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The evolution of planetary systems revealed by exoplanets

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Abstract. Nearly 30 years after the discovery of 51 Peg b — the first exoplanet detected around a main-sequence star other than the Sun — our growing knowledge of planetary systems has reached a point of maturity where we can use exoplanet data to understand the intrinsic formation processes that govern planet evolution. Statistical analyses of the exoplanet population reveal patterns that are leftovers from planetary formation. Complex models of planetary evolution are needed to reproduce these patterns, which still present weak constraints. Therefore, contributions to exoplanet detection and characterization that improve the observational constraints of these patterns have become crucial for a more thorough understanding of planetary system formation. This need, coupled with our quest for habitable worlds and, ultimately, for life on other planets, drives future efforts and investments in instrumentation. Here, I present the current state of exoplanet detections, a brief inventory of planetary systems highlighting their diversity, and an overview of state-of-the-art analyses of various aspects of the exoplanet characteristics related to the formation and evolution of planetary systems in the Universe.

Resumo. Quase 30 anos após a descoberta de 51 Peg b — o primeiro exoplaneta detectado em torno de uma estrela de sequência principal além do Sol — nosso conhecimento sobre sistemas planetários atingiu um grau de maturidade que permite utilizar os dados de exoplanetas para compreender os processos intrínsecos de formação que regem a evolução planetária. Análises estatísticas da população de exoplanetas revelam padrões que são remanescentes do processo de formação planetária. Modelos complexos de evolução planetária são necessários para reproduzir tais padrões, que ainda apresentam restrições observacionais frágeis. Assim, contribuições voltadas à detecção e caracterização de exoplanetas que aprimorem essas restrições tornam-se cruciais para um entendimento mais aprofundado da formação de sistemas planetários. Essa necessidade, somada à busca por mundos habitáveis e, em última instância, por vida em outros planetas, impulsiona os esforços futuros e os investimentos em instrumentação. Neste trabalho, apresento o estado atual das detecções de exoplanetas, um breve inventário dos sistemas planetários conhecidos destacando sua diversidade, e uma visão geral das análises de ponta sobre diferentes aspectos das características dos exoplanetas relacionadas à formação e evolução de sistemas planetários no Universo.

Keywords. Stars: planetary systems

1. Introduction

A planetary system is a group of celestial bodies—including planets, moons, asteroids, comets, and dust—that orbit a star, a multiple star system, or a stellar remnant, bound together by gravity. The science of planetary systems is a multidisciplinary field built upon four foundational pillars that together support our understanding of how planets form, evolve, and interact with their environments.The first pillar is our **Solar System**, which provides a detailed and accessible laboratory for studying the bodies of a planetary system, their compositions, interactions, and dynamical histories. The second pillar, **Stars**, represents the central engines of planetary systems, influencing planet formation, habitability, and long-term evolution through radiation, winds, and magnetic activity. The third pillar consists of **Protoplanetary Disks**, the birthplaces of planets where gas and dust surrounding young stars offer critical insights into the initial conditions and physical processes leading to planetary formation. Finally, the fourth pillar is formed by **Exoplanets**—planets beyond our Solar System—which allow us to place our planetary system within a broader cosmic context and test theories of planet formation and evolution across diverse environments. These four pillars together form the conceptual framework of modern planetary science, each providing unique but complementary perspectives on the processes that govern planetary system architecture and evolution.

Over the past three decades, exoplanet research has profoundly transformed multiple domains of science and technology. In planetary science, the discovery of more than 6,000 confirmed exoplanets has reshaped our understanding of planet formation and the diversity of planetary systems, fundamentally challenging models derived solely from Solar System observations. Figure 1 illustrates this diversity by presenting three representative planetary systems.

Exoplanet research has captured substantial scientific and public interest, establishing as one of the most dynamic and interdisciplinary areas in modern astrophysics. The term "exoplanets" ranks among the most frequently cited keywords in astrophysical literature, reflecting its significant academic impact. This momentum is supported by major international investments in dedicated space missions and instruments, including CoRoT, Kepler, TESS, JWST, PLATO, and ARIEL, underscoring the central role of exoplanets in space science endeavors. The relevance of exoplanet research was further recognized by the 2019 Nobel Prize in Physics, awarded to Michel Mayor and Didier Queloz for their landmark discovery of the first exoplanet orbiting a solar-type star, marking a turning point in the history of planetary science.

In this review I attempt to provide a broad contextualization of exoplanet research and its contributions to our modern understanding of planetary formation and evolution. Far from being a complete text of this vast field, this work offers a guided exploration of key topics that have yielded significant advances in planetary science over three decades of exoplanet discoveries and characterization studies.

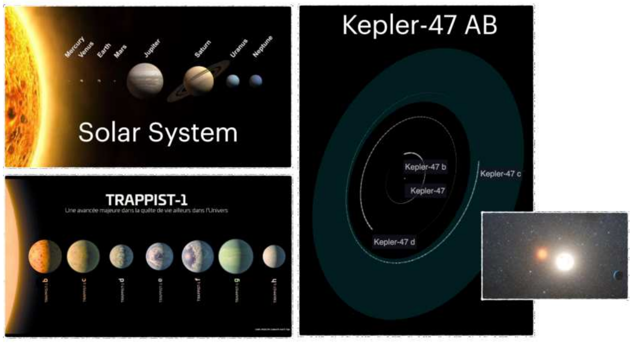

Figure 1. Three examples of planetary systems. This artistic composition highlights the diversity of architectures revealed by exoplanet research, presenting three iconic cases: our Solar System (top left panel), TRAPPIST-1 (bottom left panel), and Kepler-47 AB (right panel). The Solar System consists of the Sun and eight well-ordered planets. TRAPPIST-1, an M-dwarf, hosts seven known terrestrial planets (refs). Kepler-47 AB, on the other hand, is a close binary system composed of a Sun-like star and an M-dwarf, orbited by three planets, one of which lies within the system's habitable zone.

2. Cosmic Relevance of Planetary Systems

Although planets constitute only a small fraction of the total mass in stellar systems, they represent an important component in terms of chemical composition, angular momentum distribution, and potential habitability. In our Solar System, the combined mass of all planets corresponds to approximately 0.14% of the Sun's mass, with Jupiter alone accounting for more than 70% of the total planetary mass. Confirmed exoplanets exhibit a comparable average planet-to-star mass ratio.

The energy budget of planetary systems is also dominated by stellar sources. Nevertheless, while planets carry negligible energy compared to their host stars—for example, Jupiter's gravitational binding energy is only 10^{-5} that of the Sun—their internal energy sources play important roles in understanding planetary evolution and system history. These modest energy reservoirs stored into planets drive critical evolutionary processes and preserve fossil records of formation conditions. Planetary internal energy sources include primordial heat retained from formation processes, absorbed stellar radiation, radioactive decay of heavy elements in planetary interiors, tidal heating from gravitational interactions, latent heat release from internal phase transitions, Ohmic dissipation from atmospheric currents interacting with magnetic fields, and chemical reactions within planetary interiors. The relative importance of each source varies across different planetary classes, as summarized in Table 1.

Perhaps most remarkably, while stars dominate both mass and energy in planetary systems, planets carry the vast majority of angular momentum. In our Solar System, planets account for 98% of the total angular momentum, with Jupiter alone contributing the majority due to its substantial mass and distant orbit. This distribution directly reflects angular momentum conservation during protostellar collapse and subsequent material redistribution in the protoplanetary disk.Angular momentum plays a central role in shaping planetary system architecture and long-term evolution (Ward 1997; Laskar & Petit 2017). Processes including planet-disk interactions (Lin & Papaloizou 1986; Papaloizou & Nelson 2002), planet-planet scattering (Chatterjee et al. 2008), and tidal evolution (Ogilvie 2014) continuously redistribute angular momentum between orbital motion and stellar/planetary rotation, often leading to planetary migration, orbital eccentricity changes, or resonant configurations (Kley & Nelson 2012).

The cosmic significance of exoplanets extends beyond their dynamical contributions to their unique ability to provide environments suitable for complex chemistry and potentially life. Unlike the extreme conditions found in stellar interiors, black hole environments, or diffuse interstellar medium, planets offer moderate physical conditions—temperatures of $\sim 10^2$–10^3 K combined with pressures ranging from millibars to several bars—that can support liquid solvents and facilitate chemical reactions relevant to prebiotic processes. Planets thus occupy a unique position in the cosmic landscape as potentially the only locations where the delicate balance of conditions necessary for life can be sustained.

3. Planet Formation and Evolution

Understanding planetary formation and evolution represents a central challenge in astrophysics, connecting star formation physics, protoplanetary disk evolution, and the remarkable diversity observed in exoplanetary systems. While our Solar System historically provided the foundational paradigm, three decades of exoplanet discoveries have revealed far greater architectural diversity and formation pathway complexity than previously anticipated (Mayor & Queloz 1995; Winn & Fabrycky 2015).

3.1. Star and Protoplanetary Disk Formation

Stars form through gravitational collapse of dense regions within molecular clouds, resulting in a central protostar surrounded by an accretion disk (Shu et al. 1987; McKee & Ostriker 2007). Angular momentum conservation during this collapse naturally produces a rotationally supported disk—the protoplanetary disk—which provides the raw material reservoir for planet formation. These disks consist primarily of molecular hydrogen and helium, with dust grains and heavier elements comprising approximately 1–2% of the total mass (Williams & Cieza 2011).

Revolutionary observations from facilities such as ALMA have provided unprecedented views of disk substructures, revealing intricate patterns of rings, gaps, and spiral arms that are widely interpreted as direct signatures of ongoing planet formation processes (Andrews 2020).

Current observational studies reveal several key properties of protoplanetary disks: Typical gas disk lifetimes of 2–3 Myr after the embedded phase (Mamajek 2009; Haisch et al. 2001), with shorter lifetimes in denser stellar environments. Disk-to-star mass ratios typically range from 0.2% to 0.6% (Andrews et al. 2013). Gas disk extents span 10–100 AU, while dust disks are systematically smaller by factors of approximately 2.5 (Ansdell et al. 2018; Sanchis et al. 2021). Protoplanetary disks are found around approximately 75% of solar-type stars (Luhman et al. 2010), and their properties show minimal sensitivity to binary companion presence for separations greater than 140 AU (Ricciardi et al. 2025).

The finite disk lifetime places stringent constraints on giant planet formation efficiency, since substantial gaseous envelopes can only be accreted before disk gas dispersal through photoevaporation, viscous accretion onto the central star, and disk wind processes (Ercolano & Pascucci 2017).

Table 1. Relative importance of internal energy sources in different planet classes

Energy Source	**Hot Jupiters**	**Cold Jupiters**	**Sub-Neptunes**	**Super-Earths**	**Earth-like**
Absorbed stellar radiation	**Dominant**	Low	High (if close-in)	Low	Surface only
Primordial heat	Moderate	**Dominant**	Moderate	High (if young)	Moderate
Radioactive decay	Minimal	Negligible	Moderate	**Dominant**	**Dominant**
Tidal heating	Moderate	Low	Moderate	Moderate (variable)	Low
Latent heat (phase changes)	Low–Moderate	Moderate–High	Moderate	Low–Moderate	Moderate
Ohmic dissipation	Moderate–High	Negligible	Possible	Unlikely	Negligible
Chemical reactions	Negligible	Negligible	Negligible	Moderate	Low–Moderate

3.2. Formation Mechanisms: Core Accretion vs. Disk Instability

Two primary mechanisms explain planetary formation processes. Core accretion dominates terrestrial planet formation and giant planet formation around metal-rich stars. This process involves gradual solid core growth through planetesimal and pebble accretion until reaching a critical core mass ($\sim 10\ M_\oplus$), after which runaway gas accretion produces massive atmospheric envelopes (Pollack et al. 1996; Johansen et al. 2017). This mechanism naturally explains the observed correlation between giant planet occurrence rates and stellar metallicity (Fischer & Valenti 2005).

Disk instability (Boss 1997; Durisen et al. 2007) may explain massive gas giant formation at wide orbital separations and in young systems, where gravitationally unstable disks fragment directly into self-gravitating clumps that subsequently contract to form gas giant planets. While operating on shorter timescales than core accretion, this mechanism requires specific disk conditions and likely operates primarily in outer disk regions with high surface densities.

Current scientific consensus suggests that core accretion dominates giant planet formation in most environments, while disk instability may contribute in specific conditions or explain certain populations such as wide-orbit massive planets (Kratter & Lodato 2016).

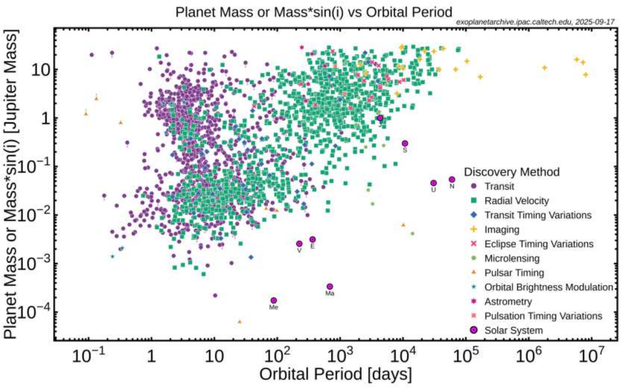

Figure 2. Mass-period diagram of confirmed exoplanets. This diagram displays all confirmed exoplanets from the NASA Exoplanet Archive (`exoplanetarchive.ipac.caltech.edu`), with different symbols representing each detection method as indicated in the legend.

4. Exoplanet Demographics and Observational Constraints

As of this writing, the number of confirmed exoplanets has exceeded 6,000, providing an unprecedented statistical foundation for understanding planetary formation and evolution processes. Figure 2 illustrates the mass-period diagram from the NASA Exoplanet Archive (`exoplanetarchive.ipac.caltech.edu`), showing all confirmed exoplanets detected by different methods. This wealth of data enables robust demographic analyses that reveal fundamental patterns in planetary system architecture, as discussed in the following sections.

4.1. Planet Occurrence Rates

One of the most significant achievements of the Kepler mission (Borucki et al. 2010; Batalha et al. 2013; Petigura et al. 2013; Burke et al. 2015; Lissauer et al. 2024) , now continued by TESS (Ricker et al. 2015; Sullivan et al. 2015; Guerrero et al. 2021), has been the determination of statistically meaningful planet occurrence rates across a wide range of planetary types and orbital configurations. These measurements provide essential constraints for planet formation theories and population synthesis models.

Current occurrence rate studies reveal that small planets (super-Earths and sub-Neptunes) are the most common planetary type, with occurrence rates exceeding those of both terrestrial planets and gas giants (Howard et al. 2012). The planet occurrence rate increases significantly with decreasing planetary radius for planets smaller than Neptune, indicating that smaller worlds are increasingly common throughout the Galaxy (Dressing & Charbonneau 2015; Bean et al. 2021).

4.2. The Radius Gap and Atmospheric Evolution

A significant discovery in exoplanet demographics was the identification of a pronounced radius gap at approximately 1.8 $R_\oplus$ (Fulton et al. 2017). This bimodal distribution separates rocky super-Earths from sub-Neptunes with substantial atmospheric envelopes. Recent observations confirm that this gap results from thermally-driven atmospheric mass loss processes (Ho & Van Eylen 2023), validating theoretical predictions of photoevaporation mechanisms.

Photoevaporation occurs when high-energy XUV photons from host stars strip away planetary atmospheres on timescales of approximately 100 Myr. For planets with H/He envelopes comprising less than 3% of their total mass, complete atmospheric loss can occur, effectively transforming sub-Neptunes into rocky super-Earths and creating the observed radius gap. The cosmic shoreline concept (Zahnle & Catling 2017) delineates the boundary between regions where planets can retain substantial atmospheres versus those where atmospheric loss processes dominate (Owen & Wu 2017). Notably, a large fraction of confirmed super-Earths falls below this shoreline, indicating that many of these planets are likely bare rocky cores that have lost their primordial atmospheres through photoevaporation.

4.3. Hot Neptune Desert

The hot Neptune desert represents a striking demographic features in exoplanet population studies—a pronounced paucity of Neptune-sized planets (typically 3–4 $R_\oplus$ or 0.1–1 M_J) with orbital periods shorter than 2–4 days (Mazeh et al. 2016; Lundkvist et al. 2016). This under-population cannot be explained by observational biases, as numerous Neptune-sized worlds have been discovered at longer orbital periods, making the absence of close-in Neptunes a genuine astrophysical phenomenon rather than a detection artifact.

The desert boundary is typically defined in period-radius or period-mass parameter space, with the region receiving strong stellar irradiation where gaseous atmospheres cannot be retained due to evaporation. The physical mechanism responsible has been hypothesized to result from photoevaporation, whereby planets spending significant time in short orbits either have sufficient mass to remain Jupiter-like or lose their envelopes entirely to become rocky cores. This creates a clear dichotomy between massive hot Jupiters that can retain their atmospheres and smaller rocky planets that have been stripped of their gaseous envelopes.

4.4. Metallicity Effects on Planet Formation

The relationship between stellar metallicity and planet occurrence provides crucial insights into formation mechanisms. Studies demonstrate that low-metallicity environments contain fewer solid building blocks for core formation, directly impacting planet formation efficiency (Johnson et al. 2010). This metallicity dependence is particularly pronounced for massive planets: Jupiter-mass planets show strong metallicity correlations, while Neptune-mass planets exhibit weaker dependencies. Interestingly, short-period planets ($P < 10$ days) show reduced metallicity sensitivity compared to longer-period planets ($10 < P < 40$ days), suggesting different formation or migration pathways for close-in planetary populations (Zink et al. 2023).

5. System Architecture and Migration Signatures

5.1. Architectural Diversity

Current exoplanet surveys reveal extraordinary diversity in planetary system architectures. The most common planets—super-Earths (1–2 $R_\oplus$) and sub-Neptunes (2–4 $R_\oplus$)—represent planetary types completely absent from our Solar System. Hot Jupiters, while relatively rare (occurring around $\sim$1% of stars), preferentially form around metal-rich hosts and provide exceptional laboratories for atmospheric characterization studies.

System architectures broadly fall into two primary categories: "peas-in-a-pod" systems containing uniformly small planets likely formed through in-situ processes, and "warm-Jupiter" systems with mixed planet sizes indicating significant migration histories (Weiss et al. 2018).

5.2. Migration and Dynamical Evolution

Planetary migration signatures provide crucial constraints on system evolutionary histories. Hot Jupiters, found at orbital separations far interior to their formation locations beyond the snow line, represent clear evidence for substantial inward migration processes. Spin-orbit misalignments measured through the Rossiter-McLaughlin effect indicate dynamically heated evolutionary histories, distinguishing between gentle disk-driven migration and violent high-eccentricity migration followed by tidal circularization.

Multi-planet systems exhibit complex dynamical interactions that reshape system architecture over time. Planet-planet scattering events can lead to highly eccentric orbits, while tidal dissipation gradually circularizes close-in orbits and can ultimately lead to planetary engulfment by host stars.

6. Galactic Context and Environmental Effects

Exoplanet occurrence rates vary significantly across different Galactic populations, providing insights into the environmental dependencies of planet formation. Studies reveal occurrence rates of 46% in the thin disk versus 28% in the thick disk for planets with $R_p = 0.5$–$12\ R_\oplus$ and orbital periods shorter than 400 days (Bashi et al. 2022). Notably, no confirmed planets have been detected in the Galactic halo, an extremely low metallicity environment with expected reduced availability of solid material for planet formation. However, the detection of exoplanets in the halo remains limited by the sensitivity constraints of current observational techniques. Population synthesis models predict that planetary systems should exist throughout the Galaxy, with occurrence rates correlated with local metallicity distributions and stellar age demographics across all Galactic components.

6.1. Atmospheric Characterization and Formation Constraints

Modern atmospheric observations enable detection of key molecular species including CO_2, CO, H_2O, and CH_4, providing direct constraints on atmospheric composition and thermal structure. These measurements constrain the atmospheric C/O ratio, a fundamental tracer of formation location relative to various molecular condensation fronts in protoplanetary disks (Madhusudhan 2012).

Direct observations of atmospheric escape through transit spectroscopy validate theoretical predictions and provide real-time constraints on atmospheric evolution processes. Three-dimensional climate modeling reveals complex heat redistribution patterns, wind systems, and temperature-pressure profiles that depend critically on atmospheric composition, stellar irradiation intensity, and planetary rotation properties.

6.2. Global Formation Models

The Bern global model of planet formation and evolution represents a major theoretical achievement, successfully reproducing observed planetary populations through comprehensive, self-consistent simulations (Mordasini et al. 2012; Emsenhuber et al. 2021, 2025). These sophisticated models incorporate gas and solid evolution in protoplanetary disks, accretion processes of gas and solids by growing protoplanets, internal structural evolution and atmospheric development, and N-body gravitational interactions including migration processes.

The model's success in reproducing observed mass-radius relations, orbital period distributions, and occurrence rate statistics validates our understanding of the fundamental physical processes governing planetary system formation and evolution.

6.3. Future Discoveries and Emerging Frontiers

Upcoming space missions including PLATO (Rauer et al. 2014) and ARIEL (Tinetti et al. 2018), along with next-generation Extremely Large Telescopes (Gilmozzi & Spyromilio 2007) and dedicated ground-based surveys, will continue exploring the diverse exoplanet population and provide more precise characterization of known systems. These observations will enable robust statistical studies of rare planetary types and extend our detection capabilities to Earth-analogs orbiting within the habitable zones of Sun-like stars.The next decade will likely witness revolutionary advances across several key areas: complete planetary censuses around nearby stars will establish statistical baselines for system diversity, while direct imaging missions including the Nancy Grace Roman Space Telescope (Spergel et al. 2015), HabEx (Gaudi et al. 2020), and LUVOIR (The LUVOIR Team 2019) will detect Earth-sized habitable zone planets and acquire reflected light spectra. Atmospheric characterization will advance dramatically through Extremely Large Telescopes (Gilmozzi & Spyromilio 2007) and space-based spectrographs capable of detecting biosignatures, while time-domain studies will reveal dynamic properties including climate variability and planetary interactions. Finally, gravitational microlensing surveys from Roman (Spergel et al. 2015) and ground-based networks (Penny et al. 2019) will extend parameter space coverage to cold planets, free-floating worlds, and wide-orbit companions beyond the reach of other methods.

7. Conclusions

The exoplanets have fundamentally transformed our understanding of planetary system formation, evolution, and cosmic prevalence. Key scientific insights include:

Formation Mechanisms: Observations confirm that core accretion dominates planetary formation, while disk instability may contribute in specific environments. The ubiquity of super-Earths and sub-Neptunes demonstrates that alternative evolutionary pathways beyond those represented in our Solar System are extremely common throughout the Galaxy.

Atmospheric Evolution: The radius gap provides direct observational evidence for photoevaporation-driven atmospheric loss, validating theoretical predictions about long-term atmospheric evolution. The hot Neptune desert represents an extreme manifestation of these atmospheric loss processes operating in high-radiation environments.

System Architecture: The remarkable diversity of planetary system architectures reflects complex interplay between formation processes, migration mechanisms, and long-term dynamical evolution. Migration signatures preserved in current orbital configurations provide fossil records of early system evolutionary histories.

Galactic Context: Planetary occurrence rates correlate strongly with Galactic population membership, stellar metallicity, and local environmental conditions, revealing the broader cosmic context of planetary system formation and suggesting that habitable worlds may preferentially occur in specific Galactic environments.

Theoretical Validation: Comprehensive global formation models successfully reproduce observed planetary populations, demonstrating robust understanding of fundamental physical processes governing planetary system formation while providing predictive frameworks for interpreting future observations.

The coming decades promise a transformative era in exoplanetary science, driven by convergence of observational capabilities, technological advances, and theoretical sophistication. These combined efforts will advance our understanding of planet formation and evolution while bringing us significantly closer to answering one of the most profound scientific questions of our time: How common are habitable worlds—and life itself—throughout the Universe?

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