Overview

In the past decade the field of exoplanet science has rapidly expanded with the discoveries of thousands of new planets, and the characterization of worlds unlike those in our solar system. From the ensuing treasure trove of exoplanet demographics and characteristics we have learned that most, if not all, stars host planets, and that planets smaller than Neptune are ubiquitous. These systems and the planets that comprise them are surprisingly diverse, with few matching the solar system. We have characterized a plethora of larger worlds for density and atmospheric properties, progressing from gas giants to large terrestrial planets, and from highly irradiated planets to cooler planets, as observational sensitivity and techniques improved. Significant advances have been made in understanding solar system planetary processes and how our planetary system formed and evolved. We have expanded our understanding of formation processes and the subsequent interactions of exoplanets with their host stars, and other components of their planetary systems, and identified planetary migration as a common process for exoplanet systems and our solar system. Complementing our studies of individual worlds, multiple techniques have pieced together a broad understanding of exoplanet classes, enabling a new era of comparative planetary system science as we work towards a more complete census.

Even though exciting progress has been made, significant key advances are still needed to place the solar system and our inhabited Earth in its cosmic context. Although we have discovered and characterized giant planets close to and very far from their stars, analogs of solar system giant planets have been beyond our reach. We have discovered close-in terrestrial exoplanets, but none in the habitable zone (HZ) of G dwarfs like our Sun. A handful of terrestrials are confirmed to orbit in the HZ of M dwarfs, but we have not been able to probe their atmospheres to understand if they are truly Earth-like, or have experienced strongly-divergent evolutionary paths. We understand that interactions within the entire planetary system are critical to understanding the formation, evolution, environment and habitability of exoplanets, but massively interdisciplinary research is still needed to better understand planets as interacting components evolving in the context of their host star and planetary system environment.

Upcoming observations of terrestrial exoplanets will enable one of humanity's grandest explorations—the search for habitable environments and life around a diversity of nearby stars. Exploring this exciting and unprecedented frontier will help place Earth's sparkling oasis of life in its cosmic context. This search is now within our scientific and technological reach, and can be informed by our exploration of larger exoplanets and solar system analogs, as well as interdisciplinary efforts that incorporate theoretical models and laboratory investigations. Below we outline key discoveries in the past decade that set the stage for these exciting future advances.

PROGRESS IN EXOPLANET, ASTROBIOLOGY, AND SOLAR SYSTEM SCIENCE SINCE NEW WORLDS, NEW HORIZONS

Exoplanet Detection and Planetary System Architectures

Since NWNH, the number of known exoplanets has increased by an order of magnitude to over 4000, with large contributions from both radial velocity (RV) and transit surveys. Early on, the typical planets detected were massive Jovians orbiting within a few AU of their host stars. *Kepler's* 2009 launch inaugurated a new era of thousands of discoveries, detecting significantly smaller, but still close-in, transiting planets (1-4 Earth radii). Most are closer than Mercury is to the Sun, but several are within the HZ of their parent stars. In parallel, microlensing surveys detected planets near the snow lines of M dwarfs, and advances in direct imaging refined our view of the outer reaches of planetary systems.

The Distribution and Nature of Giant Planets

Over the 25 years since the Nobel-Award-winning discovery of 51 Pegasi b, our understanding of giant planets has matured significantly. RV surveys have increased in sensitivity by orders of magnitude and observational campaigns begun in the 1990s now have the baselines required to detect giant planets with orbital periods similar to those of Jupiter. These surveys have revealed that hot Jupiters like 51 Peg b are rare, and that close-in brown dwarfs are rarer still. While hot Jupiters are not common, their frequency increases around more metal-rich stars, indicating that present-day system architectures are at least partially set by the initial disk mass and composition. Mass measurements of transiting planets have revealed an unexpectedly large dispersion of planetary radii at a given mass (3 orders of magnitude in density), especially for planets near Neptune mass, suggesting a diversity of compositions even at fixed mass. Giant exoplanets are enriched in heavy elements compared to their parent stars, and this enrichment seems to increase with decreasing planet mass, mirroring the trend seen in solar system planets.

However, although many planets have been found, our understanding of giant planets at a range of orbital distances comparable to those in our solar system is largely incomplete. RV and direct imaging surveys of young stars find that only 10% of solar type stars harbor giant planets between 1 and 13 Jupiter masses inside of 100 AU, and RV and microlensing suggest that for M dwarfs it is even lower, at 3%. In the outer reaches, only a few dozen planets are known with semimajor axes larger than 50 AU, and many have poorly-constrained orbits and masses. Based on all available surveys, the occurrence rate of gas giants appears to peak near a few AU and then decline at larger separations, but these estimates depend on extrapolations of power laws in mass and semi-major axis, and the ~3-10 AU region is not yet thoroughly explored. A more complete census would be needed to determine if our solar system is unusual in having a Jupiter, which has large implications for volatile delivery, planetary evolution and habitability.

The Distribution and Nature of Sub-Neptune Planets

Three of *Kepler's* key discoveries were that sub-Neptunes (1-4 Earth radii) are the most abundant type of exoplanet at orbital periods less than 200 days, that roughly 50% of stars have small planets orbiting more closely than Mercury orbits the Sun, and that M dwarfs host close-in planets at a higher frequency than Sun-like stars. Comparing the masses and radii of exoplanets to theoretical predictions and solar system planets has begun to reveal key compositional trends. At orbital periods shorter than Mercury's, intense stellar radiation has sculpted the mass-radius diagram, inflating hot Jupiters and producing a bimodal radius distribution for small planets, likely due to atmospheric escape. While highly-irradiated planets smaller than ~1.6 R_{Earth} have bulk densities consistent with a terrestrial composition, larger planets require significant fractions of volatiles, as do solar system ice giants. Near-terrestrial masses and bulk densities have been measured for transiting planets in near-resonant configurations using transit timing variations (TTVs), and spectroscopy of white dwarfs possibly polluted by disrupted planets/planetesimals have revealed abundance ratios similar to those of the bulk Earth. However, our view of the mass-radius diagram is still dominated by planets larger and hotter than Earth. Tracking the existence and location of the planet radius gap as a function of stellar mass, stellar metallicity, and lower insolation will refine our view of the formation and evolution of low mass planets.

We have discovered ~20 likely terrestrial planets ($R < 1.6\ R_{Earth}$ and roughly terrestrial densities) within the HZ, although many of these are too distant to be amenable to follow-up for characterization. Ongoing ground- and space-based surveys of nearby cool dwarfs have discovered a small but growing number of M dwarf HZ terrestrial planets whose atmospheres may be accessible to JWST and ELTs.

Mapping Planetary Architectures: The solar system In The Context of Exoplanetary Systems

Our understanding of planetary system architectures is currently in its infancy. While we have limited sensitivity to solar system-like planets, initial indications of the rarity of Jupiter analogs suggest that solar system-like architectures are rare also. Transit measurements have discovered the most multi-planet systems to date, but are biased towards finding largely co-planar, close-in, closely-packed systems that would fit within Mercury's orbit, and show signs of migration. The RV method has found more widely-spaced multi-planet systems, but is limited primarily to gas giants at longer orbital periods.

Growing knowledge of the distribution of planetesimals in our own debris disk (KBOs, comets, and asteroids) has modified our understanding of the solar system from an orderly arrangement of stationary planets to a complex system of migrating planets. The Nice and Grand Tack models of migration in our solar system's past reproduce many of the observed planetesimal distributions, and present a system-wide connection among solar system bodies, and predictions for exoplanet outcomes.

The distribution of material in mature debris disks can also inform the history of exoplanetary systems. Spatially-resolved visible-NIR images of dozens of bright debris disks, analogous to more massive versions of our Kuiper Belt, show extended halos of dust in the cold outer regions, potentially sculpted by the ISM. ALMA images of debris disks show underlying planetesimal distributions that are typically well-defined belts, indicative of sculpting by planets. Silicate emission from copious hot dust and density asymmetries in cold belts suggest possible collisional events, and disks that are more dynamic than previously thought. Directly imaged variations in the AU Mic disk resemble material being ejected by stellar winds. Dust compositions and optical properties are varied and poorly constrained, but likely silicate and water dominated. Detection of low levels of gas in debris disks via atomic absorption and molecular CO emission suggest non-solar compositions, with significant carbon enhancement in some systems. The two populations of imaged debris disks and systems with known planets, have little current overlap, in part due to disk imaging sensitivity limits. Yet many disks include belts and inclination warps, likely due to exoplanets. Mean motion resonant structures, similar to Earth's impact on the zodiacal cloud, were once considered a promising sign for exoplanets in debris disks, but have largely eluded detection and may be limited to fainter disks below detection limits.

Exoplanet Characterization and Solar System Synergy

Efforts to characterize and model exoplanet atmospheres have focused largely on giant and Neptune-sized planets; atmospheric characterization of smaller planets has just begun. Comprehensive surveys of transiting planets across a range of mass, radius, orbits, and/or insolation levels have provided key insights into interior and atmospheric composition, as well as the atmospheric circulation, chemical, and radiative properties that regulate planetary atmospheres. Observational studies have compared the atmospheric composition of dozens of planets. For directly imaged planets, spectroscopic and photometric observations have measured the abundances of multiple molecular species (H_2O, CH_4, CO) and revealed the presence of cloud decks, setting young giants on a continuum with more massive brown dwarfs. For transiting planets, atmospheric characterization first focused on more easily detectable atoms and molecules (Na, K, and H_2O) and expanded with improved observing methodologies and capabilities.

The physical conditions in planetary atmospheres, which probe processes like global circulation and radiative energy balance, have been thoroughly studied for roughly a dozen larger planets. High-resolution spectroscopy has measured precise thermal profiles, winds, and rotation rates for a handful of giant planets. *HST* and *Spitzer* thermal phase curves have constrained atmospheric circulation by comparison to 3D general circulation models, and *HST* and ground-based high-resolution spectra have detected thermal inversions arising within strongly absorbing atmospheric regions. The same techniques have detected atmospheric escape from several hot, gas-rich transiting exoplanets, confirming that escape is common and may influence the size of close-in planets. Planetary magnetic fields have been inferred for a small number of giant planets from periodic stellar activity, or from transit light curves with evidence for bow shocks. Magnetic fields provide a window into interior processes such as convection, and likely regulate atmospheric escape. How escape scales with planetary and stellar properties is still not well-understood, providing an opportunity for exoplanet/solar system synergies.

Recent discoveries of nearby terrestrial planets, including HZ worlds orbiting late-type M dwarfs, have provided some of the first terrestrial targets for characterization. However, initial characterization attempts with *HST*, *Spitzer* and ground-based telescopes have only been able to provide atmospheric constraints via non-detections of atmospheric features. *Spitzer* phase curves of a hot terrestrial planet that receives 70 times Earth's insolation indicates little or no atmosphere. *HST* and *Spitzer* observations of a handful of hot and HZ terrestrials, when combined with laboratory data and theory, make cloudless and cloudy hydrogen-dominated atmospheres less likely than denser ones.

Despite these early successes, there are many opportunities for improved atmospheric characterization. Today, chemical abundances are typically measured with a precision of only an order of magnitude, a sign of the still limited data quality of the challenging transit measurements, which preclude a detailed understanding of planetary formation and evolution. Atmospheric hazes and clouds in many exoplanets further obscure the gaseous absorbers, and narrow wavelength ranges and current approximate cloud models limit our ability to account for the effects of these atmospheric aerosols. Our reduced insight into some solar system planets (particularly Venus, Uranus, and Neptune) in turn limits our understanding of the dynamics, composition, and evolution of atmospheres, indicating the need for further study of these worlds. Transmission spectroscopy in M dwarf systems can never be sensitive to the planetary surface, supporting the need for future direct spectroscopy of potentially habitable worlds. Finally, atmospheric characterization has focused almost exclusively on shorter period, larger planets, and we cannot yet systematically connect atmospheric composition to the density/bulk compositional properties of longer period planets of all sizes, which often have less well characterized masses and radii.

Astrophysics assets and solar system science

The planetary science community has made valuable use of astrophysics assets such as *Hubble*, *Spitzer*, and *Kepler* to explore solar system science objectives, which in return advance exoplanet science and astrobiology. Planetary scientists have observed the composition and orbital dynamics of small bodies to better understand the formation of the solar system; observed solar system atmospheres to understand atmospheric processes for planets of different composition and incident solar radiation; probed the interiors of volatile-rich bodies and identified new potentially habitable environments through the study of plumes at Europa and Enceladus; and observed the effects of extreme tidal heating on the interior composition and volcanic activity at Io. This valuable coordination has led to important discoveries that benefit both space science communities.

The Dawn of Exoplanet Astrobiology: The Search for Habitable Environments and Life

In the past 10 years, exoplanet astrobiology has transformed from a field driven by promising statistical predictions, to one with targets accessible to near-term observation. Significant advances have been made in our understanding of how to identify potentially habitable worlds, and how to best search for signs of life in their environments. Theory and observations now suggest that there are many evolving interactions between a planet, star, and planetary system that affect the likelihood that a planet can support a surface ocean—and that a comprehensive, systems-level approach to habitability assessment is now needed. These studies have identified additional systems-level challenges to habitability for M dwarf HZ planets, including radiation and stellar-wind-driven atmosphere and ocean loss, and gravitational interactions that modify orbits, rotation rate, and climate.

Within the solar system, observations of Mars, Europa, Enceladus and Titan have revealed subsurface environments that potentially harbor liquid water, and greatly expanded the ocean worlds in our solar system. Comparison of the gas giant satellites provided a systems-level view of how planetary size, formation and tidal interactions work together to impact differentiation, ocean depths, pressures and surface activity. These efforts forged links with the oceanography community in understanding serpentinization, hydrothermal vents, ocean pH, circulation and ice/ocean interactions. Observations and missions to small body populations illuminated processes of volatile evolution and delivery to forming planets, while exoplanet science revealed planetary system architecture influences on small body inventories and organic delivery in debris and protoplanetary disks. Venus provided context for *loss* of habitability, with relevance for Venus-analog extrasolar planets, and studies of stellar wind/planetary atmosphere interactions at Mars discovered and informed planetary atmospheric loss processes.

The astrobiological foundation needed to guide the search for biosignatures has also advanced considerably. Improved understanding of the co-evolution of life with Earth environments over the last 4 Gy has highlighted how life has modified the Earth's atmosphere, surface, oceans and interior. Life's global impacts on a planet's atmosphere, surface, and temporal behavior may therefore manifest as potentially detectable exoplanet biosignatures, or technosignatures—if that life is technologically capable. Key frontiers in biosignature science now focus on the identification of novel biosignatures beyond the canonical O_2/O_3 and CH_4, especially those that are agnostic to life's molecular makeup or metabolism; understanding non-life planetary processes that may mimic, destroy or alter potential biosignatures; and taking the first steps towards developing a comprehensive statistical framework for biosignature assessment that uses critical observables of the star, planet and planetary system to determine the probability, and increase our confidence, that a potential biosignature is due to life.