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. ■

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