SPECIAL FEATURE: INTRODUCTION

Exoplanets

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We are in the midst of a revolution in our understanding of planets in the Universe. In the last 20 years, 200-times more planets have been discovered beyond our solar system than reside within it. Astronomers are determining their properties, are finding correlations between a star's type and its planet population, and have begun to probe exoplanetary atmospheres. One idea to emerge is that the planets of the solar system are not representative in type, mix, or orbit. Another is that comparative planetology has become a palpable reality. A third is that we are merely on the cusp of a transformation in our conceptions of planet birth and evolution. With all this progress, textbooks are being rewritten yearly. To communicate a sense of the pace and excitement of this new subject, we have assembled a collection of articles by some of the leading researchers in their subfields that summarizes the current state of play across the broadening spectrum of topics relevant to the study of exoplanets.

In "Spectra as windows into exoplanet atmospheres," Adam Burrows (1) provides a perspective on exoplanet theory and remote sensing via photometry and spectroscopy. He highlights the need for better spectra and the limitations—despite recent progress—in our current knowledge of exoplanet atmospheres. Importantly, Burrows emphasizes that the true function of the recent past of exoplanet research has been to train the next generation of scientists who will ensure that the foundations of comparative exoplanetolgy in the future will be robust.

Yoram Lithwick and Yanqin Wu (2) explore the organization of planetary orbits and systems resulting from chaos in their gravitational dynamics and mutual evolution. Eric Ford (3) also reviews ideas concerning the architectures of exoplanetary systems, and addresses some implications for their formation. In particular, Ford focuses on the creation of multiple planet systems in tight orbits, the excitation of orbital eccentricities, and the usefulness of transit timing variation caused by mutual gravitational interactions in providing constraints on the formation and orbital evolution of planetary systems with low-mass planets.

David Spiegel, Jonathan Fortney, and Christophe Sotin (4) delve into the physical structure of exoplanets. Emphasizing that the emerging data suggest that our solar system is in no way typical, these authors review the diversity of possible planet interior structures, from super-Jupiters to planets half the mass of the Earth. Along the way, they discuss the variety of material properties—from those of compressed solids to those of dilute gases—that determine the size and profiles of planets in the galaxy. The relevant equations of state are explored and the possible role of the radius-mass distribution function in informing our understanding of planet formation and evolution is investigated.

Christopher McKay (5) reviews the requirements and limits for life and habitability in the context of exoplanets. Using the variety of life on Earth as a guide, McKay emphasizes that temperature is a key and that low light levels, high UV fluxes, and low oxygen levels need not be existential problems for various possible forms of alien life, although the biological availability of nitrogen may be an issue.

Sara Seager (6) reviews the likely means by which life could be inferred on rocky exoplanets—the identification of atmospheric biosignatures in the planet's spectrum—and the many obstacles to the robust identification of those biomolecules. Seager summarizes lessons learned to date through the study of scores of giant and sub-Neptune exoplanet atmospheres and the inherent limitations of remote sensing from the Earth, and posits a way forward to reliably ascertain the presence of life beyond the solar system. Along the way, Seager suggests an expansion of the concept of habitable zone. Continuing on this theme, James Kasting et al. (7) investigate the exact thermodynamic and radiative conditions necessary to maintain liquid water. These authors then go on to argue that liquid water is necessary for carbon-based, photosynthetic life to proliferate on a rocky planet to a degree sufficient to modify its atmosphere enough to enable spectroscopic detection by us. Kasting et al. also argue that conservative habitable-zone definitions should be used for designing future space-based telescopes, but that optimistic definitions will be necessary to interpret data from such missions. Interestingly, Kasting et al. go on to estimate that the frequency of Earth-like planets around stars smaller than the Sun might be as high as 40–50%.

Natalie Batalha (8) summarizes the demographics of planetary systems that have emerged from the Kepler space mission. With more than 3,500 planet candidates and a reliability rate of 85–90%, Batalha presents the revealed distributions in planet radius and orbital period as a function of primary star. Designed to determine the prevalence of planets like the Earth, such distributions and statistics are the major products of the Kepler mission. Batalha also reviews the role of the methods of transit timing, radial-velocity measurement, and statistical validation in determining reliable planet occurrence rates, and shows that planets—in particular small planets and multiple planet systems—abound in our galaxy.

Geoffrey Marcy et al. (9) continue this theme to show that planets one- to four-times the radius of Earth, a population missing in the solar system, are common. These authors reiterate that the smallest planets are the most common and determine distributions in planet radius and orbital period. Marcy et al. supplement the Kepler data for radii with mass measurements from radial velocity techniques to reveal roughly two populations of exoplanets smaller than four-times the radius of the Earth: those with the lowest masses, whose radii imply thin atmospheres, and those with larger radii that can be explained only by the presence of thick gaseous envelopes. Although noisy, this rough systematic must reflect modes of planet formation and subsequent envelope evaporation. Marcy et al. note that rocky planets occur around stars having a range of heavy element abundances, whereas gas giant exoplanets are more common around stars rich in heavy elements. This finding leads the authors to speculate that the fast formation of rocky cores in protoplanetary disks enriched in heavy elements might

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permit the accumulation of gas from the protoplanetary disk before it vanishes, forming the giant planets.

Finally, Bruce Macintosh et al. (10) present the first-light observations from the Gemini Planet Imager (GPI), designed to discover and characterize extrasolar giant planets, brown dwarfs, and ice giants by direct imaging from under the glare of nearby parent stars. GPI is the first of a new generation of high-performance imaging systems that combines adaptive optics with a coronagraph and an integral field spectrograph to achieve maximum sensitivity to detect dim planets in wide orbits next to their bright primaries. MacIntosh et al. present here the first of what are expected to be many planet detections at wide separation that can be accomplished by no other means. In the process, the authors demonstrate the great discovery potential of high-contrast imaging to explore hitherto unreachable planetary realms.

Together, the articles of this Special Feature encapsulate both the energy of this new subject and its great variety. Touching upon most of astronomy, the science of exoplanets is likely to engage and amaze both astronomers and the public at large for years to come as it matures into a core discipline at the interface between astronomy and traditional planetary science. With this collection, we hope to convey to the reader the excitement of the recent past, as well as the anticipated excitement of the journey ahead.

1 Burrows AS (2014) Spectra as windows into exoplanet atmospheres. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304208111.

2 Lithwick Y, Wu Y (2013) Secular chaos and its application to Mercury, hot Jupiters, and the organization of planetary systems. *Proc Natl Acad Sci USA*, 10.1073/pnas.1308261110.

3 Ford EB (2014) Architectures of planetary systems and implications for their formation. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304219111.

4 Spiegel DS, Fortney JJ, Sotin C (2013) Structure of exoplanets. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304206111.

5 McKay CP (2014) Requirements and limits for life in the context of exoplanets. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304212111.

6 Seager S (2014) The future of spectroscopic life detection on exoplanets. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304213111.

7 Kasting JF, Kopparapu R, Ramirez RM, Harman CE (2013) Remote life-detection criteria, habitable zone boundaries, and the frequency of Earth-like planets around M and late K stars. *Proc Natl Acad Sci USA*, 10.1073/pnas.1309107110.

8 Batalha NM (2014) Exploring exoplanet populations with NASA's Kepler Mission. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304196111.

9 Marcy GW, et al. (2014) Occurrence and core-envelope structure of 1–4× Earth-size planets around Sun-like stars. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304197111.

10 Macintosh B, et al. (2014) First light of the Gemini Planet Imager. *Proc Natl Acad Sci USA*, 10.1073/pnas.1304215111.