Summary of the Exoplanet review paper

Exoplanet Discovery and Characterization: A Summary

The search for planets beyond our solar system has evolved into one of the most active fields in observational astronomy. The first confirmed detections of exoplanets were surprising—not around main-sequence stars, but around a pulsar, identified through variations in pulsar timing. This landmark was followed by the discovery of the first exoplanet around a Sun-like star, 51 Pegasi b, using the radial velocity method in 1995. This technique relies on detecting tiny shifts in the host star's spectrum due to the gravitational influence of an unseen planetary companion. While powerful, the radial velocity method has limitations—it cannot determine the orbital inclination of the system, and thus provides only a lower limit on the planet's true mass. Precision in these measurements has largely been enabled by high-resolution spectrographs such as HARPS and HARPS-N, mounted on telescopes in both hemispheres.

A major leap occurred in 1999 with the detection of the first transiting exoplanet, HD 209458b, wherein a planet passes in front of its host star, causing a dip in the star's observed brightness. This transit method not only confirms planetary presence but also opens a window into the planet's atmosphere through transmission spectroscopy. By comparing spectra during and outside the transit, astronomers can detect absorption features caused by atmospheric molecules. Notably, the Hubble and Spitzer space telescopes have played key roles in detecting atmospheric components like sodium, oxygen, and water vapor in hot Jupiters. However, transit detection requires very high photometric accuracy, limiting early ground-based searches to bright stars. This challenge was overcome with space-based missions like *Kepler*, which continuously monitored over 150,000 stars and discovered thousands of exoplanets. Despite a malfunction that impaired two of Kepler's gyroscopes in 2013, the mission was revived as "K2" and continued yielding important discoveries.

Another innovative method of exoplanet detection is gravitational microlensing, rooted in Einstein's theory of general relativity. When a foreground star (or planet) aligns with a background star, its gravity magnifies the latter's light. While most microlensing signals are due to stars and last for weeks or months, planetary microlensing signals are shorter—only a few days—and require intensive high-cadence monitoring. The first such event was detected in 2003. Although these events are not repeatable, well-sampled light curves can yield accurate estimates of planetary masses and orbital separations, especially when observed simultaneously from space and ground, which allows for parallax measurements. Microlensing is especially powerful for detecting low-mass planets at wide separations or even free-floating exoplanets, which do not orbit any star. Surveys like OGLE and MOA have made strides in this area, discovering ultra-short microlensing events indicative of Earth-like rogue planets.

Direct imaging of exoplanets, once considered futuristic, became possible in 2008 with the imaging of multiple planets around the star HR 8799. Using adaptive optics (AO) systems and coronagraphs on large ground-based telescopes like Keck and Gemini, astronomers were able to resolve planets at wide separations (tens to hundreds of AU) and even monitor their orbital motions. This method allows for

direct spectroscopic studies of exoplanetary atmospheres, but is limited to young, massive planets around bright, nearby stars. The formation of such wide-orbit planets challenges traditional models like core accretion and may require alternative mechanisms like cloud fragmentation or planet-planet scattering. Observational clues, such as the alignment of planetary orbits and disks, or the eccentricity distribution of planets, help distinguish between these formation scenarios.

To better understand planet formation and evolution, it is crucial to obtain both accurate masses and radii of exoplanets. While transit observations give radius estimates, they must be paired with radial velocity measurements to yield planetary masses and densities. Projects like the California Kepler Survey have enhanced precision by characterizing host stars using high-resolution spectroscopy, which in turn refines radius estimates of their planets. This effort has led to key findings, such as the bimodal radius distribution of small planets: super-Earths (~1.3 Earth radii) and sub-Neptunes (~2.4 Earth radii), with a noticeable gap around 1.8 Earth radii—a feature thought to result from atmospheric loss due to photoevaporation. Meanwhile, the mass-radius relation shows transitions at ~2 Earth masses and ~0.41 Jupiter masses, marking boundaries between rocky, Neptunian, and Jovian-type planets. Yet, composition remains ambiguous; the same density could indicate either a rocky planet with a thin atmosphere or a water-rich planet with a thick envelope.

To resolve these ambiguities, astronomers study planetary atmospheres via transmission spectroscopy. While challenging due to the faintness of the planetary signal, especially from the ground, space telescopes like Hubble and Spitzer have produced atmospheric spectra of hot Jupiters, revealing a diversity ranging from clear to hazy atmospheres. Another fundamental property is orbital distance. Initially, hot Jupiters were overrepresented due to detection bias, but improved instruments have revealed more planets in temperate, potentially habitable zones. The two main planet formation models—core accretion and disk instability—predict different mass and distance distributions, and are testable via stellar metallicity trends and system architecture. For instance, metal-rich stars tend to host gas giants, supporting the core accretion model.

Importantly, exoplanets may not remain where they form. Migration due to dynamical interactions—such as planet-planet scattering—can push one planet inward while ejecting another to distant orbits. Alternatively, planets at wide separations might have formed directly from collapsing gas clouds like binary stars. These different origins leave signatures in orbital alignments, eccentricities, and system ages. Recent microlensing surveys even suggest the existence of a large population of free-floating Jupiter-mass objects, though some results remain debated. Newer studies point toward smaller, Earth-mass rogue planets as being more consistent with known planet formation mechanisms.

Looking forward, the field of exoplanetary science is entering a new phase driven by instrumental innovation. Next-generation spectrographs like ESPRESSO (on the VLT) and the planned CODEX (for the E-ELT) aim to reach the precision needed to detect Earth-mass planets via radial velocity—down to ~10 cm/s or even 2 cm/s. However, stellar variability remains a major obstacle, often mimicking planetary signals. Mitigating this requires combining photometry and spectroscopy to disentangle stellar noise. On the transit front, missions like TESS, PLATO, and ARIEL are poised to discover and characterize thousands of new exoplanets, particularly around bright stars. From the ground, wide-field surveys like

NGTS, KELT, and TRAPPIST continue to monitor the sky, though care must be taken to correct for blending effects from background stars.

Microlensing will benefit from upcoming missions like **WFIRST**, which will deliver high-cadence, space-based observations of the Galactic bulge and uncover thousands of planets—including those in other galaxies. Simultaneous ground-space observations will enable mass measurements via parallax. The **PRIME** project, using infrared microlensing, will enhance sensitivity toward dusty galactic regions, while **LSST** will provide optical microlensing data across five filters. Direct imaging is also evolving, with new AO systems like GPI, SCExAO, and future starshade missions pushing the limits of contrast and resolution. These advances aim to image Earth-like planets in habitable zones and study them in detail.

In conclusion, the field has moved beyond simple detection. With improved data and instruments, astronomers are now probing the **formation**, **composition**, **evolution**, and **habitability** of exoplanets. The coming years hold the promise of detecting **true Earth analogs**, and perhaps, finding signs of **life beyond our Solar System**.