Reprinted 2006.

The denizens of the Unmanned Spaceflight forum (http://www.unmannedspaceflight.com/) keep track of all missions, but the coverage of Spirit and Opportunity is particularly rich.

For those fascinated by the technical details of a Mars rover, everything you could want is in ‘The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job’, Emily Lakdawalla, Springer-Praxis 2018

Phosphine

The story of Phosphine on Venus has been played out in a series of publications.

Jane’s original paper:

J. Greaves et al., ‘Phosphine Gas in the Cloud Decks of Venus’, Nature Astronomy (2021) 5(655), https://arxiv.org/abs/2009.06593

Followed by critical work:

G. Villanueva et al., ‘No Evidence of Phosphine in the Atmosphere of Venus from Independent Analyses’, Nature Astronomy (2021), 5(631),

https://www.nature.com/articles/s41550-021-01422-z

A. Akins et al., ‘Complications in the ALMA Detection of Phosphine at Venus’,

ApJL (2021), 907(2), L27, https://arxiv.org/abs/2101.09831

and replies by Jane’s team:

J. Greaves et al., ‘Low Levels of Sulphur Dioxide Contamination of Venusian Phosphine Spectra’, MNRAS (2022), 514(2), 2994, https://arxiv.org/abs/2108.08393

J. Greaves et al., ‘Recovering Phosphine in Venus’ Atmosphere from SOFIA Observations’, 2023

https://arxiv.org/abs/2211.09852

Speculative work on the life cycle of Venusian creatures is described in: S. Seager et al., ‘The Venusian Lower Atmosphere Haze as a Depot for Desiccated Microbial Life: A Proposed Life Cycle for Persistence of the Venusian Aerial Biosphere’, Astrobiology (2021), 21(10), 1206.

Enceladus

M. Meltzer, The Cassini-Huygens Visit to Saturn: An Historic Mission to the Ringed Planet, Springer-Praxis, 2015 (a history of the Cassini mission including its exploration of Enceladus)

M. Dougherty and L. Spilker, ‘Review of Saturn’s Icy Moons Following the Cassini Mission’, Reports on Progress in Physics (2018), 81(6) https://iopscience.iop.org/article/10.1088/1361-6633/aabdfb/meta (behind a paywall, sadly)

Since Cassini’s discoveries, people have been suggesting missions to return to Enceladus. Most recently, there’s TIGER: E. Spiers et al., Tiger: ‘Concept Study for a New Frontiers Enceladus Habitability Mission’, The Planetary Science Journal (2021), 2(195), https://iopscience.iop.org/article/10.3847/PSJ/ac19b7

Recent observations with JWST show Enceladus is still very active: Villanueva et al. 2023, “JWST molecular mapping and characterization of Enceladus' water plume feeding its torus”, Accepted by Nature Astronomy, 2023, https://arxiv.org/abs/2305.18678