ASTROBIOLOGY

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INSTANT EXPERT

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MICHAEL MELFORD/GETTY

manganese and iron. Some, known as extremophiles, thrive in conditions of very high or low temperature or pressure, or extreme acidity or alkalinity. The toughest can handle temperatures of over 120 °C. Others can survive radiation levels 1000 times what would be deadly to us.

Such organisms are found in environments like those of the volcanic calderas of Yellowstone National Park in Wyoming (right), or around hydrothermal vent systems at the mid-ocean ridges, often at great depths and cut off from sunlight.

As well as hinting at how life might survive elsewhere, these organisms represent the core genome of terrestrial life that has transformed the planet over billions of years, providing the oxygen we breathe and the soil we grow food in.

The modern Earth provides only a snapshot of the flora and fauna this planet could support. How alien would it have seemed 2 or 3 billion years ago? Questions like this are vital in helping astrobiologists look for the habitats and life forms that could exist elsewhere.

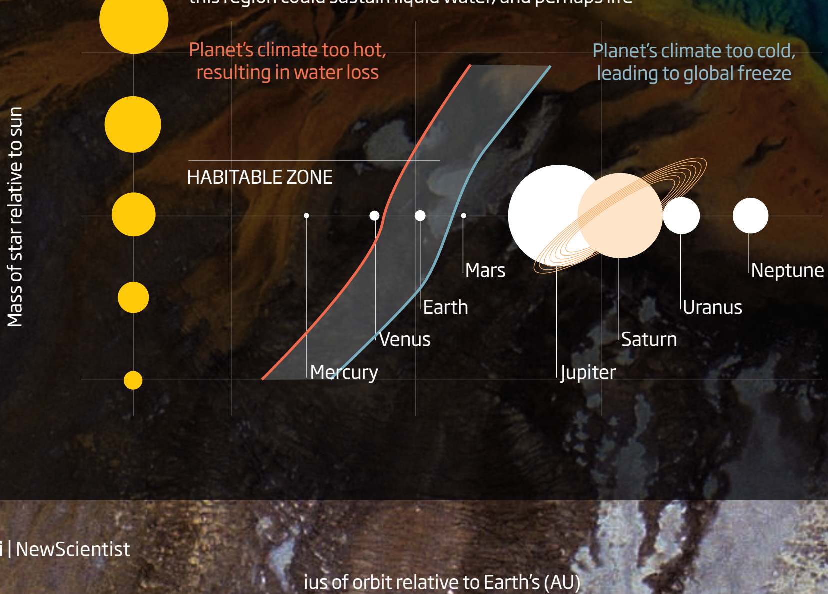
We don't know how important each of these factors is. Several moons in the solar system, including Jupiter's Europa and Ganymede, may have huge oceans beneath their icy crusts. Saturn's Enceladus may have subsurface pockets of liquid water. But these moons receive little sunlight and may have few carbon-rich chemicals in their depths.

When seeking exoplanets – worlds in other solar systems – with an Earth-like environment, a basic rule is to start by looking for a body with a surface temperature between 0 °C and 100 °C. It can't orbit too close to its star and be too hot, or orbit too far away and be too cold; it must be in a "Goldilocks" or habitable zone.

The location of this zone depends on the brightness of the star and on the greenhouse effect of a planet's atmosphere – how effectively the atmosphere holds in heat. Using mathematical models of planetary climates and knowledge of stellar radiation we can decide which planets are worth inspecting.

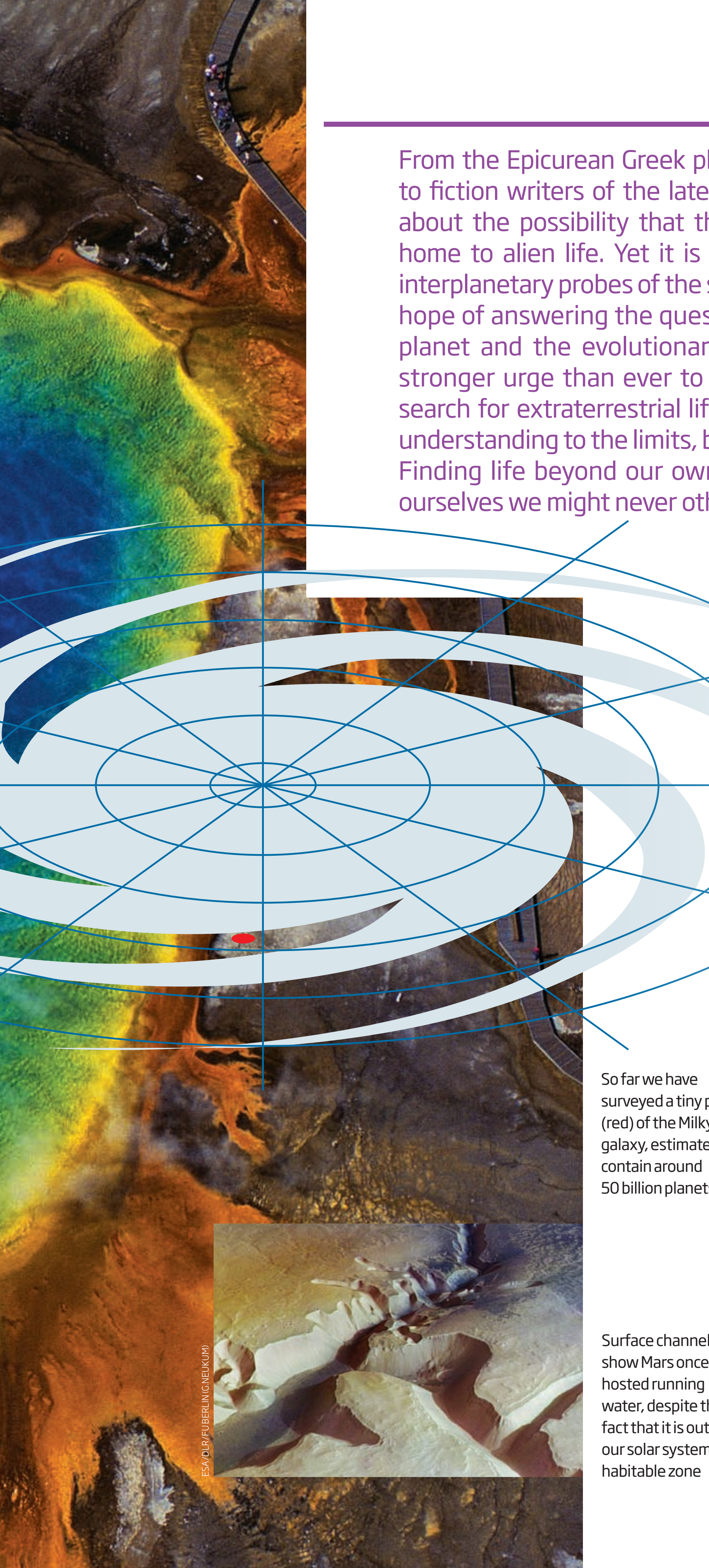
Yet this is not the whole story. Mars is just outside our solar system's habitable zone, which starts around 125 million kilometres from the sun and extends outwards by roughly the same distance (see diagram, left). Yet we know the planet had liquid surface water in the past. Around the smallest stars, 1/10th the mass of our sun and a thousand times fainter, the habitable zone is so close to the star that gravity should lock any planet's rotation so that one side is permanently day and the other night. The environment on much of the surface of such worlds will be extreme, but liquid water may still exist in some regions.

Most solar systems have a habitable zone. Earth-like planets in this region could sustain liquid water, and perhaps life



ARE WE ALONE?

From the Epicurean Greek philosophers more than 2000 years ago to fiction writers of the late 19th century, people have speculated about the possibility that there might be other worlds which are home to alien life. Yet it is only with the gigantic telescopes and interplanetary probes of the space age that we finally have a realistic hope of answering the question. As we learn more about our own planet and the evolutionary history of terrestrial life we feel a stronger urge than ever to put it into context. Embarking on the search for extraterrestrial life pushes our technology and scientific understanding to the limits, but the quest is one we should not shirk. Finding life beyond our own planet would teach us things about ourselves we might never otherwise learn.



So far we have surveyed a tiny patch (red) of the Milky Way galaxy, estimated to contain around 50 billion planets

ESA/DLR/FU BERLIN (G.NEUKUM)

Surface channels show Mars once hosted running water, despite the fact that it is outside our solar system's habitable zone

WHAT IS LIFE?

This seemingly simple question is surprisingly difficult to answer, not least because we risk being blinkered by the nature of life on our own planet.

Life on Earth is based on the uniquely versatile chemistry of carbon. The size of the carbon atom and the configuration of its electrons allow the creation of chains of carbon atoms, and the formation of varied bonds that can link with other elements. It is this that permits the formation of the vast range of carbon-based or "organic" molecules found in nature.

The building blocks of terrestrial life, including proteins and DNA, are composed mainly of carbon, along with hydrogen, oxygen and nitrogen. Together with phosphorus, sulphur and traces of iron and a few other elements, these form the molecular machinery in all known living creatures on Earth. And none of this diverse and complex biochemistry could function without a solvent with unique properties: water.

This does not mean life elsewhere will be the same. So how do we search for it, without knowing what it will look like? Modern astrobiology hopes to sidestep this conundrum by focusing on aspects of life that should allow us to recognise it, whatever form it takes.

Key to this is the fact that life cannot exist in isolation. Living organisms extract energy and raw materials from their surroundings and release waste products. As organisms grow and reproduce, they alter their surroundings. Indeed, life is an amazing geoengineer: over billions of years, living creatures have completely altered our planet's environment. Life also changes the make-up of our planet on the timescale of months and years. Photosynthetic organisms modify the appearance of land and sea, and in the atmosphere the concentrations of gases such as carbon dioxide fluctuate on an annual cycle. Alien life should influence its environment in similar ways, and astrobiologists will seek out such changes as a signpost for life.

FIRST CONTACT?

Some scientists claim that we have already observed the signs of alien life in our solar system. Most others dispute this, however, leaving the question mired in controversy.

In 1976, NASA's twin Viking landers arrived on Mars. Each carried four experiments designed to look for signs of life. They sniffed for telltale chemicals, applied nutrients and heated samples of the Martian soil. Only one experiment showed a strong reaction between the soil and a nutrient mixture. Yet there was no sign of organic compounds in the soil, and it was generally concluded that the reaction was a purely chemical one, rather than one involving any life form.

Now we are not so sure. Recent studies of soil from the Atacama desert in Chile – which resembles that on Mars – suggest that organic compounds could have been present in the Viking samples, leaving the door open for the presence of life. Only further Mars missions can settle the question.

Evidence of a different kind emerged in 1996, when NASA scientists claimed to have found microscopic traces of fossil life inside a meteorite from the Allan hills in Antarctica. The meteorite was a chunk of Mars that had been blasted away some 3 to 4 billion years ago and had wandered through space before crashing onto Earth about 10,000 years ago. Like the Viking findings, these results remain highly controversial.

The Martian atmosphere has also provided tantalising indications of a seasonally varying release of methane gas. Most of Earth's methane is produced by Archaea, so could Mars also have living methanogens? Studying the proportion of the isotopes of the carbon and hydrogen atoms making up the methane molecules might give us the answer, since living creatures have a preference for lighter isotopes.

Other intriguing results appeared in 2010, when observations of Saturn's largest moon, Titan, indicated that hydrogen gas is flowing downwards to the moon's surface and disappearing. Some areas on Titan also appear to be deficient in the hydrocarbon acetylene. Comparison with the behaviour of hydrocarbon-eating microbes on Earth suggest that some kind of life might just be responsible.

Sending instruments to these worlds will be key to solving these mysteries. NASA's latest robotic Mars explorer, Curiosity, should arrive in 2012 and will sniff for carbon compounds and other signs of life as it roams the Martian surface. In 2020 NASA and the European Space Agency are hoping to visit Europa and Ganymede, and plans are being discussed for further trips to Titan that could include a probe floating across one of its methane seas.

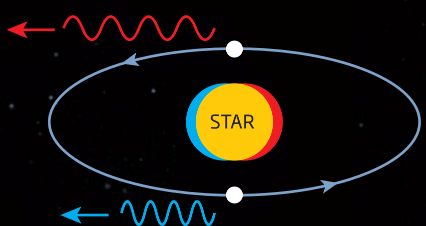
It is even conceivable that we ourselves might be descended from alien life. The controversial panspermia hypothesis suggests that life is carried across the universe on rocks or comets, and even as free-floating organisms. Within our solar system, material can certainly be transported between planets and moons when an asteroid or comet impact blasts chunks of rock or dust into space. If there have been microbial hitch-hikers tough enough to withstand the extreme conditions, maybe life on Earth has been influenced by life on other worlds. Conversely, life on Earth could have influenced life elsewhere.

JPL/NASA

By 2012, NASA's Curiosity lander should reach Mars , where it will hunt for signs of carbon chemistry

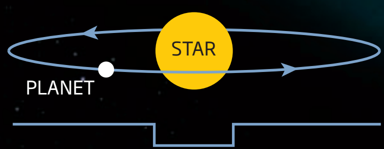
"It is even conceivable that we ourselves might be descended from alien life"

RADIAL VELOCITY TECHNIQUE



The gravity of an extrasolar planet can tug at its parent star. The star's spectrum appears to get bluer as a star moves towards us, and redder as it moves away

TRANSIT METHOD



As exoplanet passes in front of star it blocks some of its light

GRAVITATIONAL MICROLENSING

Gravity of exoplanet concentrates light from distant star

THE HUNT FOR LIFE

For the first time we have the technology that will allow us to look for life in our solar system and beyond. But with more than 20 planets and large moons around the sun and 200 billion stars in the Milky Way we need to narrow down the search. Powerful telescopes, clever astronomical techniques and field trips to some of Earth's most extreme and remote locations are helping us to identify the most promising places to start.

SEEING STARS

Astrobiologists can call on a variety of techniques to search for exoplanets (see diagram, below). Mostly these sense the presence of a planet only indirectly.

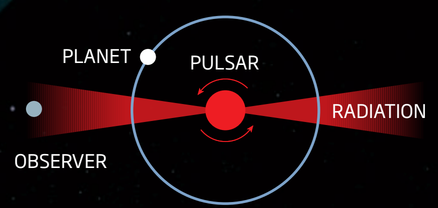
One of these methods tracks a star's motion to see if it wobbles under the influence of the gravitational pull of an orbiting planet. This radial velocity is done by monitoring slight shifts in the wavelengths of light in a star's spectrum. Stellar wobbles typically add up to a change in speed of less than a few metres per second, and measurements at thousands of different wavelengths may be needed to spot this. It is thanks to this technique that the first detection of an exoplanet was achieved in 1995, and it has since detected more than 400 new worlds.

A second technique will only find planets whose orbits happen to pass directly in front of their parent star, as viewed from Earth. When the planet itself passes in front of its parent, or "transits", it briefly blocks a tiny fraction of starlight. Measuring the changes in starlight during this transit reveals the planet's diameter. Using this powerful method, NASA's orbiting Kepler telescope has found more than 1000 likely exoplanets in one small patch of our galaxy. Sometimes we can even detect light from a planet as it passes behind a star.

Another technique exploits gravitational microlensing – a consequence of the fact that large masses distort space-time. If light from a distant star passes close to another stellar system on its way to Earth, the distortion to space-time caused by the intervening star can act like a lens, dramatically magnifying the light. An exoplanet in a suitable orbit can show up thanks to the changes it creates in the magnified light.

Finally, it is also possible to image exoplanets directly. This has been compared to spotting a firefly next to a searchlight, yet advances in telescopes and image processing have allowed astronomers to do just that. So far, the only exoplanets seen this way are Jupiter-sized or bigger, and often much hotter. Eventually, we should be able to see smaller, cooler planets too.

PULSAR TIMING



A pulsar is a rotating neutron star.
The gravity of an exoplanet creates a periodic change to the stars rotation rate

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LOOKING FOR EARTH-LIKE PLANETS

Finding planets that resemble Earth is a good start but that is not the only consideration. Though our galaxy, the Milky Way, contains several tens of billions of stars like our sun they are not in the majority. Over 70 per cent of its stars are less than half the mass of the sun and less than 1/10th as bright. The smallest are the diminutive red objects called M-dwarf stars that can be 1000 times fainter than the sun but which models predict can live for trillions of years. Most of our closest exoplanetary neighbours may orbit stars like this.

They may, however, be challenging environments for life. Planets orbiting such dim stars could sustain liquid water only if they orbited very close to their parent. At that distance, gravitational tides might "lock" a planet's rotation, so that it has permanent day and night sides. What's more, M-dwarf stars are prone to emitting massive solar flares that would irradiate the planet's surface and erode any nascent atmosphere.

Planet size also matters. Solid planets up to about 10 times the mass of Earth – often called Super-Earths – may have a range of compositions, including a greater proportion of water and other volatile substances than Earth. Though surface gravity will be a little higher, many could share with Earth some of the characteristics favourable to life, including atmospheres and geological activity. Super-Earths are easier to detect and study than smaller planets, making them good targets for observational techniques that might ultimately be used to study worlds more directly resembling our own.

SPOTTING THE SIGNS

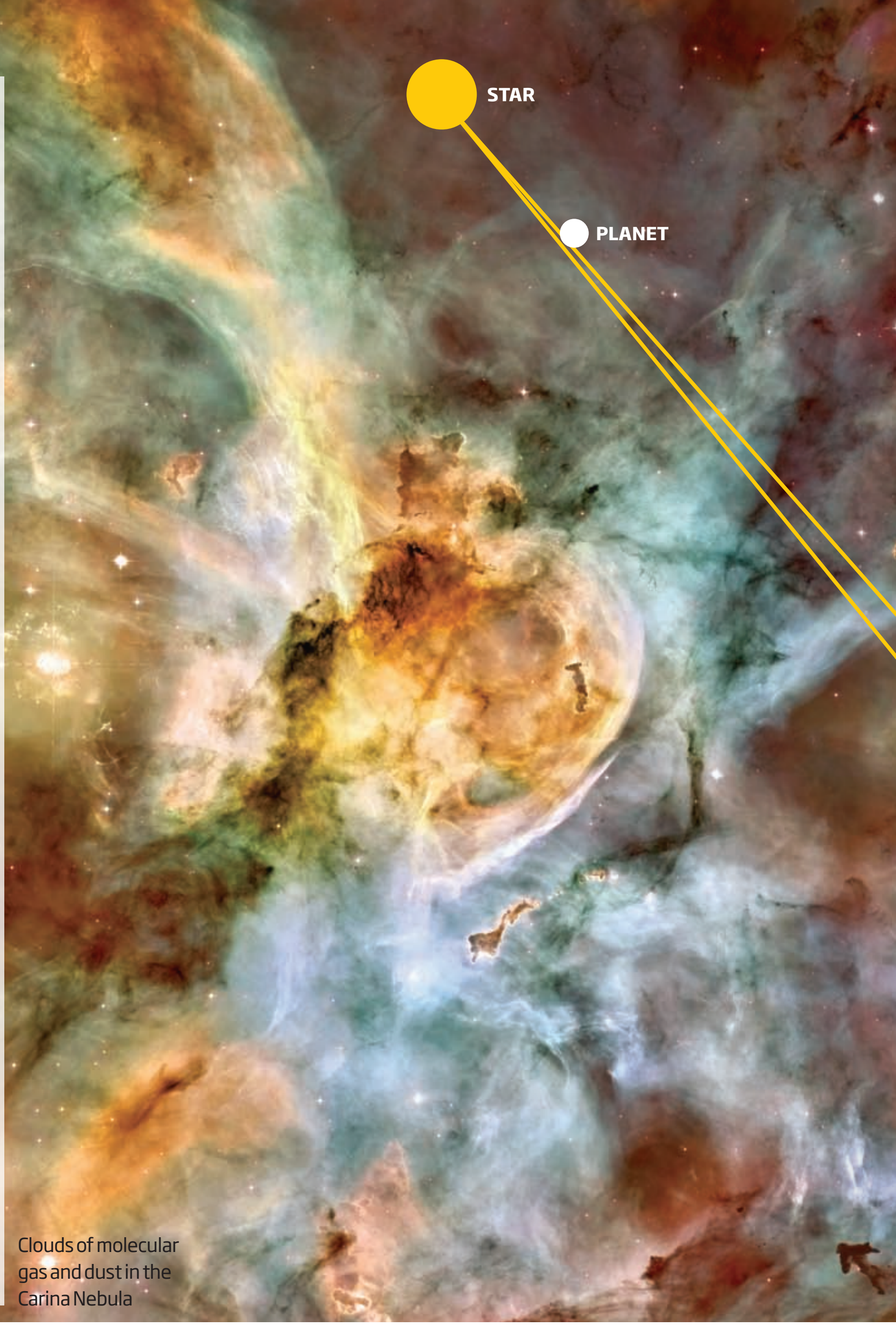
Observations with NASA's Kepler telescope indicate that at least 6 per cent of sun-like stars harbour small rocky worlds. In our galaxy alone that means there may be millions of Earth-sized planets in the habitable zone around their parent stars. Training our biggest telescopes on the nearest examples may be the key to finding life.

In particular, astrobiologists will need to sniff for the chemical signs of a well-entrenched biosphere. In the 3.5 billion years or more that microbial life has been around on Earth it has completely changed the chemical composition of land, sea and atmosphere. Oxygen, carbon dioxide and nitrogen participate in global cycles mediated by life and intertwined with geophysical and climatic processes. But will it be possible to detect such cycles on other, distant planets?

Starlight shining through a planet's atmosphere can reveal its structure and composition. Astronomers have started to exploit this phenomenon to perform rudimentary temperature and chemical analyses of giant and super-Earth planets as they transit their parent stars. This technique should work on even smaller worlds.

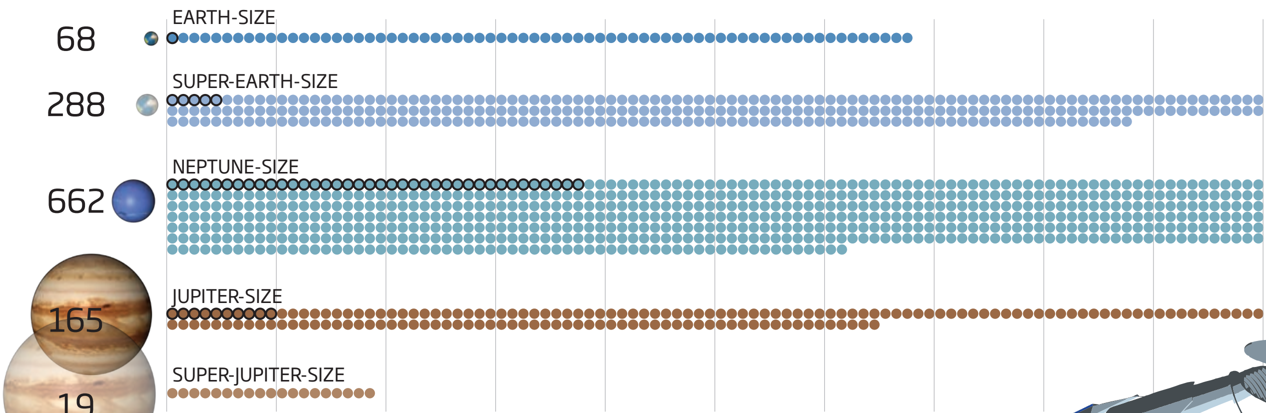
Our abilities to study distant worlds will improve significantly with the launch of the James Webb Space Telescope. This successor to Hubble will be able to probe planets around nearby lower-mass stars. By taking the temperature of these worlds and looking for signs of water, oxygen, ozone and even methane in their atmospheres we will begin to piece together their environment. We may even be able to spot signs of light reflecting from surface oceans. Over time we can monitor seasonal and other changes that might reveal the chemical "breathing" of a biosphere.

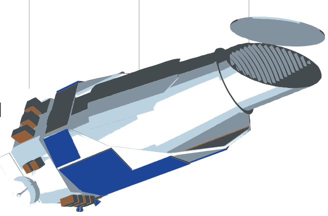
Large moons around giant exoplanets may also be prime targets. While Europa or Ganymede - two moons rich in water-ice - lie well outside the habitable zone, it is likely that there are exomoons comfortably inside the habitable zone of other stars. Ganymede and Titan are bigger than Mercury, and it seems plausible that Mars-sized or even Earth-sized moons could exist around giant exoplanets. With atmospheres and the possibility of geophysical processes boosted by strong gravitational forces these could also provide a habitable environment.



Clouds of molecular gas and dust in the Carina Nebula

NASA, ESA, N. SMITH (U. CALIFORNIA, BERKELEY) ET AL., AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)





Number and relative size of exoplanet candidates found by NASA's Kepler telescope (as of 2 February 2011). Those in their star's habitable zone are circled in black

FRONTIERS OF ASTROBIOLOGY

In 1990, NASA's Galileo spacecraft flew by Earth en route to Jupiter. Carl Sagan and colleagues seized this opportunity to train its instruments on Earth to see whether they could detect the signs of life. This was a critical demonstration of how the presence of life on other planets might be revealed: for instance, by finding oxygen and methane in the atmosphere, and hints of surface pigmentation. Picking up reflected light from the parent star would hint at liquid water on the surface. The clincher might be narrow-band radio emissions, modulated to carry information – radio and TV broadcasts, in other words. Galileo was able to pick up all these signs. But while the NASA probe came within 960 kilometres of Earth, astrobiologists have to find ways to test for life hundreds of light years away.

Recording the spectrum of a star's radiation through the atmosphere of an exoplanet can reveal its chemical constituents. Hints of prebiotic molecules may also be found in the spectra of interstellar clouds

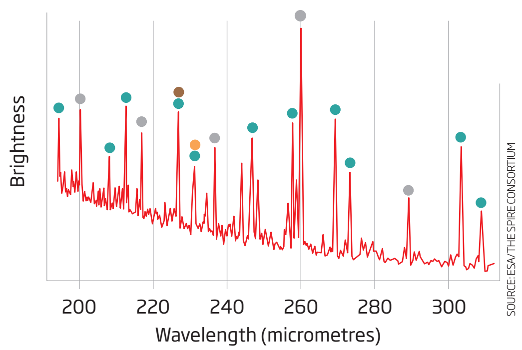
LIFE IN THE VOID

Could life exist, or even originate, off-world in the cold dust and gas of nebulae or the swirling material surrounding young stars? Certainly, the gas between stars seems to contain a rich mix of molecules. Since the first molecules in interstellar space were identified in 1937, more than 150 different compounds have been found there, and astrochemists expect to find many more. Back on Earth, lab experiments that are recreating the extreme conditions of interstellar space have generated astonishingly complex organic compounds as well as cell-like vesicle structures.

So could this mean that some of life's ingredients come from outer space? Might we find signs of these chemical precursors, or even simple forms of life, in interplanetary or interstellar space? What's certain is that in our solar system, meteorites and comets often carry a chemical smorgasbord that includes amino acids and other fragments of extensive carbon-based molecules. Carbon chemistry seems to pervade the universe: this same chemical richness is also seen in the thick planet-forming discs of gas and dust around newborn stars, where material experiences extreme temperatures and is pummelled by radiation. Under these conditions, opportunities abound for chemical reactions and for the production of carbon-based molecules.

Astronomical observations indicate that some young stars have cyanide and similar molecules in the material around them. Cyanide is a key ingredient in the production of more complex molecules that are involved in biochemistry, often called prebiotic compounds. Perhaps these molecules could act as a starter mix of organic substances, giving rocky planets the ingredients that could set life in motion.

Spectrum of microwave radiation from giant star VY Canis Majoris reveals complex chemistry in clouds around it



TOOLS OF THE TRADE

New observatories such as the space-based Herschel telescope which was launched in 2009, and the Atacama Large Millimeter Array, due for completion in 2011, are tuned to probe radiation emitted and absorbed by distant clouds of dust and gas. By examining the rich chemistry around young stars we will be able to see how, when and where prebiotic carbon-based molecules form, and learn about what may have happened in our own solar system (see diagram, left).

Lab-based experiments are revealing the fundamentals of how molecules form in such environments. The chemical pathways that combine atoms like hydrogen and carbon to make simple molecules can involve dozens of steps and different routes. By measuring which pathways are most efficient, these experiments should help reveal how the universe is cooking up biomolecules.

For a complete picture, these measurements must be combined with data from direct sampling missions. For example, in 2014, the European Space Agency's Rosetta probe will place a small lander on comet 67P/Churyumov-Gerasimenko to analyse its composition. This will help reveal the biochemical menu that existed in our own solar system when it was still young.

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Caleb Scharf is director of the Columbia Astrobiology Center in New York City. He is interested in the origins of planetary systems, climates of other planets and exomoons, and blogs on astrobiology at Life, Unbounded. He is working on a book for general audiences about the effect black holes have on the universe.

NEXT INSTANT **EXPERT**
Michael Duff
THEORY OF EVERYTHING
4 June

ARE WE UNIQUE?

Is there other intelligent life out there? To some it seems inevitable that there must be – it's a very big universe. But it is also possible that we and our home world are a rarity, a Goldilocks event in time, space and the roulette wheel of evolutionary history.

Finding the answer is going to be tough. We think there are a few hundred sextillion stars (about 10^{23}) in the entire observable universe. Suppose 1 per cent of these have small rocky planets orbiting them and suppose that 1 per cent of such planets are habitable. Then suppose that 1 per cent of these evolve multicellular life. That would mean there were about 100 quadrillion (about 10^{17}) instances of complex, potentially intelligent, life in the universe.

This sounds promising. Yet if we spread these out across the cosmos, on average such worlds will be separated by almost a million light years. Of course most stars are found in galaxies, so there could be a million instances of complex life in the Milky Way, separated by an average of only 300 light years. The problem is we have no idea what the true occurrence of genuinely habitable planets is, or the likelihood of complex life, or how often it might become recognisably intelligent and then survive long enough to be noticed. Speculation is not going to get the answer. We have to go looking.

One approach is to listen for signs of life broadcasting information. SETI, the search for extraterrestrial intelligence, has been doing this for decades. Modern, purpose-built experiments like the Allen Telescope Array in California carry on the search with state-of-the-art technology. Alternatively, if we find exoplanets with signs of biospheres then there may be clever ways to infer the presence of more than microbial life. Humans actively alter Earth. Our civilisation dumps chemicals into the atmosphere, manipulates the planetary surface, and even places thousands of artificial satellites around our world. There is no reason why intelligent life elsewhere would have to do the same, but if our neighbours do have similar dirty habits, this might lead us to them.

Finding irrefutable signs of any life beyond Earth, whether in our solar system or around nearby stars, would surely be one of the most revolutionary discoveries for human science and society. Optimistically, it could help us recognise ourselves as the single species we are, not the fragmented groups we often see ourselves as. The opportunity to finally study the incredible phenomenon of which we are a part – in its proper context, next to another example – would be extraordinarily compelling. The only remaining question would be whether we could find the ambition to go touch, smell, hear and perhaps even talk directly to this other life.

RECOMMENDED READING

How to Find a Habitable Planet by James Kasting (Princeton University Press)

The Crowded Universe: The race to find life beyond Earth by Alan Boss (Basic)

Extrasolar Planets and Astrobiology by Caleb Scharf (University Science Books)

Life in the Universe: A beginner's guide by Lewis Dartnell (Oneworld)

The Astrobiology Primer by Lucas Mix and others (bit.ly/hPaobB)

Cover image: NASA, ESA, N. Smith (U. California, Berkeley) et al, and The Hubble Heritage Team (STScI/AURA)