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Impact craters and atmospheric history on Mars provide information on how terrestrial planets form and evolve.

Exoplanet science 2.0

The study of life on and off Earth needs unified funding and a coherent plan, say **Caleb Scharf**, **Debra Fischer** and **Victoria Meadows**.

It is more than two decades since we learnt that the Universe is awash with other worlds. Since 1992, more than 3,500 exoplanets have been discovered orbiting stars other than our Sun.

The range of systems is dazzling. There is at least one planet around any star that, like the Sun, is powered by fusing hydrogen into helium. Sixty per cent of such stars harbour 'super-Earths' — rocky worlds that are more massive than ours but smaller than Neptune. One in six of these stars has an Earth-sized planet in an orbit that is tighter than Mercury's around the Sun[1].

This plethora of rocky planets raises a big question: is life common in the Universe? Even in our Solar System, there are plenty of places where organisms could potentially survive, such as in the oceans of liquid water beneath the frozen surfaces of Jupiter's satellite Europa and Saturn's moon Enceladus. Four billion years ago, life may have thrived on a warmer Mars.

Within a decade or two, we might find traces of extraterrestrial life in our Solar System. The Mars 2020 and ExoMars 2020 rovers are set to probe the Martian surface in that year. NASA's Europa Clipper and the European Space Agency's Jupiter Icy Moons Explorer (JUICE) ventures will get close to Jupiter's satellites by about 2030. The James Webb Space Telescope will look farther afield, scrutinizing the atmospheres of ▶

distant exoplanets in deep space[2].

Insights from many disciplines are needed to discover which ingredients, mechanisms and environmental pathways create and sustain life. Molecular biologists need to explain how proto-life might operate. Evolutionary biologists and ecologists need to probe life's interplay with alien environments. Geophysicists, geochemists and planetary scientists need to describe how planets evolve over billions of years. And astronomers have to detect more remote biospheres, while astrobiologists help to tie the pieces together.

Exoplanetary exploration should be central to this quest. Although exoplanets pique public attention, some astronomers see this field as niche and immature — they prefer to leave the review and funding of interdisciplinary projects in exoplanetary science to other fields. But if astronomers aren't included in such efforts, scientific quality suffers. Exoplanet science requires large and expensive teams, telescopes, satellites and computing facilities. But allied fields such as planetary and Earth science are established, vibrant and have their own wish lists of discipline-specific projects that are more ready for action than those in exoplanet research.

Competition over resources and intellectual turf is fierce among all these fields. For example, astronomers may favour building space-based observatories to gather more statistical data on exoplanets[3]. Meanwhile, planetary scientists might argue for detailed studies of a few planets. Both approaches are ultimately compatible, but that tension erodes the clarity of goals and can make funders nervous.

Crucial opportunities for scientists to learn from one another are falling between the cracks. For example, most Solar-System research is barely influenced by exoplanetary studies, and vice versa. Yet exoplanet data must be calibrated with knowledge about the Solar System, from the nature of runaway greenhouse-gas effects on Venus-like planets to how the orbits of young planetary systems are reconfigured.

INTERACTION, NOT ISOLATION

There has to be a radical shift. Now that answers about life's universality are finally within reach, funding agencies and scientists must step up. In our view, the field needs a systems-science approach[4] focused on interactions — between galactic environments, planet formation, orbital dynamics, heliophysics, atmospheres, hydrospheres, cryospheres, geospheres, biospheres and magnetospheres — rather than on components in isolation. This would extend Earth-systems science to encompass other types of planet and ecosystem.

Here we highlight three key questions that illustrate how exoplanet systems science can draw disciplines together.

Studying organisms from Yellowstone National Park's hot springs can uncover conditions needed for life.

SMITH COLLECTION/GADO/GETTY

What dictates planets' variety and properties? For example, why are the atmospheres and climates of Venus, Earth, Mars and Titan so different? To find out, we must bridge the gaps between Solar-System, exoplanet and astrophysical science. Observational data must be tied to models that simulate the evolution of the atmospheres, interiors and surfaces of planets over billions of years[5]. Tools from data science must be adapted to tackle increasingly large and complex data sets.

The Solar System should serve as one calibration point while its statistical significance is assessed. For example, structures in Jupiter's atmosphere and magnetic field revealed by NASA's Juno spacecraft are changing views of the planet's core and of how gas giants form. Studies of vortices and reflective particles in Neptune's atmosphere have shown how chemistry affects the spectra of ice giants. And the New Horizons mission to the dwarf planet Pluto and the Dawn mission to the minor planets Vesta and Ceres helped to trace how condensed volatile compounds are distributed in the Solar System.

Exoplanetary data challenge established ideas and put our understanding of the Solar System into a wider context. For example, we now know that planets can form around binary stars, extremely close to stars and in dense packs. Gas giants have a wider range of chemical compositions than was previously thought. Planetary orbits can be highly elongated or inclined. Astronomy facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile are revealing details of the agglomeration of dust and solids, and chemical zones in nascent planetary systems unlike ours.

Wider insights from astronomy are also needed. A major question is how stars influence the planets around them. Stars spin and oscillate according to their age, internal structure and activity. Young and low-mass stars can emit intense X-rays and γ-rays or eject charged particles. These may erode the atmospheres of planets and modify their composition, affecting their surface temperature and ability to hold water[6]. A planet's magnetosphere can mitigate this, but needs to be better understood.

The elements in stars influence planet formation, but it is unclear how. Elements can accumulate in different areas of the disks that ring young stars. The build-up of material might be affected by the rates at which stars and disks spin. The bulk properties of stars and their births across the Milky Way need to be investigated in more depth to establish how planets have formed from the Big Bang to today.

How can we identify worlds that are capable of harbouring life? The study of exoplanets opens up a wider range of planetary characteristics than we can observe in the Solar System alone, such as mass, composition and orbital configuration. Knowledge of Earth's deep environmental history, climate and chemical state is essential for calibrating models that explore the likelihood of life forming on other worlds, perhaps under different conditions. But a broader approach to planets would also help to interpret Earth: from the puzzles of ancient atmospheric oxygenation and chemical and climatic change, to the influence of human activity.

Geoscientists and astronomers need to develop better criteria for categorizing

planets, including those capable of hosting life. Concepts such as the 'habitable zone' around stars can guide our initial search, by simplistically identifying rocky planets that might have liquid water on the surface. But the real challenge lies in modelling and measuring actual details of surface conditions and imagining evolutionary strategies in these places[7]. The presence of temperate surfaces depends on many things, including the composition and photochemistry of the atmosphere, the tilt and rate at which a planet spins and the topography of a planet's surface[5]. A systems approach would be much more efficient at formally identifying the most important factors than current methods are.

Existing efforts that bring climate scientists together with astronomers to build generalized climate models for rocky exoplanets could be the kernel for growing this systems approach. These models, in turn, test the sensitivity of Earth's properties to atmospheric conditions and extreme forcings of climate.

Basic geological research is needed to understand the cores of planets, the weathering and transport of material on their surfaces, their magnetic fields and the probability that water is present. Exoplanetary science is stimulating advances in deep-Earth sensing, experimentation and modelling[8]. For example, the 2017 American Geophysical Union (AGU) autumn meeting hosted sessions on how heat and volcanism influence the geochemistry, mineralogy and petrology of Mercury, Venus, Earth, the Moon, Mars and asteroids.

How can we decode life's relationship with its environment? Life's possible behaviour on planets around other stars with different orbits, ages and histories is central to understanding Earth systems and the origins and early evolution of life on our planet. Microbiologists and astrobiologists need to inform speculations about life elsewhere by providing limits to its molecular capabilities. It is helpful to study terrestrial organisms that live in extreme conditions, such as around deep-sea hydrothermal vents or hot springs, but astronomers and planet modellers must know the options for life's possible effects on planetary chemistry and its interplay with abiotic processes if they are to find it. Work on metabolic pathways and on abiotic photochemistry and geochemistry is changing perspectives on chemical biomarkers and global chemical equilibria[9].

We need to know what fraction of a planet is capable of sustaining organisms, as well as which chemical and climatic properties that can be observed astronomically may reveal a biosphere. Ecological models in Earth-climate simulations need to be examined in the context of exoplanets, where radiation, rotation, planet orientation and land–ocean fractions are very different. Fundamental questions about cell function and adaptation can be tackled theoretically and experimentally using virtual and laboratory environments. Ecologists, planetary scientists and geoscientists must also examine the nature of geospheres for planets of widely different ages, as well as primitive atmospheres where molecular species such as hydrogen may be abundant.

Uncertainties about the chemical and thermal conditions of young planets must be reduced. Where do the first biomolecules come from, and what chemistry is involved in life's origins? Data from exoplanetary systems, as well as from laboratory astrochemistry and models of planet assembly, can provide scenarios for chemists and biologists to evaluate and study these processes experimentally.

NEW FRONTIERS

Exoplanetary systems science will be kick-started through the reorientation of research and the restructuring of funding programmes. Funding agencies should replace current grant silos with broader themes. For example, elements of the US National Science Foundation's (NSF's) Astronomy & Astrophysics, Geophysics and Ecosystem Studies programmes could be replaced by one exoplanetary systems science programme.

The NSF's solar and planetary research programme, NASA's Cosmic Origins programme and the European Research Council's Synergy Grant scheme still largely assign funding in traditional ways. Fields such as Solar-System science and exoplanetary science should not have to compete. It is essential that agencies and institutions support systems-inspired consortia.

> ***"Funding agencies should replace current grant silos with broader themes."***

The next-generation of space-based observatories that are being discussed for selection in 2020 and launch in the 2030s should be viewed as systems-science missions. These include NASA's Large UV/Optical/IR Surveyor (LUVOIR) or Habitable Exoplanet Imaging Mission (HabEx). Their priorities should be evaluated in an interdisciplinary light and plans should be made accordingly for how their time will be allocated[10].

Some institutions have already moved in this direction. Since 1998, the NASA Astrobiology Institute, directed from NASA's Ames Research Center in Mountain View, California, has funded astrophysics, exoplanets, biology, chemistry and planetary exploration through a single programme. Some universities, such as the University of Arizona in Tucson, the University of Washington in Seattle and McMaster University in Hamilton, Canada, have established centres and graduate programmes that bridge astronomy, planetary science, Earth science and biological sciences.

Networks are being created, such as the European Astrobiology Campus and the European Astrobiology Network Association, to foster interdisciplinary training and communication. Efforts are under way to accelerate astrobiology research in China, initiated by a team formed at the International Space Science Institute in Bern, Switzerland. Since 2015, NASA's Nexus for Exoplanetary System Science (NExSS) coalition has forged a community that supports the exchange of ideas and active collaboration. It comprises more than a dozen teams with diverse approaches to modelling and observing exoplanets.

Building more coherence into efforts such as these would be the next step towards exoplanetary systems science. It must be the subject of a bigger conversation before the next US decadal surveys, in 2020 for astronomy and in 2022 for planetary science. We encourage professional societies to address the idea. These include the American Astronomical Society, the AGU and the American Association for the Advancement of Science (AAAS) and global organizations such as the International Astronomical Union (IAU).

A good start would be for the AAAS or the IAU to convene researchers from areas that are already embracing systems approaches to share their insights with exoplanetary researchers. We have a lot to learn from genomics, systems biology, complex systems, public health, data science and machine learning. ■

Caleb Scharf *is director of astrobiology at Columbia University, New York City, New York, USA.* **Debra Fischer** *is a professor of astronomy at Yale University, New Haven, Connecticut, USA.* **Victoria Meadows** *is a professor of astronomy and principal investigator at the Virtual Planet Laboratory, University of Washington, Seattle, Washington, USA.*
e-mail: caleb@astro.columbia.edu

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