

## Introduction

The study of exoplanets—planets outside our solar system—has rapidly evolved over the past few decades, thanks to major advances in observational astronomy. This report summarizes Chien-Hsiu Lee's review paper, highlighting the historical milestones, current understanding, and future directions of exoplanet research, along with the strengths and limitations of various detection techniques.

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## Historical Milestones in Exoplanet Discovery

- **1992:** The first confirmed exoplanets were discovered around a pulsar using pulsar timing.
  - **1995:** The radial velocity method led to the detection of 51 Pegasi b, a Jupiter-like planet orbiting a Sun-like star.
  - **1999:** The transit method became prominent when HD 209458b was observed to pass in front of its star, allowing atmospheric analysis via transmission spectroscopy.
  - **2003:** The first planetary microlensing event was observed.
  - **2008:** Direct imaging captured photons from multiple exoplanets in the HR 8799 system using adaptive optics (AO) and coronagraphs.
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## Detection Methods and Their Contributions

- **Radial Velocity (RV):** Measures the Doppler shift in a star's spectrum due to gravitational tug from a planet. Requires high-precision spectrographs like HARPS. Limitations include mass-inclination degeneracy.
  - **Transit Photometry:** Detects dimming of a star's light as a planet crosses in front. Highly successful with space telescopes like *Kepler*, especially for atmospheric studies. Sensitive to small planets but limited by viewing angle.
  - **Microlensing:** Utilizes gravitational lensing effects when a planet-hosting star passes in front of a background star. It allows detection of low-mass and distant planets, even in other galaxies, but the signals are non-repetitive.
  - **Direct Imaging:** Captures light from exoplanets directly using AO and coronagraphs. Allows atmospheric characterization but is limited to large, young, and widely separated planets.
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## Current Understanding of Exoplanetary Systems

With over 3,000 confirmed exoplanets, researchers now perform **statistical analyses** to study planet formation and evolution.

- **Mass and Radius Estimates:** Combining transit and RV data helps determine planetary density and composition. Studies reveal two distinct populations: super-Earths (~1.3 Earth radii) and sub-Neptunes (~2.4 Earth radii), with a gap suggesting atmospheric loss mechanisms.
- **Atmospheric Studies:** Transmission spectroscopy reveals diverse atmospheric types even among hot Jupiters—ranging from clear to hazy/cloudy—using Hubble and Spitzer data.

- **Orbital Distances and Habitability:** Earlier detections were biased toward "hot Jupiters", but newer observations reveal more planets in the habitable zone. About 30 such exoplanets have been identified by *Kepler*.
  - **Formation Theories:**
    - **Core Accretion:** Small particles build up into massive planets; supported by a correlation between host star metallicity and giant planet occurrence.
    - **Disk Instability:** Direct gravitational collapse in the protoplanetary disk; possibly explains massive, wide-orbit planets.
  - **Migration and Dynamics:** Some exoplanets may not reside where they formed. Planet-planet scattering and disk interactions likely explain highly eccentric or widely separated orbits.
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## Future Directions

Upcoming missions and instruments will expand the exoplanet catalog and improve characterization:

- **Next-Gen Instruments:** ESPRESSO and CODEX aim for RV precision down to cm/s to detect Earth analogs.
  - **Space Missions:** TESS, PLATO, ARIEL, and WFIRST will continue Kepler's legacy with improved sensitivity and atmospheric probing capabilities.
  - **Microlensing Campaigns:** Projects like OGLE, MOA, and future PRIME will enhance detection of Earth-mass and free-floating planets.
  - **Direct Imaging Advances:** Tools like Gemini Planet Imager (GPI) and Subaru's SCExAO will improve contrast and resolution for imaging distant worlds.
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## Conclusion

The field of exoplanet research has moved from mere detection to detailed characterization, unveiling a wide variety of planetary systems. Each detection method offers unique insights, and future missions promise to address long-standing questions about planet formation, migration, and the possibility of life beyond Earth.