Overview of Observational and Theoretical Studies of Planetary Systems Around Red Dwarfs: Postprint

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Date: 2023-12-15T00:00:00+00:00

Abstract

Red dwarfs are the lowest-mass and least-luminous class of main-sequence stars. With advances in detection techniques, a rich population of planets has been detected around them, exhibiting distribution characteristics distinct from those around other stellar types. Around red dwarfs, terrestrial planets have a relatively high occurrence rate, and the architectures of planetary systems are remarkably compact. The habitable zone lies closer to the host star, which is more favorable for the search for habitable planets. The distribution characteristics of the transition radius between super-Earths and sub-Neptunes also differ from those around Sun-like stars. The discovery of giant planets around low-mass stars poses a significant challenge to theoretical models. The mass of solid material in protoplanetary disks decreases rapidly with stellar mass, and whether this can explain the origin of giant planets remains an unsolved mystery. Thanks to observations from telescopes such as TESS (Transiting Exoplanet Survey Satellite), James Webb, and ALMA (Atacama Large Millimeter/submillimeter Array), new insights and opportunities have been provided for research on planet formation. This review will examine observations of different planetary populations around red dwarfs and summarize the latest understanding of planet formation theory around these stars.

Full Text

Preamble

Vol. 64 No. 6

Nov., 2023

Acta Astronomica Sinica

doi: 10.15940/j.cnki.0001-5245.2023.06.001

A Review of Observational and Theoretical Studies of Planetary Systems Around Red Dwarfs

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Abstract

Red dwarfs are the smallest and dimmest main-sequence stars. With advancing detection capabilities, a rich population of planets has been discovered around them, exhibiting distinct distribution characteristics from planets orbiting other stellar types. Earth-like planets show higher occurrence rates around red dwarfs, and their planetary systems display extremely compact architectures. The habitable zone lies closer to the host star, facilitating the search for potentially habitable worlds. The distribution of the transition radius between super-Earths and sub-Neptunes also differs from that around Sun-like stars. Moreover, the discovery of giant planets around such low-mass stars poses significant challenges to theoretical models. The mass of solid material in protoplanetary disks declines rapidly with decreasing stellar mass, leaving the origin of giant planets an unsolved mystery. Observations from telescopes such as TESS (Transiting Exoplanet Survey Satellite), James Webb, and ALMA (Atacama Large Millimeter/submillimeter Array) have provided new insights and opportunities for planetary formation research. This review examines the observations of different planetary populations around red dwarfs and summarizes the latest theoretical understanding of planet formation in these systems.

Key words: planets and satellites: formation; planets and satellites: terrestrial planets; planets and satellites: gaseous planets; stars: low-mass

1. Introduction

The 2019 Nobel Prize in Physics recognized breakthrough contributions in astrophysics, including the 1995 discovery of the first exoplanet orbiting a Sun-like star [1]. This milestone marked humanity' s expansion beyond the Solar System in planetary research. Over the subsequent two decades, the field has advanced rapidly, with the exoplanet census growing continuously. Planets orbiting Sun-like FGK-type stars constitute a significant portion of known exoplanets.

Red dwarfs represent the lowest-mass and coolest main-sequence stars, characterized by stellar activity and spectral types distinctly different from the Sun, providing unique environments for planet growth and evolution. In 1998, Marcy et al. [3] detected the first warm giant planet around the red dwarf Gliese 876 (0.32 $M_{\odot}$) using radial velocity measurements, a planet with an orbital period of only 61 days located 4.7 pc from Earth. This discovery inaugurated a new era of planet detection and research around red dwarfs. While no strict definition of red dwarfs exists in the literature, most studies refer to M-type dwarfs, occasionally including late K-type dwarfs or mid-to-late M dwarfs with masses below 0.3 $M_\odot$. This review primarily focuses on mid-to-late M dwarfs with masses between 0.08-0.3 $M_\odot$, with specific applicability noted for particular problems.

As our understanding of planets around Sun-like stars has matured, international research focus has increasingly shifted toward planets orbiting red dwarfs for several compelling reasons. First, red dwarfs are the most numerous stellar type in the Milky Way [4-6], and studies indicate that planet occurrence rates around these hosts exceed those around Sun-like FGK stars [7-8]. Consequently, they dominate the actual planetary population, making their study universally significant. Second, transit photometry—the primary method for large-scale planet surveys—has detection sensitivity proportional to the planet-to-star radius ratio. Red dwarfs' substantially smaller radii make them ideal targets for terrestrial planet observations. Third, the search for habitable planets represents a major frontier in exoplanet science. For Sun-like stars, only NASA' s Kepler space telescope possessed the capability to detect potentially habitable planets, a goal that remained unattainable for some time after Kepler's retirement. However, red dwarfs' low luminosity places their habitable zones at orbital periods of 10-30 days, ideally suited for long-term monitoring by both ground-based and space-based telescopes. Once discovered, the James Webb Space Telescope can conduct follow-up atmospheric spectroscopy to search for biosignatures [9-10]. These advantages have motivated numerous international projects dedicated to finding planetary systems around red dwarfs, including NASA' s TESS [11-12], the Harvard-Smithsonian Center for Astrophysics' MEarth project [13-14], the TRAPPIST survey [15], the SPECULOOS ground-based transit survey [16], the EDEN network [17], Subaru' s infrared radial velocity observations [18], and the CARMENES near-infrared spectrograph survey [19].

Approximately 150 planets have been observed orbiting red dwarfs (0.08-0.3 $M_\odot$), with the majority being terrestrial planets (0.5-2 $M_\oplus$, 0.5-1.25 $R_\oplus$) and super-Earths (2-10 $M_\oplus$, 1.25-2 $R_\oplus$). Neptune-like planets (10-30 $M_\oplus$, 2-4 $R_\oplus$) and gas giants (>30 $M_\oplus$ or >0.1 M_J, >4 $R_\oplus$) constitute approximately 10% and 26.7% of the population, respectively. Compared to planets around Sun-like stars, terrestrial planets occur more frequently around red dwarfs [20], and their orbital periods are notably short, with most orbiting within 0.01-0.1 au [21]. [Figure 1: see original paper] illustrates the distribution of semi-major axes and masses for planets around red dwarfs, where dot size indicates planetary radius and color represents stellar mass. Light green plus symbols denote planets within the habitable zone. Gas giants exceeding 0.1 M_J (dashed line) predominantly cluster near 1 au, typically one to two orders of magnitude farther from their host stars than terrestrial planets. The occurrence rate of hot Jupiters around red dwarfs is substantially lower than around Sun-like stars [22-23], suggesting either reduced giant planet formation efficiency or formation at greater distances without substantial inward migration before gas disk dissipation. Notably, no clear correlation exists between giant planet mass or orbital position and host star mass within the red dwarf mass range ([Figure 1: see original paper]).

[Figure 2: see original paper] displays observed multi-planet systems around red dwarfs, most of which consist of terrestrial planets in extremely compact orbital configurations. Peak period ratios near 2:1, 3:2, and 5:3 resonances are evident [24–27], though these resonant structures can be disrupted by processes such as planetary mass growth or loss [28], gas disk dissipation [29], and perturbations from outer giant planets [30], resulting in non-resonant configurations. Systems composed of giant planets exhibit relatively looser architectures [21, 31]. With the exception of KMT-2020-BLG-0414L—which contains both a giant planet and a terrestrial planet [32]—all other systems comprise planets of similar sizes. These statistical distribution characteristics and their differences from planets around other stellar types make planet formation around red dwarfs a critical research topic, with giant planet formation around low-mass stars representing a particularly formidable challenge.

Current planet formation theories fall into two categories: core accretion and gravitational instability. [Figure 3: see original paper] schematically illustrates the evolutionary pathways in these models [34]. In core accretion, planet formation begins with sub-micron dust grains that settle toward the disk midplane under gravity and coagulate through electromagnetic forces into centimeter-to-meter-sized pebbles. A leading theory suggests that local pebble concentrations trigger streaming instability, forming kilometer-sized planetesimals. These planetesimals grow through pebble accretion or mutual collisions, eventually accreting gas to form terrestrial planets, Neptune-like planets, or gas giants [35]. As the dominant formation theory, core accretion is widely applied to explain various planet types. Alternatively, gravitational instability posits that in massive, cold protoplanetary disks, gas can directly fragment and collapse into giant planets when pressure cannot counteract self-gravity [36–39] ([Figure 3: see original paper], yellow arrow).

This review summarizes the current observational and theoretical status of planets around red dwarfs, organized by planetary mass into three categories: terrestrial planets, Neptune-like planets, and gas giants, concluding with future prospects for the field.

2.1 Terrestrial Planet Observations

Terrestrial planets have masses and radii similar to Earth (M_p = 0.5-2 $M_\oplus$, R_p = 0.5-1.25 $R_\oplus$) and are primarily rocky in composition. Compared to Sun-like stars, red dwarfs offer significant advantages for observation: transits produce deeper photometric signals, habitable zones are closer-in with shorter orbital periods, and atmospheric characterization is more feasible. Terrestrial planets exhibit higher occurrence rates around red dwarfs [40]. Kepler transit data reveal an average of 0.15 terrestrial planets (0.8-1.25 $R_\oplus$) per Sun-like FGK star with orbital periods of 0.8-50 days [41]. Around red dwarfs, the occurrence rate of Earth-sized planets (1–1.5 $R_\oplus$) within similar orbital periods (<50 days) is approximately 3–4 times higher [7], reaching 0.56–0.61 [20, 42]. Expanding the search to periods below 100 days increases the occurrence rate to approximately 0.65 [20].

Several studies have attempted to explain the differing occurrence rates and system architectures between red dwarfs and Sun-like stars [43–45]. The high formation efficiency of terrestrial planets around red dwarfs can be summarized through several mechanisms: (1) Protoplanetary disks around red dwarfs have lower masses, preventing planetary embryos from accreting sufficient material to form massive cores capable of subsequent gas accretion [46–47]; (2) In pebble accretion models, planetary growth is limited by pebble isolation mass, with the maximum solid mass an embryo can achieve scaling with stellar mass ($M_{iso} \propto M_{\star}^{k}$, $k \approx 1$) [56]. For red dwarf planets, isolation masses are only ~1–3 $M_{\oplus}$, insufficient for gas giant formation [35]; (3) Migration theory suggests that Type I migration is faster around low-mass stars, leaving insufficient time for substantial growth and resulting in final orbits at short periods favorable for transit detection [48]; (4) According to pebble accretion models, giant planet formation can block radial pebble drift, suppressing terrestrial planet formation in the inner disk. The higher occurrence of massive planets around Sun-like stars may thus explain the dearth of terrestrial planets around more massive hosts [49].

2.2 Planet Accretion Models

Planetary embryos grow through planetesimal accretion or pebble accretion. Planetesimal accretion relies on gravitational interactions between embryos and planetesimals, proceeding through rapid runaway growth followed by slower oligarchic growth [50–52]. Miguel et al. [43] employed planetesimal accretion models to study planet formation in 100 au disks, finding that Mars-mass planets only form when stellar mass exceeds 0.07 $M_{\odot}$ and disk mass exceeds 10^{-2} $M_{\odot}$, with Earth-sized planets requiring even more stringent conditions. If the star has a higher accretion rate, concentrating disk material (15 au) closer to the star, lunar-mass embryos can more efficiently accrete planetesimals to form terrestrial planets, potentially creating systems with 6–8 terrestrial planets [44], comparable to TRAPPIST-1.

Pebble accretion offers higher efficiency due to better coupling between pebbles and disk gas, enabling accretion under combined gravitational and gas drag forces [35, 53–54]. In this model, maximum solid mass is limited by pebble isolation mass, beyond which planets open shallow gaps that halt pebble drift, preventing further growth for both the planet and inner embryos [55]. Pebble isolation mass scales with stellar mass ($M_{iso} \propto M_{\star}^{k}$, $k \approx 1$) [56], predicting that terrestrial planet mass should correlate positively with host star mass [57]. Limited by low isolation masses around red dwarfs, stars below 0.2 $M_{\odot}$ can only form planets up to ~3 $M_{\oplus}$, which struggle to accrete substantial gas envelopes and become gas giants.

Both planetesimal and pebble accretion can explain terrestrial planet formation around low-mass stars. To better understand their distinct effects, Coleman et al. [58] placed 30 embryos of 0.1 $M_\oplus$ in disks spanning 1-5.5 au, finding that both accretion modes produce similar distributions in mass, eccentricity, inclination, and period ratios. The key difference lies in water content: water ice in pebbles may evaporate when crossing the planetary envelope [59-61], creating desiccated planets. Planetary water content could thus distinguish between accretion models, though surface oceans might also form through chemical reactions between primordial hydrogen atmospheres and magma [62-63]. The specific formation pathway and water origin require further investigation.

2.3 System Dynamical Evolution

Beyond accretion, planets undergo dynamical evolution. Migration theory posits that planets form at larger radii and exchange angular momentum with the gas disk, moving inward [64-65]. Alternatively, in situ formation models suggest planets form at their observed locations without substantial migration [66-69].

Migration models can be categorized as inward migration [70-72] or convergent migration [73-76] based on disk temperature structure. Planet migration arises from Lindblad and corotation torques, with direction determined by the net torque [77]. In isothermal disks, outer Lindblad resonances exert stronger torques than inner ones, causing inward migration. In non-isothermal disks with viscously heated inner regions and stellar-irradiated outer regions, strong corotation torques can reverse migration direction [78].

Pan et al. [45] compared three dynamical evolution scenarios and their effects on terrestrial planet formation in the inner disk. Using planetesimal accretion, they found that in situ models yield low accretion rates and cannot efficiently accrete water-rich material beyond the snow line, producing 7-8 dry, low-mass terrestrial planets. Inward migration models produce planets that rapidly migrate to the inner disk edge, resulting in high water content but orbits within 0.01 au where water cannot persist. Convergent migration models allow planets to reverse migration direction in the inner disk, accreting water-rich material while settling near the habitable zone after gas disk dissipation, creating potentially habitable worlds.

[Figure 5: see original paper] compares mass, semi-major axis, eccentricity, and period ratio distributions across different models. Shaded regions show observational data, while green dash-dotted, blue dotted, and orange solid lines represent in situ, inward migration, and convergent migration scenarios (without observational bias correction). Despite neglecting atmospheric accretion, convergent migration reproduces observed distributions in mass and semi-major axis, peaking near 0.1 au. In situ models produce more uniform semi-major axis distributions. Convergent migration better explains the observed high-eccentricity planets. Overall, convergent migration provides the best match to observations and favors the formation of water-rich planets while accounting for resonant chain architectures.

2.4 Characteristic Planetary Systems

Several notable planetary systems have been discovered around red dwarfs, with Proxima Centauri and TRAPPIST-1 garnering particular attention.

Proxima Centauri, a 0.12 $M_\odot$ red dwarf located 4.3 light-years away, forms a triple system with Sun-like stars Alpha Centauri A and B. Triple systems are typically vulnerable to chaotic disruption, only remaining stable when the third body is much less massive or extremely distant. Proxima Centauri orbits ~8700 au from the central pair, providing a stable environment for planet formation. In 2016, radial velocity measurements revealed Proxima Centauri b [79], an Earth-mass planet at 0.05 au with an 11-day orbital period squarely within the habitable zone. As the nearest exoplanet, Proxima Centauri b may harbor liquid water [80], making its formation, orbital stability, and habitability immediate research priorities. Subsequent observations suggest an additional inner planet with a ~5-day period and minimum mass of 0.26 $M_\oplus$ [81], and a possible super-Earth at 1.48 au with minimum mass 5.8 $M_\oplus$ [82], though further observations are needed.

The TRAPPIST-1 system, discovered via transit photometry, comprises seven Earth-sized planets with similar masses and densities orbiting an ultra-cool 0.09 $M_\odot$ red dwarf [83-85]. With orbital periods of 1.5-18.8 days, the system exhibits a tightly packed resonant chain architecture, containing three planets within the habitable zone—the most of any known system. Its unique configuration makes it a prime target for studying planet formation around red dwarfs and searching for biosignatures.

To explain the compact orbital structure and resonant chain, Ormel et al. [86] proposed a snowline formation mechanism where embryos initially form near the snowline and migrate inward, accreting dry pebbles until crossing the inner disk edge into a gas-free cavity. Planets form sequentially, establishing resonances with previously formed planets. Later atmospheric loss further compacts the system [87]. Planets b-c and c-d have crossed the 2:1 first-order resonance, establishing 8:5 and 5:3 higher-order resonances, likely due to early cavity entry [88]. Schoonenberg et al. [89] and Ogihara et al. [90] modeled the system’ s mass distribution. While migration typically produces water-rich planets, observations suggest TRAPPIST-1 planets contain \$ \$10 wt% water, with the inner three essentially dry, indicating substantial water loss [58].

2.5 Planetary Habitability

Red dwarfs’ low temperatures place habitable zones at close orbital distances, offering natural advantages for habitable planet searches. Most known habitable planets orbit red dwarfs [91]. However, their habitability remains controversial.

First, close-in planets are susceptible to tidal locking, creating extreme temperature contrasts between permanent day and night sides. The frigid nightside can freeze atmospheric constituents, hindering atmospheric circulation and habitability [92-93]. Additionally, red dwarfs exhibit strong magnetic activity and intense UV/X-ray radiation that can vaporize surface water and strip atmospheres [94].

Nevertheless, studies show that even thin atmospheres can drive planets away from synchronous rotation [95], with atmospheric circulation patterns varying systematically with rotation period [96]. Cloud feedback and atmospheric circulation can heat the nightside [97-98]. While photodissociation causes hydrogen escape, chemical processes like $CO + OH \rightarrow CO_2 + H$ can produce secondary atmospheres, making habitability dependent on secondary atmosphere formation capacity [99].

Water is essential for life' s origin, making planetary water content a critical habitability factor. The prevailing view attributes water to accretion of ice-rich pebbles or planetesimals. Formation location is crucial: inside the snowline, water exists as vapor, while ice accretion only occurs beyond it. Water content depends on migration and disk temperature evolution [56, 86]. System architecture also affects habitability; Clement et al. [100] showed that scattering of outer asteroid belt bodies by Neptune-mass planets could deliver water to habitable zone planets. Alternatively, primordial atmospheres may react with magma oceans to produce water. Embryos reaching 0.2 $M_\oplus$ can accrete hydrogen-rich primordial atmospheres sufficient to produce abundant water through oxidation of magma oceans, even from initially dry material [63]. Planetesimal-based core accretion models predict that 5–10% of terrestrial planets around early-to-mid M dwarfs could develop life-supporting oceans [62].

3. Super-Earths and Sub-Neptunes

Super-Earths and sub-Neptunes represent common exoplanet populations discovered through transits, radial velocities, and microlensing [41]. They typically possess rocky or icy cores surrounded by hydrogen/helium envelopes. Super-Earths are generally defined as planets with radii of 1.25-2 $R_\oplus$ (masses 2–10 $M_\oplus$) [101], while sub-Neptunes have radii of 2–4 $R_\oplus$ (masses between super-Earths and Neptune) [102–103].

3.1 Observations of Super-Earths and Sub-Neptunes

Super-Earths and sub-Neptunes occur less frequently than terrestrial planets around red dwarfs. Dressing et al. [20] found occurrence rates of ~46% for super-Earths (1.5-2 $R_\oplus$) within 50-day periods and 57% within 100-day periods around M dwarfs (0.1-0.6 $M_\odot$), both slightly lower than for terrestrial planets. Sub-Neptunes are even rarer, with an occurrence rate of ~19%. Radial velocity surveys yield slightly higher super-Earth frequencies; Tuomi et al. [104] combined UVES and HADES observations of 41 M dwarfs (0.1-0.8 $M_\odot$) to find an average of 1.02 super-Earths ($M_p \sin i$ = 3-10 $M_\oplus$) with periods of 10-100 days [105-106]. This contrasts with recent CARMENES results: Ribas et al. [8] analyzed 362 M dwarfs (0.08-0.6 $M_\odot$) from 2016-2020, finding average super-Earth counts of 0.67 for 10-100 day periods, 0.39 for 1-10 days, and 1.37 for 1-1000 days.

Both the fraction of stars hosting planets and system diversity increase with decreasing stellar temperature and mass. Approximately 30-35% of Sun-like stars ($T_{eff} > 6500$ K) host super-Earths or sub-Neptunes detectable by Kepler, with an average of 1.8 planets per system [108-109]. Around red dwarfs (T_{eff} < 5000 K), ~75% of stars host transiting planets, with an average of 2.8 planets per system [108].

3.2 Short-Period, High-Eccentricity Sub-Neptunes

Many sub-Neptunes orbit extremely close to their stars (0.01-0.03 au), experiencing strong tidal forces that circularize their orbits. However, some high-eccentricity sub-Neptunes have been observed, such as TOI-2406 b and K2-25 b, which have ~3-day periods but eccentricities of 0.26 [110] and 0.43 [111], respectively, possibly formed through high-eccentricity migration [112]. Notably, TOI-2406 b orbits a very low-mass, metal-poor star ([Fe/H] = −0.38, $M_* =$ 0.162 $M_\odot$). The formation of short-period sub-Neptunes around such low-mass, metal-poor stars and the dynamical evolution of high-eccentricity short-period planets are active research topics.

Sub-Neptunes are not always isolated. Some interesting system architectures have been found near these planets [113]. The red dwarf TOI-2096 hosts a super-Earth (TOI-2096 b, R_p = 1.2 $R_\oplus$) and a mini-Neptune (TOI-2096 c, R_p = 1.9 $R_\oplus$) with a period ratio near the 2:1 mean motion resonance [114]. Statistical studies reveal a bimodal radius distribution with peaks at ~1.3 $R_\oplus$ and 2.4 $R_\oplus$ and a valley at 1.5-1.8 $R_\oplus$ [115-116]. The TOI-2096 planets straddle this radius valley, and their near-resonant configuration, combined with future mass/density constraints from TTVs or radial velocities and atmospheric analysis with James Webb, could provide crucial insights into the radius valley' s formation mechanism.

3.3 The Radius Valley

The radius distribution of small exoplanets (R_p < 4 $R_\oplus$) exhibits a distinctive bimodal-valley structure, with peaks near 1.3 $R_\oplus$ and 2.4 $R_\oplus$ and a deficit at 1.5-2.0 $R_\oplus$. Planets smaller than 1.6 $R_\oplus$ (super-Earths) have high densities, suggesting rocky, Earth-like compositions [101, 117], while larger planets have lower densities, likely possessing atmospheric envelopes or icy cores [102, 118-119].

The transition radius depends on orbital period and stellar properties [120]. [Figure 6: see original paper] shows its distribution across parameter spaces of orbital period, stellar irradiation, stellar mass, and metallicity. Rocky super-Earths typically orbit closer to their stars, while distant planets more commonly have atmospheres ([FIGURE:6(a)]), following a power-law relation $R_p \propto P^{-0.11}$ [121]. The transition radius also correlates with stellar irradiation, with more strongly irradiated planets being smaller ([FIGURE:6(b)]). Van Eylen et al. [122] confirmed this power-law relationship for red dwarfs (0.15-0.6 $M_\odot$), while Cloutier et al. [123] found an opposite trend ($R_p \propto F^{-0.06\pm0.025}$), attributing the discrepancy to sample selection and methodology. The transition radius shifts to smaller values with decreasing stellar mass but shows no significant metallicity dependence ([FIGURE:6(c,d)]). For Sun-like stars, the radius valley lies near 1.8 $R_\oplus$, while for early M dwarfs (~0.5 $M_\odot$) it appears near 1.5 $R_\oplus$. Around lower-mass red dwarfs, the bimodal structure may become less pronounced or disappear entirely [123].

Three main theoretical explanations exist for the radius valley. First, formation location depends on disk gas mass: super-Earths form in gas-poor disks [124-125], while sub-Neptunes form in gas-rich environments [126]. This model predicts $R_p \propto P^{0.11}$ [127], contradicting [FIGURE:6(a)] but matching Cloutier et al. [123]. It also predicts $R_p \propto M_*^{0.14}$, consistent with Petigura et al. [120].

Second, all planets may initially accrete substantial atmospheres to become sub-Neptunes, with some later losing most or all of their envelopes to become super-Earths [128-130]. Atmospheric loss mechanisms include stellar UV/X-ray irradiation [131-132] and core-powered mass loss [133-136]. Both mechanisms predict orbital period and stellar mass dependencies opposite to the gas-poor formation model, matching Petigura et al. [120] and Van Eylen et al. [122]. The photoevaporation and core-powered models differ in their predictions for low-mass red dwarfs. Red dwarfs exhibit stronger activity and high-energy radiation, and their planets orbit closer, experiencing more intense irradiation and photoevaporation. Core-powered models are less dependent on stellar radiation but may produce narrower radius valleys due to stellar luminosity evolution [137].

Third, the bimodal distribution may be an inevitable outcome of planet formation. Dust grains have different compositions inside and outside the snowline, allowing planets to accrete either dry or ice-rich pebbles, forming ~3 $M_\oplus$ rocky planets or ~10 $M_\oplus$ ice-rich planets, respectively [138-139]. Alternatively, planets forming beyond the snowline may migrate inward and experience runaway greenhouse expansion, inflating radii beyond 2.3 $R_\oplus$ even with minimal gas accretion, making the valley separate rocky from water-rich planets [140]. Izidoro et al. [141] proposed that late-stage giant impacts could also strip primordial atmospheres, creating a radius valley near 1.8 $R_\oplus$, though the period dependence requires further investigation.

The radius valley’ s location and its scaling relations with orbital period and stellar mass around red dwarfs remain uncertain, requiring more observations. Different theories predict opposite trends, and future statistical studies of super-

Earths and sub-Neptunes—especially atmospheric characterization of planets near the transition radius with James Webb—will constrain the valley' s origin.

4. Giant Planets

4.1 Giant Planet Observations

Fewer than ten gas giants (>30 $M_\oplus$) have been detected around red dwarfs (0.08-0.3 $M_\odot$) via transits and radial velocities [142]; most discoveries come from gravitational lensing surveys like KMTNet [143] and OGLE [144].

TESS observations indicate hot Jupiter occurrence rates of only 0.27% around early M dwarfs (0.45-0.65 $M_\odot$) [22] and ~0.137% around low-mass red dwarfs (0.088-0.26 $M_\odot$) [23]. Around Sun-like stars, hot Jupiter occurrence rates are 0.43-0.71% [41, 145-151], 3-5 times higher than around low-mass red dwarfs. Radial velocity surveys place upper limits of <1% on hot Jupiter occurrence around red dwarfs [105, 152], compared to 0.84-1.5% around Sun-like stars [153-156]. Warm (10-100 days) and cold giants (<3000 days) occur at ~2% around red dwarfs [106, 152], far below the 10.5% rate for cold giants (2-2000 days) around FGK stars [153].

Gravitational lensing preferentially detects planets at 2-4 au $(M_*/M_\odot)^{1/2}$ [157-158], revealing numerous gas giants at ~1 au around low-mass red dwarfs [143, 159-160], comprising ~20% of the red dwarf planet population.

Giant planets are common in the Solar System, yet their formation remains poorly understood, especially around low-mass stars. Early observations with the SMA submillimeter array suggested a linear relation between protoplanetary disk mass and stellar mass ($M_d \propto M_*$) for Class II stars, with disks comprising 0.2-0.6% of stellar mass [161]. Assuming a gas-to-dust ratio of 100:1, dust disk masses around red dwarfs would be only 0.5-6 $M_\oplus$. Subsequent ALMA observations revealed a super-linear relation ($M_d \propto M_*^{1.3-1.9}$) [47], clearly insufficient for giant planet formation. Additionally, dust radial drift timescales are shorter in red dwarf disks, leading to faster disk dissipation and further hindering gas giant formation. However, disk masses vary significantly across star-forming regions and ages [162-163], and some massive disks around red dwarfs may provide viable formation sites [164]. Giant planet cores may also have formed during the Class 0/I protostellar phase.

4.2 Giant Planet Formation Theory

In core accretion, accretion and migration timescales critically determine final planet mass. Burn et al. [44] proposed that gas giants like GJ 3512 b (M_p = 0.463 M_J) could only form via planetesimal accretion in massive disks with significantly suppressed migration. Pebble accretion is limited by isolation mass; although isolation mass is larger in the outer disk, lower pebble scale heights and surface densities yield low accretion rates, preventing embryos from reaching the 5-10 $M_\oplus$ cores needed for runaway gas accretion before disk dissipation [35, 56-

57]. Morales et al. [165] combined pebble and planetesimal accretion, assuming 1% of initial gas mass converted to 100 km planetesimals, finding that giant planets only form when the stellar accretion rate ($3 \times 10^{-7} M_{\odot} \mathrm{yr}^{-1}$) approaches that of Sun-like stars. Rapid migration would then produce only hot Jupiters at <0.05 au, inconsistent with the observed ~0.1-0.27% occurrence rate and the prevalence of more distant, longer-period giants.

Current pebble accretion studies typically consider single embryos, but multiple embryos forming across tens to hundreds of au can interact gravitationally, collide, and grow beyond isolation mass limits, potentially forming giants (Pan et al. in prep). [Figure 7: see original paper] presents a case where 20 lunar-mass embryos in a 0.1 $M_{\odot}$ star' s disk grow slowly. When some embryos become massive enough for rapid migration, they trigger violent collisions, with survivors migrating inward to form compact near-resonant chains. A second collisional phase ultimately produces three gas giants >0.1 M_J, one exceeding 100 $M_{\oplus}$ at ~0.2 au.

Gravitational instability offers an alternative formation pathway. In massive, cold disks, spiral density waves transport angular momentum outward [167]. When rapid cooling prevents pressure from supporting the disk against self-gravity, collapse occurs, forming giant planets quickly [168–170]. This process typically operates in massive outer disks. For a 0.2 $M_{\odot}$ star with a 60 au disk, a disk-to-star mass ratio $q_{disk} \approx 0.3$ triggers instability, while a 120 au disk requires $q_{disk} \approx 0.6$ [39].

5. Summary and Outlook

Red dwarfs, the lowest-mass main-sequence stars, are small, cool, and constitute over half of all stars in the Milky Way. Studying their planetary systems is both universally significant and provides a crucial testbed for planet formation theory under extreme conditions. Initially difficult to detect due to faint host stars, improved observational precision has revealed an increasingly rich population of red dwarf planets, offering broader perspectives on planet formation.

Current statistics indicate that each red dwarf hosts at least one terrestrial planet on average, with occurrence rates exceeding those around FGK stars. These planets exhibit distinct orbital distributions, orbiting very close to their stars in tightly packed multi-planet systems, some with resonant chains. Various theoretical models—including planetesimal and pebble accretion, in situ formation, inward migration, and convergent migration—can explain these architectures, though differences in mass distributions, resonance types, and water content remain. The specific formation pathway for any given system remains unclear, requiring future constraints on planetary composition and atmospheric properties. Habitability of terrestrial planets around red dwarfs is a perennial topic, with red dwarfs hosting the most known habitable zone planets. However, their actual habitability remains debated, necessitating observations of water content, tidal locking, and atmospheric retention.

Super-Earths and sub-Neptunes display a bimodal-valley radius distribution. Multiple theoretical mechanisms explain this feature, but predict contradictory trends for the transition radius with respect to orbital period, stellar irradiation, and stellar mass. Current observational samples around red dwarfs are insufficient to determine these relationships, preventing definitive conclusions about the radius valley’ s origin. Future discoveries of planets near the transition radius and atmospheric characterization with James Webb will clarify this distribution.

Giant planets are rare around red dwarfs, particularly hot Jupiters. However, microlensing has revealed numerous gas giants at ~1 au, challenging formation theory. The preference for distant giants may support migration models. Both core accretion and gravitational instability require massive disks, inconsistent with most observations. Combined with James Webb atmospheric observations, these discoveries may constrain formation locations and reveal evolutionary histories.

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