The physical properties of extra-solar planets

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Received 5 March 2009, in final form 6 October 2009
Published 23 December 2009
Online at stacks.iop.org/RoPP/73/016901

Abstract

Tremendous progress in the science of extrasolar planets has been achieved since the discovery of a Jupiter orbiting the nearby Sun-like star 51 Pegasi in 1995. Theoretical models have now reached enough maturity to predict the characteristic properties of these new worlds, mass, radius, atmospheric signatures, and can be confronted with available observations. We review our current knowledge of the physical properties of exoplanets, internal structure and composition, atmospheric signatures, including expected biosignatures for exo-Earth planets, evolution, and the impact of tidal interaction and stellar irradiation on these properties for the short-period planets. We discuss the most recent theoretical achievements in the field and the still pending questions. We critically analyze the different solutions suggested to explain abnormally large radii of a significant fraction of transiting exoplanets. Special attention is devoted to the recently discovered transiting objects in the overlapping mass range between massive planets and low-mass brown dwarfs, stressing the ambiguous nature of these bodies, and we discuss the possible observable diagnostics to identify these two distinct populations. We also review our present understanding of planet formation and critically examine the different suggested formation mechanisms. We expect this review will provide the basic theoretical background to capture the essentials of the physics of exoplanet formation, structure and evolution and the related observable signatures.

(Some figures in this article are in colour only in the electronic version)

This article was invited by J C B Papaloizou.

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1. Introduction

The end of the 20th century saw a revolution in our knowledge of planetary systems. The discovery of the first extra-solar planet in 1995 marked the beginning of a modern era and a change of our perception of planets. The discoveries continue apace and reveal an extraordinary diversity of planetary systems and exoplanet physical properties, raising new questions in the field of planetary science. More than 400 exoplanets have now been unveiled by radial velocity measurements, microlensing experiments and photometric transit observations. They span a wide range of masses from a few Earth masses to a few tens of Jupiter masses [1]. The realm of terrestrial exoplanets starts to open its doors with the lightest known exoplanet, GJ 581e, detected by radial velocity and having a mass \( M \) \( \cdot \) \( \sin i = 1.9 \) Earth masses \( (M_\oplus) \) [2]. At the opposite end of the mass range, an ambiguity appears on the nature of newly discovered objects. It now becomes clear that giant planets and brown dwarfs share a common mass range, likely between a few Jupiter masses and several tens of Jupiter masses.

Coincidently, the first brown dwarf was discovered at nearly the same time as the first exoplanet, but with different technologies and observational strategies. Identifying these two astrophysical body populations remains an open issue. Brown dwarfs are supposed to form like stars through the gravitational fragmentation of a molecular cloud while planets are thought to form in a protoplanetary disk subsequently to star formation. A brown dwarf is an object unable to sustain stable hydrogen fusion because of the onset of electron degeneracy in its central region. This definition provides a theoretical upper limit for their mass: objects below \( \sim 0.07 \) solar masses \( (M_\odot) \) or 70 Jupiter masses \( (M_{\text{Jup}}) \) belong to the brown dwarf realm [3]. But brown dwarfs with increasingly small masses have now begun to be discovered, reaching masses characteristic of our solar system gaseous giants. In parallel, planet hunters have discovered massive objects around central stars with orbital properties characteristic of planetary systems. They have been faced with an unprecedented difficulty to name their favorite object and the community even called into question the definition of a planet [4]. This uncertainty about how to name these objects yields some sterile, semantic debates which shed more confusion than light.

On a theoretical point of view, the physical properties of giant planets and brown dwarfs can be described within similar theoretical frameworks, the two families of objects being closely related in terms of atmospheric and interior properties. Because of different formation processes, distinctions are expected concerning their composition and content of heavy elements and these differences must be taken into account in theoretical models. But clearly, the nascent theory for exoplanets has inherited from our knowledge of the Solar System planets, mostly developed during the past century, and from the recent progress performed in the modeling of brown dwarfs. Therefore, the description of the physical properties of exoplanets is built on a combination of our knowledge in planetary and stellar science.

The aim of our review is to present the status of the modern theory describing atmospheric, interior and evolutionary properties of exoplanets, as well as their formation mechanisms. Most exoplanets yet detected through radial velocity and photometric transits are giant planets, characterized by the presence of a gaseous envelope mostly made of hydrogen and helium [1]. Crucial constraints on their structure are revealed by photometric transit and Doppler follow-up techniques, which provide a measure of their mass and radius. Information on the mean density and bulk composition of several exoplanets is thus now available, drastically extending the knowledge of planetary structures restricted till recently to our four giant planets. Atmospheric properties of exoplanets are also starting to be measured and the first constraints on temperature structure, composition and dynamics are now available. At the dawn of their discovery, no observational constraints on Earth-like exoplanets are yet available. Our review is thus essentially devoted to giant planets and we will only briefly describe the first theoretical efforts devoted to the description of terrestrial exoplanets.

The review is organized as follows. As introductory sections to the field, sections 2 and 3 provide brief overviews of solar and extra-solar system planets and of our current understanding of planet formation, respectively. Interior structure properties of terrestrial to Jovian planets are described in section 4, while section 5 is devoted to their atmospheric properties. Evolutionary properties, describing planet cooling and contraction history and the mass–radius relationship are presented in section 6. Tidal effects and star–planet interactions are examined in section 7. Current observational constraints (e.g. transiting radii, planetary light detection) are analyzed in section 8. Finally, some future advancements expected in the field are discussed in section 9.

2. A brief overview of observations

In this section, we present observed properties of solar and extra-solar planets which are relevant for the understanding of exoplanet physical properties. For more details, we invite the reader to refer to the reviews by [5,6] on Solar System giant planets and by [1] on statistical properties of exoplanets.

2.1. Lessons from our Solar System

The understanding of planetary structure starts with the extensive works conducted on our Solar System giant planets. Important constraints on interior structures of our four giant planets are provided by measurement of their gravity field through analysis of the trajectories of the space missions Voyager and Pioneer. Our giant planets are fast rotators, with rotation periods of about 10 h for Jupiter and Saturn and about 17 h for Neptune and Uranus. Rotation modifies the internal structure of a fluid body and yields departure of the gravitational potential from a spherically symmetric potential. Within the framework of a perturbation theory largely developed for rotating stars and planets, sometimes referred to as the theory of figures [7], the gravitational potential can be expressed in terms of even (for axysymmetric bodies) Legendre polynomials and gravitational moments \( J_2 \). The latter are related to the inner density profile of the rotating
object. Measurements of $J_2$, $J_4$ and $J_6$ for the four giant planets yield stringent constraints on their inner density profile. An abundant literature exists on the application of the theory of figures to our four giant planets and most models are based on the so-called three-layer model [8]. For Jupiter and Saturn, models assume that the planetary interior consists of a central rocky and/or icy core, an inner ionized helium and hydrogen envelope, and an outer neutral He and molecular H₂ envelope (see [5, 10] and references therein). Table 1 summarizes the results of a detailed analysis performed by [11], taking into account uncertainties on the equation of state for hydrogen at high density. More recent models for Jupiter were derived by [12,13] based on improved equations of state for H and He derived from first-principles methods. They, however, reach contradictory conclusions. While [13] essentially agrees with the results of [11], in contrast, [12] finds a larger core, of about $16M_⊕$, and exclude a solution without a core. These two recent works illustrate the remaining uncertainties on planetary modeling and on equations of state of matter under conditions characteristic of giant planet interiors (see section 4.1).

The lighter giant planets, Uranus and Neptune, are more enriched in heavy elements than their massive companions. A wide variety of models can match the mass/radius of these planets. Three-layer models with a central rocky core, an ice layer and an outer H/He envelope suggest an overall composition of 25% by mass of rocks, 60–70% of ices and 5–15% of gaseous H/He [14]. Other solutions exist, as suggested by [15], assuming, instead of a pure ice second layer, a mixture of ice, rock and gas (see table 2). According to recent estimates, an upper limit for the H/He mass fraction is about $5M_⊕$ for Uranus and $4.7M_⊕$ for Neptune if only rock and H/He are present [16].

Interestingly enough, models for Uranus assuming that each layer is homogeneous with an adiabatic temperature profile fail to reproduce the gravitational moments. An interesting solution for this problem, suggested by [15], is to assume that some parts of the layers are not homogeneously mixed. In the presence of a persistent molecular weight gradient, convection can be confined in numerous homogeneous layers separated by thin diffusive interfaces. This process, known as layered or double-diffusive convection, provides a solution to reproduce the observed gravitational moments in Uranus [15]. We will see in section 8.1 that this process may also be relevant for extrasolar transiting planets.

Table 1. Interior properties of Jupiter and Saturn according to [11]. $M_{\text{core}}$ is the mass of the rocky/icy core; $M_Z$ the mass of heavy elements in the envelope; $M_Z^{\text{tot}} = M_{\text{core}} + M_Z$ the total mass of heavy elements; $Z/Z(J)$ is the ratio of heavy elements in the planet to that in the Sun.

|          | Jupiter (317.8$M_⊕$) | Saturn (95.1$M_⊕$) |
|----------|-----------------------|---------------------|
| $M_{\text{core}}$ | 0–11$M_⊕$            | 9–22$M_⊕$          |
| $M_Z$    | 1–39$M_⊕$            | 1–8$M_⊕$           |
| $M_Z^{\text{tot}}$ | 8–39$M_⊕$          | 13–28$M_⊕$         |
| $Z/Z(J)$ | 1–6                   | 6–14                |

The analysis of the atmospheric composition of our giant planets also shows a significant enrichment in heavy elements. Abundances of several elements (C, N, S, Ar, Kr, Xe) have been measured in situ by the Galileo probe for Jupiter and they show a global enrichment compared with solar values of about a factor 3 [6,17]. For Saturn, spectroscopic detections of methane and ammonia suggest significant enrichment of C (about a factor 6 [17]) and N (about a factor 2 [6]), although with large uncertainties for the latter element. For Uranus and Neptune, carbon is significantly enriched, with large factors $>20$ [17] while the abundance of N/H is comparable to that of Jupiter and Saturn [6].

The interior and atmospheric properties of our giant planets bear important consequences on our general perception of planetary structure. The observational evidence that our giant planets are enriched in heavy material supports our general understanding of planet formation (see section 3) and guide the development of a general theory for exoplanets.

2.2. Observed properties of exoplanets

The description of exoplanet physical properties must encompass the wide variety of planetary masses and orbital separations yet discovered, as illustrated in figure 1. About 30% of exoplanets have an orbital separation $a$ less than 0.1 AU. Irradiation effects from their parent star must thus be accounted for for a correct description of their structural and evolutionary properties. Another compelling property of exoplanetary systems is the correlation between planet–host star metallicity and frequency of planets. The probability of finding giant planets is a strong function of the parent star metallicity, indicating that an environment enriched in heavy material favors planet formation [11]. This correlation, however, is not observed for light Neptune-mass planets [11], although the statistics is still poor. About 20 of these light planets have yet been discovered [1]. These trends provide clues about their formation process, as discussed in section 3.

Crucial information on the interior structure and bulk composition of exoplanets are unveiled by objects transiting in front of their parent star. About 60 of these planets have yet been detected, revealing an extraordinary variety in mean planetary densities and composition. As illustrated in figure 2, the metallicity is defined as the mass fraction of all chemical elements heavier than helium.

3 The term ‘rock’ usually refers to silicates (Mg-, Si- and O-rich compounds) and the term ‘ice’ involves a mixture of volatiles dominantly composed of water, with traces of methane and ammonia.

4 The metallicity is defined as the mass fraction of all chemical elements heavier than helium.
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some exoplanets are significantly denser, thus more enriched
in heavy material than our own giant planets. One of the
most remarkable discoveries is the Saturn mass planet HD
149026b with such a small radius that more than 70
M\(_\oplus\) of heavy material is required to explain it [18]. This discovery
raises the question of the formation process of planets with
such a large amount of heavy material. More importantly, it
tells us that exoplanets may contain large amounts of heavy
material, like our Solar System planets, supporting our current
understanding of planetary formation (see section 3).

Another puzzling property revealed by figure 2 is the
abnormally large radius of a significant fraction of transiting
planets. Oddly enough, the very first transiting planet ever
discovered, HD209458b [20], was found with a large radius
which still challenges our understanding of planetary structure.
At the time of this writing, the two most inflated exoplanets
known are TRES-4b, with a radius \(R_p = 1.78R_{\text{Jup}}\) and a mass
\(M_p = 0.9M_{\text{Jup}}\) [21] and WASP-12b, with \(R = 1.79R_{\text{Jup}}\) and
\(M_p = 1.4M_{\text{Jup}}\) [22]. These observations indicate that new
mechanisms are required to inflate close-in planets. Whether
these mechanisms are peculiar, operating only under very
specific conditions and planetary system configurations, or
whether basic physics is missing in the modeling of close-in
giant planets are still open questions. Several mechanisms
have been proposed since the discovery of HD209458, but no
firm answer has been obtained for now. In this review, we
will present the main proposed mechanisms and discuss their status
(section 8.1).

3. Planet formation

3.1. Core-accretion model

The current most widely accepted scenario for giant planet
formation is the so-called core-accretion model [23, 24]. In

this model, solid cores grow oligarchically in the surrounding
nebula by accreting small planetesimals, located within
the protoplanet’s zone of gravitational influence, called the
feeding zone, which extends over a few Hills radii (\(R_H = \alpha(M_p/3M_\star)^{1/3}\)), where \(M_p\) and \(M_\star\) denote the protoplanet
and star mass, respectively, and \(\alpha\) the planet’s orbital radius). The
planetesimal accretion rate \(dM_p/dt \propto \Sigma_i \approx 10^{-5}M_\oplus/yr\),
where \(\Sigma_i\) denotes the local surface density of solids at the
orbital radius (\(\Sigma_i \approx (a/S\,\text{AU})^{-3/2} \, \text{g cm}^{-2}\) for the minimum-
mass solar nebula (MMSN\(^6\)).

Once the solid core has grown of the order of a Mars mass
\((\sim 0.1M_\oplus)\), it starts capturing an envelope of nebular gas and the
protoplanet’s growth is governed by a quasistatic balance
between radiative loss and accretion energy due dominantly
to planetesimals (planetesimals are supposed to sink to the
planet’s central regions whereas the accreted gas remains
near the surface), with a negligible contribution from the
\(P\,dV\) contraction work. Both solid and gas accretion rates
are relatively constant during this phase, with gas accretion
exceeding the planetesimal one. Above a critical mass \(M_{\text{crit}}\),
a static envelope can no longer be supported. Gravitational
contraction is now necessary to compensate the radiative
loss, which increases in turn gas accretion, leading to a
runaway process, and the core accretes a massive gas envelope,
becoming a newborn giant planet. For an envelope dust-

dominated opacity (\(k \sim 0.1-1\,\text{cm}^2\,\text{g}^{-1}\)), \(M_{\text{crit}} \sim 10M_\oplus\),
although with large possible variations due to the sensitive

5 Defined as solid objects present in protoplanetary disks.
6 The minimum-mass solar nebula is defined as the protoplanetary disk of
solar composition that contains the minimum amount of solids necessary to
build the planets of our Solar System [25, 26].
The main problem faced by the conventional core-accretion model is that core growth takes longer than typical protoplanetary disk lifetimes, \( \lesssim \) a few Myr [30]. Giant planet cores can be obtained within the appropriate timescale either by severely increasing the disk density compared with the MMSN or by reducing drastically the accreting envelope opacity, allowing rapid core contraction. A reduced opacity implies dust grains significantly larger than in the ISM, and thus efficient settling in the warmer parts of the disk, where they are destroyed [31, 32]. Spiral density waves generated in the gas by the core, however, cause this latter to migrate inward, the so-called type-I migration, with a characteristic timescale 

\[
t_1 = a/|a| \sim \Omega^{-1}(M_\ast/M_p)(M_\ast/\Sigma_{\text{gas}}^2)(H/r)^2 \approx (M_\ast/M_p)(r/1 \text{ AU}) \text{ yr},
\]

for values appropriate to the MMSN, where \( \Omega \) denotes the protoplanet’s Keplerian angular velocity and \( H \) the disk scale height [33, 34, 35]. This timescale is much shorter than the time required to build up a 10\( M_\oplus \) core in standard core-accretion models. These calculations, however, assume that the disk is laminar (linear planet-disk perturbations). Simulations including the effect of (MHD) turbulence in the disk show that the mean torque does not converge toward the value obtained in a laminar disk (at least for the duration of the simulations) and that the usual type-I migration is disrupted by turbulence [36, 37]. Analysis of these stochastic torques suggests that a planet can overcome type-I migration for several orbital periods, \( P = 2\pi/\Omega \). Above a critical mass, of the order of 30\( M_\oplus \) at 5 AU (although with large uncertainties) for typical protoplanetary disk conditions, the planet’s gravitational tidal force exceeds the viscous torque, eventually stopping the motion of the protoplanet. Deposition of angular momentum in the planet’s vicinity, due to shock and viscous dissipation, pushes material away from the planet, clearing an annular gap in the disk [33, 38]. The planet is now locked in the disk and undergoes type-II migration with a timescale given by the disk viscous timescale 

\[
t_\text{II} \simeq 5 \times 10^6 \Omega^{-1}(10^{-4}/\alpha)(10^{-1}/H/r)^2(r/10 \text{ AU})^{3/2} \text{ yr},
\]

assuming a Shakura–Sunyaev type viscosity law, \( \nu = \alpha c_s H \), where \( c_s \) is the isothermal sound speed averaged over the vertical structure [33, 38]. Note that this timescale is now independent of the protoplanet’s mass. Gap clearing and disk dissipation will limit the accretion onto the central core once the nebula starts falling down around it—although further accretion is possible if the protoplanet has an eccentric orbit—and the planet’s final mass is set up by these limits.

Taking into account migration processes in the core-accretion model has been found to speed up core growth by increasing the supply of planetesimals, avoiding the depletion of the feeding zone obtained in the in situ formation models and solving the timescale problem of the standard core-accretion scenario [39, 40]. Planets, including our own Solar System giants, now form on a timescale consistent with disk lifetimes, with the appropriate observational signatures [39]. These models, however, have to reduce the conventional type-I migration rate by a factor \( \gtrsim 10 \). It is not clear whether turbulent-induced stochastic migration can yield such a decrease over significant \( (\gtrsim 10^5 \text{ yr}) \) timescales and the real impact of stochastic migration remains an open issue. Interestingly, recent core-accretion simulations including the concurrent growth and migration of multiple embryos find a global negative impact on planet formation: while migration indeed extends the domain of accretion for an embryo, this latter must also compete with other earlier generation embryos which have depleted the inner regions of solid material, reducing the final number of giant planet cores [41].

In summary, including migration in the conventional core-accretion model succeeds in forming giant planets within appropriate timescales down to the inner edge of the disk. These models, however, use disk surface densities or dust-to-gas ratios about 2–3 times larger than the MMSN (suggesting that giant planet cores are unlikely to form in a MMSN) and require adequate planetesimal sizes and/or viscosity parameters in order for giant planet cores to grow rapidly before type-I or type-II migration moves them into the star. Unfortunately, these parameters, which involve complex processes such as grain growth/fragmentation or turbulent viscosity are very uncertain and can vary over orders of magnitude.

### 3.2. Gravitational instability

The alternative theory for giant planet formation is direct gravitational fragmentation and collapse of a protoplanetary disc, the so-called gravitational instability (GI) scenario [42, 43], originally suggested to circumvent the timescale problem of the original core-accretion scenario. Instability to axisymmetric (ring-like) perturbations in a disk occurs when Toomre’s stability criterion is violated, i.e. \( Q = c_\kappa \kappa /\pi G \Sigma \sim T^{1/2}/\Omega/\Sigma \sim (M_\ast/M_d)(H/r) < 1 \) [44], where \( c_\kappa \) is the epicyclic frequency at some point in the disk (for Keplerian orbits, the orbital and epicyclic frequencies are nearly the same whenever the disk mass is small compared with the stellar mass), \( \Sigma \approx M_d/r^2 \) is the surface density, \( H \sim c_s/\Omega \) is the disk vertical scale height and \( M_d \) is the disc mass contained within radius \( r \). According to the Toomre criterion, the disk becomes unstable to its own gravity whenever the stabilizing influence of differential rotation or pressure is insufficient. Note that this criterion is governed by the local density and is thus a local criterion for fragmentation. In the nonlinear regime, global spiral waves develop for values of \( Q \lesssim 1.3–1.7 \) with a growth time of a few orbital periods. This solution involves spiral modes that either saturate at low-amplitude via mode coupling,
leading to rapid non-local angular momentum redistribution restoring gravitational stability with no disk fragmentation [45] or fragment the disk. Estimates of disk surface densities and the fact that typically $H/r \sim 0.1$ for protostellar disks indicate that disks with $M_{d} \lesssim 0.1M_\odot$ are usually stable to GI. A disk, however, might become unstable during its evolution, for instance during its formation, if mass builds up faster than it is accreted by the star or, at later times, if the outer part of the disk, where stellar radiation is negligible, becomes sufficiently cool. For fragmentation to occur, however, the disk must cool quickly enough to avoid entering a self-regulated phase, i.e. the disk cooling time $t_{cool}$ must satisfy the condition, often called Gammie criterion, for very-thin disks $t_{cool} < \xi \kappa^{-1}$, with $\xi \sim 3$ [46]. Indeed, the energy loss rate determines the effect of the instability: isothermal disks, in which energy is easily lost (and gained, in gas expansion), remain unstable and evolve violently whereas adiabatic disks tend to heat up and become more stable.

Energy transport and dissipation processes are thus key issues to determine whether or not planets can form from gravitational instabilities in a disk. A detailed analysis of these conditions [47] shows that planet formation by GIs can occur only in very massive disks, $M_{d} \gtrsim 0.1M_\odot$, at the very upper end of the observed distribution, and at large orbital distances, $a \gtrsim 100$ AU. Even when vigorous convection occurs, it does not lower $t_{cool}$ enough to lead to fragmentation [48, 49]. Note also that stellar irradiation tends to hamper fragmentation.

An other key issue for planet formation by GI is the fate of the fragments. Even if the disk cools fast enough for fragmentation to occur, the fragments have to last long enough to contract into planet embryos before being disrupted by tidal stresses, collisions or shocks. Moreover, the typical mass scale associated with the fastest-growing density perturbations in a disc undergoing GI, for $H/r \sim 0.1$ and $M\approx 1M_\odot$, is of the order of a few Jupiter masses [47]. An important question is whether such a fragment can form a core since at such relatively high initial central temperatures, less than 1% of the gas can condense into grains and one has to invoke efficient sedimentation of silicate and iron grains to the center during the early contraction phase to be consistent with the enhanced heavy element abundances relative to solar values inferred for our giant planets (see section 2.1 and tables 1–2). Therefore, it is far from clear that the peculiar composition and structure of our Jovian planets can be explained with the GI model. Fragmentation by GI thus remains controversial, with markedly different results from various groups, and requires that the disk detailed thermal energetics are properly taken into account (see, e.g., [50, 51] for recent reviews).

### 3.3. Core-accretion versus gravitational instability

It is interesting to point out that disk instability predicts that even very young ($\lesssim 1$ Myr) stars should harbor gas giant planets, whereas the formation of such planets with the core-accretion scenario requires a few Myr. Observational searches for the presence of genuine giant planets around $\sim 1$ Myr-old stars will thus provide crucial tests for the two formation scenarios\(^7\). As mentioned above, determination of the heavy element abundances of extrasolar planets also provides a definitive test: compositional similarity of planets and their parent star would strongly favor gravitational collapse whereas significant heavy element enrichment of the planet with respect to the parent star composition would rule it out. The large heavy element enrichment inferred for several transiting planets (see section 2.2) clearly supports the core-accretion model. Last but not least, the efficiency of planet formation by GI should not depend on the disk metallicity, since gravitational collapse from the protoplanetary disk is a compositionally indiscriminating process, in contrast to the core-accretion scenario. The observed clear dependence of planet frequency with the host star metallicity (see section 2.2) and the suggested trend that metal-depleted stars seem to harbor lower mass planets ($M \sin(i) \lesssim 1M_{\text{Jup}}$), i.e. the lack of massive planets around metal-poor stars and the fact that stars hosting Neptune-mass planets seem to have a flat metallicity distribution [1] clearly suggest that metallicity plays a crucial role in planet formation, in agreement with the core-accretion model. Furthermore, statistical analysis of null detections in direct imaging surveys place constraints on the occurrence of giant extrasolar planets around FGKM stars. Calculations based on probability distributions, derived from observed mass and semi-major axis distributions of extra-solar planets [52], show that $4M_{\text{Jup}}$ and larger planets are found around less than 20% of stars beyond about 60 to 180 AU, depending on the planet theoretical models, i.e. beyond the equivalent of extra-solar Kuiper belts, at 95% confidence level [53, 54]. Even though these calculations must be taken with caution (they do not include the few detected large orbit planets) and need to be confirmed by more detailed statistical analysis, they suggest that extra-solar giant planets at large separations ($\gtrsim 60$ AU) are rare. This observational constraint, combined with the statistical conclusion that the less massive the star the lower the likelihood to host a giant planet ($>0.8M_{\text{Jup}}$) [55] and with the theoretical constraints mentioned in section 3.2, strongly weakens the GI model and reinforces the core-accretion one. This latter thus appears most likely as the dominant scenario for planet formation.

The recently detected $3M_{\text{Jup}}$ object Fomalhaut-b at projected separations $>100$ AU from the central star [56], and other similar discoveries, challenge planet formation theories. Although local formation by GI is not excluded [57], formation by core accretion at shorter orbital distances remains a possibility, the planets having migrated outward under the action of either planet–planet scattering [58, 59] or resonant interactions with an other planet in a common gap [60]. GI-induced planet formation, however, remains a plausible explanation in some peculiar situations, like for instance for the planets recently discovered orbiting a double SdB–M dwarf system [61]. In that case, the circumbinary disk is likely to be massive enough to become unstable.

\(^7\) For this test to be meaningful, it is crucial to identify the stellar companion as a genuine metal-enriched planet, not as a brown dwarf of similar mass. Indeed, GI-induced fragmentation can occur during the early (dynamical) stages of protostellar collapse and rapid disk accretion, but objects formed by fragmentation in these cases are companion stars or brown dwarfs, not planets.
4. Interior structure properties

The impact of planetary internal compositions on their radius goes back to the pioneering works of Zapolsky and Salpeter [62], who considered various zero-temperature single element compositions, and to Stevenson [8] for H/He, ice and rock planet compositions. Modern calculations, although basically similar to these studies, present improvements upon these works as they include modern equation of state (EOS) calculations, notably for H/He, and accurate atmospheric boundary conditions, taking into account irradiation from the parent star when necessary (see section 6.3).

4.1. Thermodynamic properties

The mechanical structure and internal heat profile of a planet are entirely determined by the EOS of its chemical constituents. Indeed, due to efficient convective transport, the internal temperature profile is quasi-adiabatic. In the pressure–temperature ($P$–$T$) domain characteristic of planet interiors, elements go from a molecular or atomic state in the low-density outermost regions to an ionized, metallic one in the dense inner parts, covering the regime of pressure dissociation and pressure ionization. Interactions between molecules, atoms, ions and electrons are dominant and degeneracy effects for the electrons play a crucial role, making the derivation of an accurate EOS a challenging task. We examine below our present knowledge in this domain.

4.1.1. Equation of state for H/He.

The most widely used EOS to describe the thermodynamic properties of the gaseous H/He envelope of giant planets is the Saumon–Chabrier–VanHorn EOS (SCVH) [63]. This semi-analytical EOS recovers numerical simulations and experimental results in the high-density and low-density regimes, respectively, while, in its simplest form, interpolating over the pressure-ionization regime. Thanks to the growth of computational performances, the properties of dense hydrogen can now be calculated from first-principle or nearly first-principle quantum mechanical calculations. The last generation of these ab initio calculations seem to converge toward an agreement and to predict a substantially less compressible EOS for hydrogen, i.e. predict a compressible Hugoniot result [65,66], in agreement with the recent experiments seem to converge toward the ‘stiff’ (least compressible) Hugoniot parameter. The dotted lines indicate regions probed by single, double and triple shock experiments on deuterium while filled squares show recent near entropic compression data [84]. The open squares indicate single and double shock data for helium [85] while the small polygon indicates the locus of recent shock wave experiments from pre-compressed initial states [67]. The heavy solid line illustrates the isentrope of Jupiter. Figure kindly provided by Saumon.

Figure 3. Phase diagram of hydrogen. Solid lines indicate dimensionless physical parameters ($\Gamma = (Ze)^2/kT\alpha_i$, where $\alpha_i$ is the mean interionic distance, is the so-called plasma parameter, with $\Gamma = 1$ delineating weakly correlated from strongly correlated plasma regions and $\Gamma = 178$ indicating the solid–liquid melting line for a bcc-lattice and $\theta = kT/kF$, where $kF$ is the electron fluid Fermi energy, is the so-called degeneracy parameter). The dashed curves indicate the 50% dissociation and ionization boundaries. The dotted lines indicate regions probed by single, double and triple shock experiments on deuterium while filled squares show recent near entropic compression data [84]. The open squares indicate single and double shock data for helium [85] while the small polygon indicates the locus of recent shock wave experiments from pre-compressed initial states [67]. The heavy solid line illustrates the isentrope of Jupiter. Figure kindly provided by Saumon.

shock, as given by the Rankine–Hugoniot relations, force the family of shocked states, which correspond to different shock velocities, to follow a Hugoniot curve in the $(P,\rho,T)$ phase diagram. Dissociation or ionization processes absorb the corresponding amounts of energy and thus yield high degrees of compression with a modest temperature increase, whereas in the absence of such processes the energy of the shock is expended mostly in the kinetic degrees of freedom with a corresponding increase in temperature, following a different Hugoniot for the same initial state. Figure 3 portrays the phase diagram of hydrogen, with the pressure range presently probed by high-pressure dynamical experiments on H and He, together with Jupiter’s internal adiabat. Various experimental techniques, however, give different results, with a ~30–50% difference in $P(\rho)$ in the maximum compression region for deuterium, ~0.5–1.5 Mbar, although the most recent experiments seem to converge toward the ‘stiff’ (least compressible) Hugoniot result [65,66], in agreement with the aforementioned quantum mechanical simulations (see [64] for various theory-experiment comparisons). This issue must be settled before hydrogen pressure ionization can be considered as correctly understood.

For the less explored case of liquid helium, recent high-pressure experiments have been achieved up to 2 Mbar for various Hugoniot initial conditions, allowing to test the EOS over a relatively broad range. These experiments show a larger

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8 Because of the higher density of deuterium compared with hydrogen, higher shock pressures can be achieved experimentally for a given impact speed.
compressibility than for hydrogen, due to electronic excitations\textsuperscript{[67]} and are in good agreement with the SCVH EOS while \textit{ab initio} calculations\textsuperscript{[68]} underestimate the compressibility. Clearly more of these experiments, exploring the so-called ‘warm dense matter’ domain, are needed to fully assess the validity of the various EOS models, with a crucial impact on our knowledge of the structure of Jovian planets\textsuperscript{[11–13]} (see section 2.1).

The combined interactions of H and He in the mixture increase drastically the degree of complexity in the characterization of the plasma. Not only the interactions between the two fluids will affect the regime of pressure ionization compared with the pure components, but partial immiscibility between the two species has been suggested to explain Saturn’s excess luminosity for the age of the Solar System\textsuperscript{[69–71]}, and may occur inside some exoplanets. A phase separation in the interior of a planet strongly affects its cooling history. Indeed, if H/He phase separation (or immiscibility of other species with H) occurs in a planet’s interior, He-rich droplets will form in a surrounding H-rich fluid and will sink to the planet’s center under the action of the gravity field. This extra source of gravitational energy converted into heat slows down the planet’s cooling, or alternatively yields a larger luminosity for a given age. The strongest suggestion for a phase separation in Jupiter or Saturn interiors comes from the observed depletion of helium in their atmosphere, with a mass fraction $Y = 0.238 \pm 0.05$ measured by the Galileo probe for Jupiter, and a more uncertain determination, $Y = 0.18–0.25$ inferred from Voyager observations for Saturn, to be compared with the protosolar nebula value, $Y = 0.275$\textsuperscript{[6]}. Unfortunately, given the aforementioned difficulty in modeling the properties of H or He alone, and the necessity to simulate a large enough number of particles for the minor species (He in the present case) to obtain statistically converged results, no reliable calculation of the H/He phase diagram can be claimed so far. As mentioned above, pressure ionization of pure hydrogen and helium must first be fully mastered before the reliability of the calculations exploring the behavior of the mixture can be unambiguously assessed\textsuperscript{9}.

Resolving these important issues concerning the H and He EOS must await (i) unambiguous experimental confirmation of the H and He EOS at high pressure, (ii) unambiguous confirmation of the reliability of the theoretical calculations, in particular in the pressure-ionization regime, (iii) guidance from experiments to predict the behavior of the H/He mixture under planetary interior conditions. Progress both on the experimental and theoretical side will hopefully enable us to fulfill these criteria within the coming years (see section 9).

4.1.2. Equation of state for heavy elements. According to the composition of the protosolar nebula, the next most abundant constituents after hydrogen and helium in gaseous giant planets, but the most abundant ones in ice giants and Earth-like planets, consist of C, N and O, often referred to as ’ices’ under their molecule-bearing volatile forms ($\text{H}_2\text{O}$, the most abundant of these elements for solar C/O and N/O ratios, $\text{CH}_4$, $\text{NH}_3$, $\text{CO}$, $\text{N}_2$ and possibly $\text{CO}_2$). The remaining constituents consist of silicates (Mg, Si and O-rich material) and iron (as mixtures of more refractory elements under the form of metal, oxide, sulfide or substituting for Mg in the silicates). The behavior of these different elements as a function of pressure, under the conditions typical of giant planet interiors is not or poorly known. At very high pressure, the categorizations of gas, ice and rock become meaningless and these elements should become a mixture of closed-shell ions. The most widely used EOS models for such elements are ANEOS\textsuperscript{[74]} and SESAME\textsuperscript{[75]}, which describe the thermodynamic properties of water, ‘rocks’ (olivine (fosterite $\text{Mg}_2\text{SiO}_4$) or dunite in ANEOS, a mixture of silicates and other heavy elements called ‘drysand’ in SESAME) and iron. These EOS consist of interpolations between existing Hugoniot data at low to moderately high ($\lesssim 0.5$ Mbar) pressure and Thomas–Fermi or more sophisticated first-principle calculations at very high density ($P \gtrsim 100$ Mbar), where ionized species dominate. Interpolation, however, provides no insight about the correct structural and electronic properties of the element as a function of pressure, and thus no information about its compressibility, ionization stage (thus conductivity), or even its phase change, solid or liquid. All these properties can have a large impact on the internal structure and the evolution of the planets. A detailed comparison between these EOS and the impact of the uncertainties on the radius determination for Neptune-like and Jupiter-like planets has been conducted in\textsuperscript{[19]}. The largest difference between the various EOS models, reaching up to $\sim 40–60\%$ in $P(\rho)$ and $\sim 10–15\%$ on the entropy $S(P, T)$, occurs in the $T \sim 10^3–10^4$ K, $P \sim 10^2–1$ Mbar interpolated region, the typical domain of Neptune-like planets\textsuperscript{[19]}. For these objects, such an uncertainty on the heavy element EOS translates into a $\sim 10\%$ uncertainty in the radius after 1 Gyr, and to larger uncertainties at earlier ages (figure 3 of\textsuperscript{[19]}).

For solids, the lattice structure energy dominates the thermal vibration (phonons) contribution and, once the planet becomes cool enough for the core to become solid, the thermal contribution of this latter to the cooling of the planet can be neglected. This is not true at higher temperature, i.e. during the earlier stages of the planet’s evolution, when the heavy elements are predicted to be in a liquid state, according to their EOS. In that case, thermal effects can substantially modify the zero-temperature structure contribution and assuming a zero-T or low-T core, i.e. neglecting the core release of thermal energy $(dU/dV)_{\text{core}}$ and gravitational energy $(P(dV/d\rho))_{\text{core}}$ can drastically underestimate its true gravothermal contribution, affecting the general cooling of the planet. The thermal contribution of the heavy elements to the cooling of the planet must then properly be taken into account for a correct description of the planet’s evolution\textsuperscript{[19]}.\textsuperscript{9}

\textsuperscript{9} Note that the recent claim\textsuperscript{[72]} that H/He phase separation cannot take place in Jupiter’s interior, because metallization of He should occur at lower pressure than previously expected, is not correct. Although such a facilitated metallization (by itself a model-dependent result) could exclude the suggested H$^–$He immiscibility\textsuperscript{[73]}, it does not preclude at all the H$^+$He$^{++}$ one.
4.2. Internal structure and composition

There is compelling evidence from our own solar system planets that they are substantially enriched in heavy elements (C,N,O), with a $\sim$3 to $\sim$6 times solar value for Jupiter and Saturn, respectively, and even larger contrasts for Uranus and Neptune (see section 2.1), as expected from a formation by core accretion. This should apply as well to the discovered exoplanets. Indeed, the small radii of some of the observed transiting planets can only be reproduced if these objects are substantially enriched in heavy material, with a total of several tens to hundreds of Earth masses. For all these objects, including our own Jovian planets, however, uncertainties remain on (i) the total amount of heavy material, (ii) the respective fractions of ‘rocks’ (silicates) and ‘ices’ and (iii) the distribution of this heavy material in the planet’s interior. As mentioned above, the first uncertainty (i) stems primarily from the present uncertainties on the various EOSs and should decrease with further experimental and theoretical progress. Addressing the two other issues necessitate to differentiate gaseous from solid/liquid planets.

4.2.1. Earth-like to super-Earth planets ($\lesssim 10 M_\oplus$). As discussed in section 3, planets below about $10 M_\oplus$, usually denominated as super-Earth down to Earth-like planets, are not massive enough to enter the unstable, runaway regime leading to rapid accretion of a large gaseous envelope onto the central core. Post-formation degassing or oxidization processes can only produce a tenuous gaseous atmosphere, with no significant consequences for the planet’s contraction. Therefore, these objects consist essentially of solids or liquids rather than gases, making their structure determination from mass–radius observations less uncertain than for more massive planets (see below). The mass–radius relationship for these low-mass planets has been parametrized as $R = R_{\text{ref}}(M/M_\oplus)^\alpha$, with $R_{\text{ref}} = (1 + 0.56 \alpha) R_\oplus$ and $\alpha = 0.262(1-0.138 \alpha)$, for the rocky or ocean super-Earth planets in the mass range $1-10 M_\oplus$ [76], where $\alpha$ denotes the water mass fraction and $\beta = 0.3$ for planets between $10^{-2}$ and $1 M_\oplus$, with a weak dependence upon the iron to silicate ratio Fe/Si [77]. Note that incompressible (constant density) material corresponds to $\beta = 1/3$. These parametrizations appear to be rather robust, despite the uncertainties in the EOS and in the iron/silicate fraction [77–79]. This provides a sound diagnostic for transiting Earth-like planet detections and the possible identification of the so-called ‘ocean planets’, planets composed dominantly of water [80, 81], as opposed to the terrestrial (Fe-rich) planets. As mentioned in section 4.1.2, current uncertainties in the high-pressure behavior of silicates, ices and iron alloys prevent more precise information such as the detailed internal composition or the size and the nature, solid or liquid, of the central core. Exploration of the iron phase diagram and melting curve, in particular, a subject of prime importance for the characterization of the Earth inner core, has become even more interesting since the discovery of exoplanets of a few Earth masses (see section 1) and the expected wealth of transiting Earth-size planets with the Kepler mission [82]. While dynamic (Hugoniot) experiments produce too large a temperatures at the pressure of interest for the Earth, they might become relevant for the super-Earth objects. This again points out the need for high-pressure experiments for planetary materials in the appropriate $\gtrsim 10^4$ K, > Mbar regime.

4.2.2. Neptune-like to super-Jupiter planets ($\gtrsim 10 M_\oplus$). For planets with a $\gtrsim 10$% by mass gaseous (H/He) envelope, this latter essentially governs the gravothermal evolution of the planet. For instance, a $10 M_\oplus$ planet retaining a modest 10% H/He envelope is 50% larger than its pure icy counterpart [19, 83]. Under such conditions, a variety of internal compositions, either water-rich or iron-rich can produce the same mass–radius signature [19, 83] and detailed information about the planet’s internal structure, other than inferring its bulk properties, becomes elusive. One of the main uncertainties about the internal structure is that we do not know whether these heavy elements are predominantly concentrated into a central core or are distributed more or less homogeneously throughout the gaseous H/He envelope.

A summary of the main consequences of the uncertainties (i) in the EOS, (ii) in the chemical composition and (iii) in the distribution of the heavy elements for planets with masses $\gtrsim 10 M_\oplus$ can be found in [19]. In particular, [19] shows that for a global metal enrichment $Z \gtrsim 15$%, all heavy material being either gathered in a core or distributed homogeneously throughout the envelope yields a $\gtrsim 10$% difference in radius after 1 Gyr for Neptune-mass planets and a $\gtrsim 4$% difference for Jovian-mass planets.

4.3. Energy transport properties

4.3.1. Giant planets. The large radiative opacity of planetary material yields completely inefficient heat transport by photons, except in the most outer layers close to the planet photosphere (see section 5). Transport by conduction, resulting from collisions during random motion of particles, may in some cases be relevant. In the central part of H/He dominated planets, thermal conductivity is dominated by electronic transport with conductivity $\kappa_T \sim 10^{-1}$ cm s$^{-1}$ [69]. If no electrons are available, as in the outer envelope, conductive transport is dominated by the less efficient molecular motions with thermal conductivity $\kappa_T \sim 10^{-2}$ cm$^2$ s$^{-1}$ [69]. Conduction by electrons (or eventually phonons) may also dominate in central cores composed of heavy material (see [19]). But the dominant energy transport mechanism in giant planet interiors is convection. Large-scale convection is extremely efficient in transporting heat [86, 87] and the temperature profile is close to adiabatic. Superadiabaticity is extremely small, with $\nabla_T - \nabla_{ad} \lesssim 10^{-8}$ in most of the interior$^{10}$. For H/He dominated planets, convective velocities derived from the mixing length formalism vary between $\sim 10$ cm s$^{-1}$, in the central regions, and a few 100 cm s$^{-1}$ in the outer layers.

As initially stressed by [87], it is a conventional assumption in giant planet modeling to postulate that their interiors are fully convective and thus homogeneously mixed.

\[^{10}\] $V_T = \frac{d\ln T}{d\ln P}$ is the local temperature gradient and $\nabla_{ad} = \left(\frac{d\ln T}{d\ln P}\right)_S$ the adiabatic gradient.
This assumption has never been proven to be valid and has been questioned in the case of our own giant planets by [87]. As mentioned in section 2.1, more recent models for Uranus have also suggested the possible existence of non-homogeneous regions where convection is not efficient. If compositional gradients exist, convection can break into convective layers separated by thin diffusive layers, the so-called double-diffusive or layered convection, or, if layers do not persist, overstable modes of convection can lead to the growth of small-scale fluid oscillations, the so-called oscillatory convection, becoming more alike an enhanced diffusion process than a large-scale convective process [9, 70]. Layered convection is known to occur in laboratory experiments and in some regions of the Earth's oceans or great lakes. In these conditions, the heat flux transport is significantly reduced because of the presence of multiple diffusive layers. If this process is present under conditions characteristic of giant planet interiors, heat transport in the diffusive layers is due to conduction with above-mentioned thermal conductivities [88]. Because diffusion limits heat transport, the internal heat flow of the planet is significantly reduced compared with that of a fully convective object. This may bear important consequences on the planet structure and evolution, as discussed in section 8.1, slowing down its global cooling and contraction [87, 88].

4.3.2. Terrestrial exoplanets. Many efforts are devoted to the modeling of massive terrestrial planets, or super-Earths, essentially composed of heavy material, with a negligible amount of gas. Simplified models have been developed in order to investigate a wide range of compositions and masses [78, 79]. These models involve simple internal structures and compositions (see section 4.2.1). They use zero or uniform, low-temperature equations of state for the heavy material and thus do not consider the planet’s thermal structure. Such simplified models are advocated on the basis that, so far, only exoplanet bulk compositions can be inferred from mass and radius measurements, so that detailed planet interior models are not necessary [79]. In the future, however, internal structure models reaching a degree of sophistication comparable to our own Earth’s description might become required for terrestrial exoplanets. In this perspective, detailed models of massive Earth or super-Earth analogs have been developed [77, 89, 90]. They rely on our knowledge of the Earth’s internal structure, appropriately rescaled to super-Earth masses. They involve layered internal structures with different compositions and phase changes, including an iron-rich core, lower and upper mantles composed of silicates and an outer water layer (icy and/or liquid), as well as the related temperature profiles. The effect of large amounts of water, characterizing the so-called ‘ocean planets’, on the mass–radius relationships has also been investigated by [81]. The thermal profile is constructed according to the Earth thermal structure, which is determined by convective transport in each layer and is characterized by important variations at the interfaces. According to [89], the thermal structure has little effect on the radius of an Earth-like planet but imposes conditions on the compositional phases, particularly for water at the surface. This is of prime importance for the characterization of ocean planets, in order to know whether or not they can have a liquid water surface [76, 81]. Typical terrestrial geological processes such as plate tectonics are now introduced in some exo-Earth models, with the claim that this mode of convective transport mechanism might be important for massive terrestrial planets [91].

5. Atmospheric properties

The wide variety of planets both in and out of our solar system provide excellent laboratories for understanding how atmospheres evolve with time and react to their environments. Atmospheres by themselves hold a nearly endless supply of complex and interesting physical problems, but are also the primary link between observations and theory. The majority of observational techniques for studying planets involve capturing photons that have emerged from the atmosphere, placing extreme importance on our ability to successfully model atmospheric behavior. The grouping and location of substellar mass objects (brown dwarfs and giant planets) on color–color and color–magnitude diagrams are largely due to the sculpting of the emergent spectrum by atmospheric opacity sources. Also, as already mentioned above, the atmosphere regulates the release of energy from the interior and establishes the upper boundary condition for interior models. In the following sections, we discuss several of the important aspects of atmosphere modeling.

5.1. Chemistry, clouds and opacities

Chemistry is at the heart of most atmospheric phenomena and establishes the distribution of the elements among various compounds. Among these compounds are the primary opacity sources which in turn play key roles in the radiative transfer. Planetary atmospheres are commonly assumed to be ideal gasses in chemical equilibrium. These assumptions greatly simplify the determination of mole-fractions (or partial pressures) of most compounds that, under these assumptions, depend only on temperature and pressure.

In principle, chemical equilibrium models are extremely simple and require the solution of a set of coupled nonlinear equations (for mass and charge conservation and including either equilibrium constants or chemical potentials). There are, however, practical considerations such as obtaining the necessary thermochemical data (specific heat, entropy, enthalpy etc) of enough compounds to ultimately end up with a realistic picture of the ensemble of chemical species. One must also correctly handle phase-transitions that produce liquid and solid species, which may or may not remain aloft in the atmosphere. Some of the first chemical equilibrium models applied to gas giant atmospheres were carried out for Jupiter and Saturn [92, 93]. Later, with the discovery of brown dwarfs, a variety of chemical equilibrium models were explored [94, 95].

The temperature structures for Jupiter, Saturn, a hot-Jupiter exoplanet (HD 189733) and a cool brown dwarf (of T spectral type) are shown in figure 4. In this figure pressure is used as a proxy for height, with pressure
Figure 4. Temperature versus pressure for the atmospheres of Saturn, Jupiter, the brown dwarf Gl 229B and the hot-Jupiter HD189733b. The dotted lines are the condensation curves of H$_2$O(ice), MgSiO$_3$ and Fe (from left to right). Equal mole fractions of CO and CH$_4$ follow the dashed line, with CO favored at higher temperatures.

Increasing toward the center of the object. For the two solar system planets the temperature structures have been carefully measured, while the brown dwarf and hot-Jupiter structures are theoretical predictions (while accommodating most available observational constraints). Figure 5 compares the mole fractions (or equivalently the partial pressure divided by the total pressure) for several of the most important molecules in a gas having the same element abundances as the Sun. Molecular hydrogen and He are by far the dominant constituents of the gas since H and He are orders of magnitude more abundant in the Universe than any other element. The next three most abundant elements (C, N and O) make up the other dominant gas-phase molecules, H$_2$O, CO, CH$_4$, N$_2$ and NH$_3$. From Jupiter to a hot-Jupiter, the atmospheric temperature range is in the thousands of kelvin spanning a regime where water ice can form (in the case of Jupiter) and where all the water is in the gas phase. This broad temperature range also leads to a role reversal for CO and CH$_4$ as the dominant carbon-bearing molecule. In Jupiter, equilibrium chemistry predicts essentially no CO and nearly all of the carbon bound in CH$_4$, while the reverse is true for the hot-Jupiter. The brown dwarf has intermediate temperatures but is in the region where water and methane are substantially more abundant than CO. Ammonia begins to increase in concentration near the temperature found in the brown dwarf example, and becomes increasingly important in the very low temperature atmospheres of Jupiter and the other solar system giant planets.

At the low temperatures encountered in planetary atmospheres, phase transitions can occur resulting in the formation of liquid and solid ‘condensates’. The formation of condensates substantially alters the overall gas-phase mole fractions and, for example, explains the fairly dry conditions in Jupiter’s atmosphere as water is expected to condense into ice with water clouds deep in the atmosphere (~5 bar). At higher temperatures other perhaps less familiar condensates are expected to form involving silicate grains and many other minerals (Fe, MgSiO$_3$, Mg$_2$SiO$_4$, Al$_2$O$_3$ and so on). In the presence of gravity and vertical/horizontal mixing, these condensates can potentially form stable clouds or potentially sink completely out of the atmosphere, taking with them elements that can no longer participate in the chemistry. Including clouds in atmosphere models is a significant ongoing challenge and a variety of approaches are being explored. Extreme limiting assumptions include either no clouds at all or clouds in pure chemical equilibrium, resulting in thick clouds extending high up in the atmosphere. More sophisticated models are used to explore the intermediate cases, many of which are phenomenological in design, with the expectation that the important cloud properties can be described by a manageable set of parameters with values ultimately determined empirically. The cloud-model parameters most frequently used control cloud thickness, particle size and particle distribution. Alternatively, some models attempt to follow the micro-physics of nucleation and grain growth coupled to mixing within the gas. So far, no single model provides a comprehensive physical description of clouds. There is a long history of cloud modeling for the giant planets in our Solar System [96] and many of these have inspired cloud models used for exoplanet atmospheres [97]. Through the study of brown dwarf atmospheres, a great deal has been learned about cloud formation across a wide variety of low-temperature environments that can be directly applied to exoplanet atmospheres. For a review of competing cloud models, mostly applied to brown dwarf atmospheres, see [98].

The importance of the chemistry and clouds are translated to the rest of the model atmosphere via the opacities, either directly or indirectly. Opacity sources are crudely divided up as either continuous (e.g. scattering, bound-free or free-free) or line opacities (atomic and molecular transitions) and the relative importance of these is highly dependent.
on temperature and pressure as well as wavelength. The continuous opacity sources are generally well characterized in atmosphere models; however, for many grains, optical constants have either incomplete wavelength coverage or are not available at all. Perhaps the most problematic source of opacity over the years has been the molecular line opacity, where either the line data were simply not available or the ability to include all of the necessary lines was computationally prohibitive (requiring straight-means, \( K \)-coefficients or the ‘just overlapping line approximation’ (JOLA) to be used. For a description of these, see [99]). Modern computers are now quite capable of include millions of spectral lines, and model atmospheres can now include all the line data available to produce very realistic spectra. Some of the biggest improvements have been made in the completeness of line data for water vapor [100, 101]. Other molecules such as CH\(_4\) still lack important line data at high temperatures (that are now very important given the temperature ranges encountered in planetary atmosphere studies).

5.2. Irradiation effects

Of the more than 400 planets known, a third of these orbit their host star within 0.1 AU and, thus, receive a substantial amount of energy from the star. This large number of short-period exoplanets is attributed to observational selection effects but, nonetheless, has greatly broadened our expectations for giant planets and in particular the conditions present in their atmospheres. In most of these cases, the amount of extrinsic energy received by the planet from the star greatly exceeds the energy leftover from the planet’s formation that slowly leaks from the interior. Consequently, unlike longer period planets and isolated brown dwarfs, the dominant energy source is a function of the orbital separation and the spectral type of the host star and is less dependent on an exoplanet’s mass and age (except for very young planets).

The incident flux can be defined by the following equation, where \( R_* \) and \( T_\star \) are the host star radius and effective temperature and \( \alpha \in [1/4, 1] \) is a scaling factor used to crudely account for day-to-night energy redistribution.

\[
F_{inc} = \alpha \left( \frac{R_*}{r(t)} \right)^2 \sigma T_\star^4.
\]

Since exoplanets are found with a wide range of eccentricities, the general (time-dependent) planet–star separation is given by,

\[
r(t) = \frac{a(1 - e^2)}{1 + e \cos \theta(t)},
\]

where \( a \) is the semi-major axis, \( e \) is the eccentricity and \( \theta(t) \) is the angle swept out by the planet during an orbit.

The atmospheric temperature of isolated stars (and of widely separated planets and brown dwarfs) is often described by a single characteristic temperature, \( T_{\text{eff}} \), defined such that \( \sigma T_{\text{eff}}^4 \) equals the total energy per unit area radiated from the surface. A similar characteristic temperature is useful for describing the temperature of irradiated planets, however, it is customarily called the equilibrium temperature \( T_{\text{eq}} \) to avoid confusion with the internal \( T_{\text{int}} \) effective temperature which is a measure of the energy contribution from the interior. Since energy is conserved, a planet in equilibrium must reradiate the energy it receives from the star along with the energy escaping the planet’s interior. Thus the equilibrium effective temperature is given by,

\[
\sigma T_{eq}^4 = \sigma T_{int}^4 + (1 - A) F_{inc},
\]

where \( A \) is the bond albedo.

As one would expect, the extrinsic flux heats the day-side of giant planet atmospheres to temperatures well above those found in our Solar System. The predicted temperature structure of HD189733b (figure 4) illustrates this point. The intrinsic flux of this planet is very close to that of Jupiter, while the predicted temperatures across the day-side atmosphere are entirely maintained by stellar heating. The discovery of the first hot-exoplanet, 51 Peg b, inspired many predictions for the properties of irradiated planetary atmospheres [106–110] with each of these early works employing simplifying assumptions ranging from ad hoc temperature structures, artificial upper/lower boundary conditions and sparse chemistry and opacity descriptions. Despite simplifying assumptions, these early models successfully predicted many of the fundamental properties now revealed by observations and paved the way for more detailed models. More sophisticated 1D models including state-of-the-art chemical and radiative transfer simulations have been explored for a broad range of hot-exoplanet atmospheres, and have demonstrated the diversity and complexity one should expect in hot-Jupiter atmospheres, both chemically and spectroscopically [111–116].

Early on, it was clear that traditional 1D model atmospheres faced a geometric problem concerning the natural division of a hot-exoplanet into day- and night-sides. Many of the short-period planets should be synchronously rotating (see section 7), ensuring that the planet is irradiated constantly on the same hemisphere. This of course was not a new problem as stellar and planetary atmosphere modelers have been dealing with this issue for decades earlier. In many ways, the situation is far more similar to what is often encountered in irradiated stellar atmospheres since the expected day–night temperature differences for hot-exoplanets greatly exceeds what one finds in the Solar System (assuming hydrostatic and radiative–convective equilibrium). The frequently used approach is to model the two sides (day and night) separately and scale the incident flux by a geometric factor (\( \alpha \) in the equations above) to account for the redistribution (or lack of) of absorbed stellar flux across either the day-side or the entire atmosphere.

The value of this global redistribution factor has only recently been estimated using observations in a few cases and more sophisticated 3D dynamical simulations are needed to predict wind speeds and horizontal heat transport. Early 3D global circulation models [117] found that wind speeds could exceed 1 km s\(^{-1}\) and that day–night temperature differences of 500 K were possible at photospheric depths (i.e. the spectrum forming region). These authors also stressed that dynamics has consequences for the chemistry, potentially leading to observable departures from equilibrium (see below). Different approaches have been used to model the circulation patterns
in hot-exoplanets, including 2D [118–120] and 3D [121–124] models, most of these motivated by varying successes within the Solar System planets. To accommodate the computational expense of following multi-D global circulations, these models make various levels of sacrifices when it comes to the radiative transfer in the atmosphere models. There still remains a substantial disconnect between the 1D static atmosphere models with sophisticated radiative transfer and the multi-D global hydrodynamical models; however, efforts are underway to bring the two together [125]. While these circulations models differ in the details (some have large vortices such as the spots on Jupiter, while others have single dominant westward jets), most agree that strongly irradiated planets will develop a small number of broad flows/jets [126]. This differs from the Solar System planets which have numerous narrow jets. See [127] for a recent detailed review of exoplanet circulation models.

5.2.1. Albedo. Observational upper limits on the reflected starlight of hot-Jupiters yield a rather small value for the geometric albedo. None of the attempts to detect the reflected light from the ground during secondary eclipses has been successful so far. Space-based photometric observations of HD209458b at visible wavelengths are the most constraining upper limit so far, and give a value less than 0.17 at 99.5% confidence level [128], significantly smaller than Jupiter’s value of 0.5. These observations suggest that most of the incident starlight of a hot-Jupiter, at least for HD209458b-like conditions, is absorbed, ruling out the presence of many reflective clouds in this type of object. Further observations on a large sample of transiting planets are necessary in order to obtain more stringent information about the albedos and the atmospheric properties of these objects.

5.3. Non-equilibrium chemistry

Departures from equilibrium chemistry can occur for a variety of reasons, such as non-local phenomena (external radiation) and time-dependent mixing (vertical and/or horizontal). For example, it is believed that enhanced tropospheric CO in Jupiter’s atmosphere is due to rapid vertical mixing and very slow chemical reaction timescales to convert CO back to CH4. Similar mixing-induced equilibrium departures are thought to occur in the atmosphere of brown dwarfs (e.g. Gl 229B), impacting both the CO/CH4 ratios and the N2/NH3 ratios.

The (net) chemical reactions responsible for converting CO to CH4 and N2 to NH3 are

\[ \text{CO} + 3\text{H}_2 \xrightarrow{\text{slow}} \text{CH}_4 + \text{H}_2\text{O}, \]  

(4)

and

\[ \text{N}_2 + 3\text{H}_2 \xrightarrow{\text{slow}} 2\text{NH}_3. \]  

(5)

The individual times (\(\tau_{\text{chem}}\)) for the two reactions above are very long, from left to right, at low temperatures and pressures (often greater than 10^6 yr) compared with vertical upwelling, which operates on year timescales or less. In both planetary and brown dwarf atmospheres the true mixing timescales (\(\tau_{\text{mix}}\)) in the radiative layers are highly uncertain and often approximated as \(\tau_{\text{mix}} \approx H^2/K_{zz}\), where \(H\) is the pressure scale height and \(K_{zz}\) is the eddy diffusion coefficient—a free parameter ranging from 10^5 to 10^7 cm^2 s^-1 (see [129] for more details). When \(\tau_{\text{mix}} \gg \tau_{\text{chem}}\), the chemistry is expected to be in equilibrium. All other reaction pathways involving important opacity sources occur very rapidly and, thus, are not expected to be perturbed from equilibrium by mixing. See [129–131] for applications of this procedure to brown dwarf atmospheres and [132] for CO in Jupiter’s atmosphere.

As already mentioned above, global circulations can lead to horizontal/vertical mixing and cause departures from equilibrium chemistry. In many of the hot-Jupiters large mole fractions of CO can persist even in cool regions (\(P < 1\) bar) where chemical equilibrium predicts CH4 as the dominant carbon-bearing molecule in a manner very similar to that described above for brown dwarf atmospheres [122]. Looking back at figure 5, mixing is expected to elevate the CO mole fractions at low pressures (\(P < 1\) bar) by many orders of magnitude above the chemical equilibrium curves shown. NH3 could also be an order of magnitude below the equilibrium value through much of the atmospheres shown. Photochemistry driven by external irradiation has been studied extensively in Solar System planets (see [133] for a review) but has only been studied in close-in giant exoplanets for a few specific cases [134]. Also, a new field develops with the study of photochemistry of Earth-like atmospheres, one of the motivations being the analysis of ‘false positive’ signals of life due to photochemistry ([135, 136], see below).

5.4. Biosignatures

No Earth analogs have been yet detected, but their search is one of the major goal of ground- and space-based research programs of the coming decades. Our current understanding of planet formation suggests that terrestrial planet formation should be an efficient process. We thus expect these planets to be common, as illustrated by our Solar System which has three such planets (Earth, Mars and Venus). The search for signatures of life on exo-Earths is one of the main motivations for these programs and certainly one of the most exciting scientific inquiries at the beginning of the century. Huge activity is now devoted to astrobiology and we will only mention in this review the most basic biosignatures currently suggested. Biogeochemical activity on a planet could manifest itself through spectral features of the atmosphere. Current search strategies, as derived for DARWIN/TPF [137], are thus based on the spectroscopic detection of compounds that could not be present on a planet in the absence of life. The search for biomarkers is based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth. This later is based on carbon chemistry and requires liquid water as solvent. Other paths for life, based on a different chemistry, could perhaps exist but the signatures of the resulting life-forms are so far unknown. The need for liquid water leads to the concept of habitable zone defined as the region around a star where the surface temperature of Earth-like planets allows the presence of liquid water (see figure 6). This zone depends on the stellar luminosity and thus evolves in time with the star. Its
definition also depends on complex processes on the planet, such as the concentration of greenhouse gases or geological activity (see [136, 138] and references therein). Any biomarker should include the signature of H$_2$O, which is a requisite for ‘Earth-like’ life. The presence of H$_2$O, O$_2$ (or O$_3$) and CH$_4$, NH$_3$ or CO$_2$ would imply some biological activity, so that these elements are considered as favorite biomakers [137,138]. However, as pointed out by [135], the unique detection of one of these compounds may be ambiguous. Indeed, O$_2$, and hence O$_3$, can be produced by photochemistry. The combined detection of O$_2$ with H$_2$O and CO$_2$, which are important for habitability, would however, provide a robust signature of biological photosynthesis [135, 137, 138]. Similarly, the presence of CH$_4$ or NH$_3$ together with O$_2$ or O$_3$ would be good biomarkers (see [137] and reference therein), as demonstrated by the observations of the Galileo probe, as it passed near the Earth and detected simultaneously O$_2$ and CH$_4$ [139]. Note that methane and ammonia are not expected to be abiotically produced on habitable, Earth-size planets, in contrast to a common production in cold hydrogen-rich atmospheres of giant planets (see section 5.1 and figure 7). The analysis of biological spectral signatures on an exoplanet is thus optimized if its physical properties, such as its mass and radius, can be also determined.

6. Evolutionary properties

6.1. Basics of evolutionary models

Planetary evolution is described by the standard conservation equations, written in a spherically symmetric configuration and widely used in stellar evolution calculations [5]. The complete evolutionary problem requires the coupling between interior (see section 4) and atmospheric (see section 5) structures. The rate at which internal heat escapes depends on the surface properties, and thus on the outer boundary conditions connecting interior and atmospheric structures. Modern models for planets incorporate realistic atmospheric boundary conditions using frequency dependent atmosphere codes as described in section 5. This is required for a correct description of the thermal profile and effective temperature of objects having cold molecular atmospheres [3, 140]. The inner and outer temperature profiles are connected at large optical depths, where either the atmosphere becomes fully convective or radiative transport only involves Rosseland mean opacity, which is a weighted mean over all frequencies of the inverse monochromatic opacity $\kappa_\nu$, using the temperature derivative of the Planck distribution as weighting function (see [141]). The connection is done either at fixed pressure, usually at a few bars [5, 142, 143] or at fixed optical depth, usually at $\tau_{Rosseland} = 100$ ([3]). The numerical radius, corresponding to the outer boundary condition, provides an excellent approximation the planet’s photospheric radius, where the bulk of the flux escapes ($\tau_{Rosseland} \sim 1$). This stems from the negligible atmospheric extension between the photosphere and the depth characteristic of the outer boundary conditions.

6.2. Initial conditions

Planet evolution is characterized by the release of gravitational and internal energy from an initial (unknown!) entropy state. The usual procedure, similar to the brown dwarf and stellar cases, assumes a high initial entropy state, i.e. a large initial radius and luminosity [140, 144, 145]. Since this implies a relatively small ($\lesssim$Myr) Kelvin–Helmholtz timescale, this yields a rapid early evolution so that the initial conditions are forgotten within a few Myr and do not influence the subsequent evolution [148]. The assumption of a hot initial state for planets has recently been questioned by [29]. Using initial
conditions derived from the core-accretion model, they find lower initial entropy states than aforementioned. These authors thus suggest that young giant planets should be fainter and smaller than predicted by standard evolutionary models, and thus fainter and smaller than young brown dwarfs at the same age. Although based on the planet embryo’s core-accretion history rather than on a totally arbitrary initial condition, this approach, however, still suffers from the lack of a proper treatment of the final accretion shock, which determines the nascent planet’s initial energy content and radius (see section 3.1). The results of [29] are a direct consequence of the assumption that the accreting gas loses most of its internal entropy through the shock. Such assumption is derived from the shock boundary conditions of [146], which were initially developed for the study of accretion onto protostars. Multi-D radiative transfer and hydrodynamical simulations of the accretion process and the resulting shock could provide more rigorous post-shock initial conditions for young planet models. Although still very challenging, this level of complexity seems to be required in order to improve the field. Therefore, the determination of the planet initial conditions remains so far an unsolved issue, as discussed in [28, 147].

Such a high sensitivity of early planet evolution to initial conditions, as previously stressed for low-mass stars and brown dwarfs [148], has major consequences on the identification of planetary mass objects in young clusters and on detection strategies of future projects such as SPHERE and Gemini Planet Imager. The work of [29] also raises the question whether the faintness of young planetary mass objects may be used as a criterion to distinguish a brown dwarf from a planet. The answer is non-trivial but one must keep in mind that accretion through a disk (circumstellar or circumplanetary) is a common process of both star and planet formation. Moreover, the conclusion that young planets should be faint relies on a treatment of accretion which can also be applied to the formation of protostars and proto-brown dwarfs (see [147] and section 3). Thus, for the same reasons, brown dwarfs may as well be fainter than predicted by current evolutionary models.

### 6.3. Cooling and contraction history

A planet contracts and cools down during its entire life on a characteristic thermal timescale \( \tau_{KH} \sim GM^2/RL \). For a 1M_Jup gaseous planet, \( \tau_{KH} \sim 10^7 \) yr at the beginning of its evolution, starting from a hot initial state with luminosity \( L > 10^{28} \text{ erg s}^{-1} \), and \( \tau_{KH} > 10^{10} \) yr after 1 Gyr, reaching luminosities \( L \approx 10^{25} \text{ erg s}^{-1} \) (see [144, 145]). As mentioned in section 2.2, a non-negligible fraction of exoplanets are at a close distance from their parent star and their evolution is affected by irradiation effects. These effects are accounted for through the coupling of interior and irradiated atmosphere structures (see section 5). The heating of the outer layers by the incident stellar flux yields an isothermal layer between the top of the convective zone and the region where the stellar flux is absorbed. The top of the convective zone is displaced toward larger depths, compared with the non-irradiated case. The main effect is to reduce the heat loss from the planet’s interior, which can maintain higher entropy for longer time. Consequently, the gravitational contraction of an irradiated planet is slowed down compared with the non-irradiated case and the upshot is a larger radius at a given age. This effect is illustrated in figure 8 on the evolution of a 1M_Jup planet.

![Figure 8. Effect of irradiation and of heavy element enrichment on the radius \( R \) as a function of time of a 1M_Jup planet. Time is in year. Solid line: no core and no irradiation; dash–dotted line: irradiation from a Sun at 0.045 AU, no core; dashed line: no irradiation and a central core of water of 10% of the planet’s mass (\( M_{core} = 31.8M_\oplus \)); dotted line: irradiation and \( M_{core} = 31.8M_\oplus \). (Models from [19]).](image)

For Saturn and Jupiter-mass planets with orbital distances 0.02–0.045 AU, the typical effect of irradiation on the radius is about 10–20% [78, 142, 145, 149]. Since the total binding energy and the intrinsic luminosity of a planet decrease with its mass, the lighter the planet, the smaller the ratio of its intrinsic flux to a given incident stellar flux. Consequently, the evolution and radius of a Neptune-like or smaller planet will be significantly more altered by irradiation effects, compared with the non-irradiated counterpart, than for a more massive planet at a given orbital distance (see section 6.4 and figure 9). Irradiation effects are thus quantitatively important and must be accounted for in the modern theory of exoplanet evolution.

Furthermore, a consistent comparison between theoretical radius and observed transit radius requires a subtlety due to the thickness of the planet atmosphere [142, 145, 151]. The measured radius is a transit radius at a given wavelength, usually in the optical, which involves atmospheric layers above the photosphere. Atmospheric extension due to heating of the incident stellar flux can be significant, yielding a measured radius larger than the theoretical or photospheric radius. This effect can add a few per cent (up to 10%) to the measured radius [142, 145].

Inspection of transiting object mean densities suggests that some exoplanets, such as the giant planets of our Solar System, are enriched in heavy material. Models devoted to the analysis of their properties must then account for such enrichment. Many efforts are now devoted to the construction
of models, covering a wide range of masses, including (i) different amounts of heavy elements and (ii) different heavy material compositions [19, 78, 79, 150, 151]. Exploration of effect (ii) is limited by available equations of state valid under conditions encountered in planetary interiors (see section 4.1.2). The most commonly considered materials are water, rock and iron. For sake of simplicity, and given the currently large uncertainties on EOSs, on the nature of the heavy elements and on their distribution inside the planet, current models often assume that heavy materials are all contained in a central core. A detailed analysis of the main uncertainties in current planetary models, due to EOS, composition and distribution of heavy material within the planet has been conducted in [19] (see section 4.2.1). As shown in figure 8, the radius of a heavy material enriched planet is smaller, at a given time, compared with the H/He gaseous counterpart. Figure 8 also illustrates the competitive effects of irradiation, which increases \( R \), and of the presence of heavy material, which diminishes \( R \).

6.4. Mass–radius relationship

The mass–radius relationship of a planet at a given time of its evolution is entirely determined by the thermodynamic properties of its internal constituents and its ability to transport and evacuate its internal entropy content. Figure 9 portrays the behavior of the mass–radius relationship of Earth-like to Jupiter-like planets. The essential physics characteristic of the shape of the relation was described in the pioneer work by [62]. Two competitive effects yield the well-known flattening in the \( M–R \) relationship around a few \( M_{\text{Jup}} \). In the low-mass regime, down to Earth masses, the dominant electrostatic contribution from the classical ions yields a relation \( R \propto M^{1/3} \) characteristic of incompressible matter. As mass and density increase, the effects of partially degenerate electrons start to dominate over Coulomb effects, yielding a reversal of the \( M–R \) relation. Consequently, a maximum radius exists at a critical mass which depends on the planet composition. Reference [62] found a critical mass of \( 2.6M_{\text{Jup}} \), corresponding to a maximum radius of \( \sim 1R_{\text{Jup}} \) for a gaseous H/He planet under the assumption of zero-temperature plasma. More recent calculations, based on improved EOS as described in section 4.1, yield a critical mass \( \sim 3M_{\text{Jup}} \).

Figure 9 also illustrates the increasing effect of irradiation on the planetary radius as mass decreases for planets retaining a substantial atmosphere (see section 6.3). The radius of a \( 20M_{\oplus} \) planet with 50% H\(_2\)O is enhanced by \( \sim 35\% \) if irradiated by a Sun at 0.045 AU [19]. For terrestrial planets, the mass–radius relationship, derived from detailed models assuming the same complex composition as for the Earth ([76], see section 4.2.1) is shown by the long-dashed line in figure 9. As discussed in section 4.3.2, these predictions are extremely close to the one derived from more simple models, assuming 100% rock [78]. High accuracy (less than 5%) on radius measurement, and to a lesser extent on mass measurement, is thus required to infer the detailed composition of a super-Earth exoplanet [76, 77, 79, 90]. As shown by [90], if the uncertainty on the radius of a super-Earth planet is less than 5%, the amount of water can be determined with an accuracy of less than 13%.

7. Star–planet interaction. Tidal effects

7.1. Star–planet orbital parameters

The geometry of an orbiting star–planet system of respective masses \( M_\star \) and \( M_p \), illustrating the formation and dynamical evolution of the system, is encapsulated in three main parameters: the semi-major axis \( a \), associated with the mean orbital motion, \( n = 2\pi/P \approx (GM_\star/a^3)^{1/2} \), where \( P \) is the orbital period and \( G \) the gravitational constant, the eccentricity \( e \) and the stellar obliquity \( \epsilon \), defined as the angle between the angular momentum vectors of the planetary orbit and the stellar rotation axis. This latter quantity, which determines the spin–orbit angle, is an interesting diagnostic for inferring the dominant interaction mechanisms at play in a protoplanetary disk: close spin–orbit alignment (as is the case for our solar system) is expected from quiescent tidal interactions or migration processes of a planet within the disk whereas planet scattering events are prone to misalignments of planetary orbit angular momentum and stellar spins [162]. The inclination angle of the orbit relative to the sky plane is usually denoted \( i \) so that the line-of-sight projected value of a quantity retains a sin \( i \) indetermination. A transit observation implies that \( i \approx 90^\circ \). Although the stellar obliquity is generally
not measurable, Doppler shift observations on the parent star through a transit offer the possibility to determine the angle between the sky projections of the two angular momentum vectors, i.e. the projected spin–orbit angle \( \lambda \), which gives a lower limit of the true three-dimensional spin–orbit angle\(^\text{11} \). The angle \( \lambda \) is determined through the so-called Rossiter–McLaughlin (RM) spectroscopic effect [153, 154], originally applied to eclipsing binaries and recently extended to transiting planets [155–157] (see [157, 158] for recent reviews on RM observations). To date, the RM effect has been measured for 12 transiting systems. For nine of these systems, the determinations are consistent with a small (\( \lesssim 3^\circ \)) or even zero-value of \( \lambda \), although with significant error bars in some cases, indicative of well-aligned spin and orbit, similar to the solar system, even though one should keep in mind that these observations provide minimum (projected) values of the true stellar obliquity, as mentioned above. Alignment of the stellar spin and the planetary orbital axis is a strong confirmation of planets forming in a spinning protoplanetary disk surrounding the central protostar. Spin–orbit misalignment, on the other hand, as found for the HD17156 [159], XO-3 [160] and WASP-14 [161] systems, can be produced by planet scattering or Koziak mechanism due to the presence of a third body (e.g. [162]). Interestingly, this spin–orbit alignment shows that the star’s rotation and the orbit angular momentum evolution are not significantly altered during the early episodes of angular momentum loss characterized by outflows and disk–star magnetic coupling. A less frequently addressed tidal parameter is the planetary obliquity, i.e. the angle between the planetary spin axis and the orbit normal. Although the planet’s obliquity is expected to be rapidly damped by tidal dissipation, a persistent nonzero planet obliquity has been suggested as a result of the capture in a Cassini 2 spin–orbit resonance state as the nebula dissipates [163]. This scenario, however, has been excluded for hot-Jupiter-like planets [164–166]. Indeed, the resonant equilibrium is eventually destroyed by the strong tidal torque, leading the system to leave the Cassini 2 state and spiral toward the Cassini 1 state, with negligible obliquity [164,166]. Therefore, close-in planets quickly evolve to a state with the planet’s spin axis nearly normal to the orbit plane, i.e. a negligibly small planet obliquity. Note that the determination of stellar companion’s obliquities would provide an interesting diagnostic to distinguish planets from brown dwarf companions, these latter being formed from the same original gravoturbulent collapse of the parent cloud as the star, leading to arbitrary spin angle distributions.

### 7.2. Orbital evolution

For close planets, gravitational interactions between the planet and the star lead each of these bodies to raise tides on the other one, generating torques in the tidal bulges. Through exchange of angular momentum, these strong tidal interactions affect the system orbital (eccentricity, semi-major axis, obliquity) and rotational (stellar and planetary spin, \( \omega_s \), \( \omega_p \)) properties. In the first calculations addressing tidal effects in the discovered extra-solar close-in star–planet systems [167, 168], coplanarization of the orbit and the stellar equator (i.e. stellar spin–orbit alignment), planet spin–orbit alignment, circularization of the orbit and synchronization of the stellar and planetary rotation with the orbital motion were implicitly assumed to represent the asymptotic equilibrium states, characteristic of the endpoint of tidal evolution, although the orbit might be unstable, leading eventually to star–planet merging [168]. Accordingly, the associated timescales were generally characterized by an exponential relaxation toward an equilibrium state [169, 170]. Furthermore, in the calculations of [167], only tides raised by the star on the planet were considered whereas tides raised by the planet on the star were ignored. A proper derivation of the evolution of all orbital and rotational parameters, however, requires to solve consistently the complete nonlinear coupled tidal equations, taking both the planetary and the stellar tides into account. Note that tides raised in the star transfer angular momentum between the star’s rotation and the planet’s orbit, so that, in the presence of stellar tides, the planet’s orbital angular momentum is not conserved during the tidal evolution, even if the planet’s rotation is synchronized. Such consistent calculations lead to markedly different dynamical evolutions with significantly different rotational and orbital evolution timescales, and thus different eccentricity values from the ones obtained when neglecting stellar tides [171–176].

As mentioned above, most of the early studies implicitly assumed the existence of a tidal (possibly unstable) minimum energy equilibrium state at given angular momentum for the orbiting planets, characterized by circular orbits (for the stable state), synchronous rotation and spin–orbit alignment. However, as demonstrated recently [174], none but one, namely Hat-P-2b, of the transiting planets discovered at this time (26 objects) has such an equilibrium state. Indeed, for all these systems, the total star–planet angular momentum, \( L_{\text{tot}} \), is lower than the critical angular momentum defined as \( L_c = 4(\Gamma^2/27)(M_1M_2^3)/(M_1 + M_2)(I_p + I_*)^{1/4} \), where \( I_p \) and \( I_* \) denote the polar moments of inertia of the planet and the star, respectively. Consequently, no equilibrium state exists and all these planets will ultimately merge with the star [177,178]. This result does not depend on any particular tidal model and bears major consequences on our analysis of the discovered transiting systems and, possibly, of the non-transiting ones too. First of all, it implies that the conventional tidal exponential damping estimates for the timescales for semi-major axis evolution, synchronization of the spins and spin–orbit alignment are not valid, because the implied corresponding equilibrium states do not represent the endpoint of the tidal evolution. The full tidal calculations, taking into account the strong nonlinear coupling between \( e, a, \epsilon, \omega_s \), and \( \omega_p \), show that the timescales characteristic of the semi-major axis and the stellar spin and obliquity evolution of these systems are now comparable, and equal to the lifetime of the system itself [174]. These quantities are found to evolve only moderately from their initial values, until they quickly
go to zero or diverge during the final merging episode with the host star, the true endpoint of the tidal evolution for these systems. The only exception is the pseudo-synchronization of the planet’s rotational velocity with the orbital motion, such as \( \omega_p \sim n \), which occurs at a timescale comparable to the one estimated with the equilibrium tide theory, \( \sim 10^5 – 10^6 \) yr for hot-Jupiter typical parameters [167, 168, 174]:

\[
\tau_{\text{sync}, p} = \frac{I_p}{\Gamma_p} |a| \approx 5.0 \left( \frac{\alpha}{0.25} \right) \left( \frac{Q_p}{10^6} \right) \left( \frac{M_p}{M_{\text{Jup}}} \right) \left( \frac{R_p}{R_{\text{Jup}}} \right)^{-3} P_d \text{ Myr},
\]

where \( I_p = \alpha M_p R_p^2 \) is the planet’s moment of inertia (\( \alpha \approx 0.25 \) for Jupiter), \( \Gamma_p = \frac{3}{2} (GM_p^2 R_p^5)/(Q_p a^6) \) the amplitude of the torque exerted by the star on the planet, \( P_d \) the orbital period in days and \( Q = Q/k \), where \( Q \) (respectively \( Q \)) denotes the planet (respectively star) tidal quality factor. This latter is defined as the ratio of the maximum potential energy stored in the tidal distortion over the energy dissipated per tidal period, roughly equal to the inverse of the tidal phase lag associated with the (equilibrium) tidal oscillation in the body of interest (e.g. [179]), and \( k \) denotes the star or planet second order Love number, representative of the body’s deformability (typical values of the Love number for Sun-like stars and for Jupiter are \( k_\odot \approx 0.02 \) and \( k_{\text{Jup}} \approx 0.38 \), respectively, although with large uncertainties). This quick planet pseudo-synchronization stems from the fact that the planet’s rotation angular momentum is much smaller than the orbital angular momentum. This state, however, corresponds to a temporary state, as the ultimate planet–star orbital collapse eventually causes the planet to spin up dramatically [174]. Once the planet is pseudo-synchronized, there is no further exchange of angular momentum between its rotation and its orbit; the only exchange occurs between the orbit, the eccentricity and the stellar rotation at constant total orbital angular momentum. These quantities are also modified by the tides raised by the star on the planet, in the case of a nonzero eccentricity, and by the tides raised by the planet on the star even when/if the orbit is circularized.

This lack of tidal equilibrium state for the transiting systems bears other important consequences. First of all, it implies that, even for a circular orbit (\( e = 0 \)), ongoing tidal dissipation keeps taking place in the star, leading, by conservation of angular momentum, to the planet’s endless orbital decay and, inevitably, to a merging of the planet with the star. It also means that stellar spin synchronization with the orbit can never occur for these systems, since, once the planet is pseudo-synchronized, the tidal torque raised by the planet onto the star yields this latter to spin up constantly (indeed, for \( n \gg \omega_p \), energy is transferred from the orbit to the spin [170]), the stellar spin evolving within the same timescale as the orbital distance. The decrease in stellar rotation velocity with time due either to stellar winds or magnetic braking may counteract this tidal spin-up. Strong stellar wind episodes, however, mainly occur at the early stages of evolution and these effects are probably unimportant at the age of the observed systems. Magnetic braking is a more complex issue and is found to compensate or even dominate tidal spin-up if \( Q_* \gtrsim 10^4 \) for OGLE-TR-56b, the presently discovered extra-solar giant planet closest to its parent star [180].

As mentioned above, a proper determination of the various timescales, including the lifetime of the system, i.e. the time for the planet to merge with its host star (or more exactly to reach the Roche Lobe limit, \( a \sim 2.5 (\rho_\ast /\rho_p)^{1/3} R_\ast \)), requires to solve consistently the complete non-linear coupled dynamical equations for \( a, e, e, \omega_p \) and \( \omega_\ast \). No analytical solution exists. In the limit of small eccentricity (\( e \ll 1 \)) and for \( M_p \ll M_\star \), however, the timescale for orbital evolution is dominated by the tides in the star [172–174]12. In that case, providing that the orbital period is much shorter than the stellar rotation period (\( \omega_\ast \ll \omega_{\text{orb}} = 2\pi /P \)), a fulfilled condition for most of the observed transits (\( P_{\text{rot}, \ast} \sim 3–70 \) days whereas \( P \lesssim 4 \) days see e.g. table 1 of [174])), and that the stellar obliquity is small (also a generally fulfilled condition), the orbit evolution timescale, given by the inverse ratio of the torque exerted by the planet on the star over the orbital angular momentum, can be estimated as (e.g. [170, 172, 174, 179, 181])

\[
\tau_a \approx \frac{\Gamma_*}{M_p a^2 n} \approx 0.06 \left( \frac{Q_*}{10^6} \right) \left( \frac{M_*}{M_p} \right) \times \left( \frac{a /0.02 \text{ AU}}{R_\star/R_\odot} \right)^5 P_d \text{ Myr}
\]

\[
\approx 0.05 \left( \frac{Q_*}{10^6} \right) \left( \frac{M_*}{M_p} \right) \left( \frac{\tilde{\omega}}{\tilde{\omega}_\odot} \right)^{5/3} P_d^{13/3} \text{ Myr}. \tag{7}
\]

Note that this timescale quickly decreases with finite eccentricity since tidal effects increase drastically at the apside [174]. We stress again that equation (7) is only a rough estimate and that the proper determination of the orbit evolution requires a consistent solution of the full tidal equations. Moreover, the true calculation of the timescale depends to some extent on the used tidal model. Equation (7), however, provides some useful information. Since indeed, at very small eccentricity, \( \tau_a \) only depends on (or more exactly is dominated by) tidal dissipation within the star, not within the planet, as seen from equation (7), a first consequence of this equation is that, for hot-Jupiter like systems:

\[
\tau_a \lesssim \langle \tau_r \rangle \sim 10 \text{ Gyr} \Rightarrow P \lesssim 3.4 \left( \frac{Q_*}{10^6} \right)^{-3/13} \text{ day}, \tag{8}
\]

where \( \langle \tau_r \rangle \) is the average value of the lifetime of stars harboring planets (\( \sim 10 \) Gyr for solar-type stars). Therefore, although all the planets for which \( L_{\text{rot}} < L_\odot \) will merge with their host star, for the ones with orbital periods in the range \( P \sim 1–10 \) days, i.e. semi-major axis \( a \sim 0.02–0.09 \) AU, for a range of uncertainty \( 10^9 \gtrsim Q_* \gtrsim 10^4 \), the merging will occur within the stellar lifetime. Note from equation (7) that this planet’s lifetime decreases with increasing planet–star mass.

\[12\text{ As mentioned in [174], even though only the outermost layers of solar-type stars are convective and dissipate efficiently, ultimately the convective and radiative zones will synchronize and dissipation will occur throughout the entire star. This will affect the timescale for tidal evolution, but this latter will qualitatively remain the same.} \]
ratio, which has two major consequences. First of all, the more massive the planet, the faster the orbital decay and thus the shorter the system’s lifetime, which may partly explain the lack of hot-Jupiters for \( P \lesssim 3 \) d [172, 183, 184]. Second of all, for a given orbital distance and comparable stellar masses, small transiting planets should be discovered around older systems, a trend which seems to be supported by observations [184, 185]. The often used assumption that tidal evolution is always dominated by tides raised by the star in the planet leads to the opposite behavior. Conversely, as seen from equation (7), the determination of the age of the system from the age of the host star provides a constraint on the minimum value for \( Q_\star \). As mentioned earlier, for observed transiting planets, the orbital period is shorter than the stellar rotation period, so that tidal dissipation in the central body (the star in the present context) decreases the orbital semi-major axis \((a < 0)\), by conservation of total angular momentum. This is similar for instance to the Mars–Phobos system but contrasts with the Earth–Moon one. In this latter case, the Moon revolution period is longer than the Earth rotation one so that tidal dissipation in the Earth leads to an increase in the Earth–Moon distance.

As for the orbital evolution timescale, there is no simple analytical solution for the orbit circularization timescale, \( \tau_e \), and one needs to solve the whole dynamical equation system. One can try, however, to estimate \( \tau_e \), as done above for \( \tau_a \). The rate of eccentricity decay reads

\[
\frac{de}{dt} \approx -\left(\frac{1}{\tau_{e,p}} + \frac{1}{\tau_{e,*}}\right),
\]

where \( \tau_{e,p} \) and \( \tau_{e,*} \) denote the characteristic timescales associated with the contributions stemming from the tides raised by the star in the planet and by the planet in the star, respectively. It can easily be shown (e.g. [181, 182]) that (for zero stellar obliquity):

\[
\frac{\tau_{e,p}}{\tau_{e,*}} = \left(\frac{M_p}{M_\star}\right)^2 \left(\frac{R_p}{R_\star}\right)^5 \left(\frac{Q'_p}{Q'_\star}\right).
\]

It can be verified that, for the majority of the presently observed transit planets, \( \tau_{e,p}/\tau_{e,*} < 1 \) (for \( Q'_p \lesssim Q'_\star \)), so that the eccentricity damping is dominated by tidal dissipation of the torque exerted by the star on the planet. In that case, the orbit circularization timescale can be estimated as

\[
\tau_e \approx \tau_{e,p} \approx \left(\frac{\Gamma_p}{M_p a^2 n}\right)^{-1} \approx (5.3 \times 10^3) \left(\frac{Q'_p}{10^6}\right) \left(\frac{M_p}{M_\star}\right)^2 \left(\frac{a/0.02 \text{ AU}}{R_p/R_{\text{Jup}}}\right)^5 P_p \text{ Myr}
\]

\[
\approx 5 \left(\frac{Q'_p}{10^6}\right)^{2/3} \left(\frac{M_\star}{M_p}\right) \left(\frac{R_p}{R_{\text{Jup}}}\right)^{-5} P_\text{d}^{13/3} \text{ Myr}
\]

\[
\approx 0.04 \left(\frac{Q'_p}{10^6}\right)^{2/3} \left(\frac{\rho_p}{\rho_{\text{Jup}}}\right)^{5/3} P_\text{d}^{13/3} \text{ Myr},
\]

As seen from equations (7) and (11) (and as expected from the fact that \( \tau_{e,*} \sim \tau_a \) for \( e \ll 1 \)), the ratio of the orbital and circularization timescales in the limit of small eccentricity reads

\[
\frac{\tau_c}{\tau_a} \approx \left(\frac{M_p}{M_\star}\right)^2 \left(\frac{R_p}{R_\star}\right)^5 \left(\frac{Q'_p}{Q'_\star}\right).
\]

i.e. \( \tau_c/\tau_a \approx 0.1(Q'_p/Q'_\star) \) for typical hot-Jupiter conditions. Therefore, for \( Q'_p/Q'_\star \lesssim 10 \), tidal damping may explain the circularization of initially eccentric orbits. Indeed, calculations solving the complete tidal dynamical equations show that tidal dissipation for short-period planets may have produced the present eccentricities from larger initial values similar to the longer period planet eccentricity distribution, providing an explanation for the smaller eccentricity (\( e \lesssim 0.3 \), \( \langle e \rangle \sim 0.1 \)) of short-period (\( a \lesssim 0.2 \) AU) planets compared with more remote ones (\( e \lesssim 0.9 \), \( \langle e \rangle \sim 0.3 \)), depending on the values of \( Q'_p \) and \( Q'_\star \) [173, 175, 176, 186]. For \( Q'_p/Q'_\star \gtrsim 10 \), however, the orbit does not have time to circularize within the lifetime of the system [174, 187]. In such cases, there is no need to invoke undetected companions to maintain the eccentricity. Note that a value \( e = 0 \) is often assumed when constraining the orbital parameters by inferring a solution for \((a, e)\) from the observed light curves in fitting the orbits of close-in planets. Eccentricity values for short-period planets should thus be taken with caution.

Integrating the complete coupled tidal evolution equations back in time from present eccentricity and orbital values\(^{13}\) may provide some clues about the initial eccentricity distribution of exoplanets, at the end of their formation process, and thus about the outcome of planet–disk interactions. Numerous Lindblad or corotation resonances take place between a disk and a planet, exerting torques which deposit or remove angular momentum from the resonance locations. This modifies the planet’s eccentricity during the disk evolution [188]. The net effect of these disk–planet interactions on the eccentricity, however, remains uncertain, and it is not clear whether eccentricity is damped or excited, with possibly both solutions being valid depending on the disk and planet properties [189]. To first order, however, the eccentricity evolution due to disk torques is \( \dot{e} \approx 1/\sqrt{a} \) [188], so it is expected that short-period planets are more affected than the ones located further away. Planets could thus form with finite eccentricities, damped either by interactions with the disk [189] or by tidal interactions after the disk dissipation for the low eccentricity objects. On the other hand, large initial eccentricities can be produced by planet–planet scattering or gravitational perturbations by a stellar companion [162, 190].

As discussed in the next subsection, the orbital and rotational evolution timescales, however, cannot be determined accurately, as they depend on the ill-determined tidal forcing and dissipation processes, as well as on the internal structure of the star and the planet (radiative envelope, the presence of a dense core, etc), which translates into values of \( Q \) uncertain by several orders of magnitude.

\(^{13}\) Present attempts to address this issue [173, 175, 176] do not consider the evolution of the stellar spin and use tidal equations truncated at the order \( e^2 \), only valid for small eccentricity values, and thus yield quantitatively unreliable results.
7.3. Tidal energy dissipation

If the planet’s orbit is circular, the tidal bulge is motionless in the planet’s frame and there is no energy release. In the case of a maintained finite eccentricity or obliquity, however, the persisting tidal friction leads to energy dissipation in the planet, at the expense of the orbital and rotational energies. If the tidal heating induced in the planet by tidal dissipation dominates the planet’s main sources of energy, gravothermal contraction and solar irradiation, about \(10^{25} \text{erg s}^{-1}\) for typical Gyr-old hot-Jupiters (i.e. \(\sim 1 M_{\text{Jup}}\) at \(\sim 0.05 \text{AU}\) from a Sun-like star) and lasts over a timescale comparable to the planet’s thermal timescale, this extra source of energy will slow down the planet’s contraction, leading to a larger radius (and luminosity) at a given age than otherwise expected. At second order in eccentricity (i.e. in the limit \(e \ll 1\)), the tidal dissipation rate in a pseudo-synchronously rotating \((a_p \approx n)\) planet with zero obliquity is given, at given \(a\) and \(e\), by (e.g. [170, 191–193]):

\[
\frac{dE_{\text{tide}}}{dt} = -\frac{21}{2} \frac{G^{3/2} M_{\text{p}}^{5/2}}{Q_p} \left(\frac{R_p}{a_{15/2}}\right)^5 \left(\frac{M_\star}{M_{\odot}}\right)^{5/2} e^2
\approx -5.2 \times 10^{27} \left(\frac{Q_p}{10^6}\right)^{-1} \left(\frac{M_\star}{M_{\odot}}\right)^{5/2} \times \left(\frac{R_p}{a_{0.05 \text{AU}}}\right)^5 e^2 \text{erg s}^{-1},
\]

(13)

where the terms of orbital evolution only include the contributions due to the planetary tides, since we are presently interested in the energy dissipated in the planet. Tidal dissipation has been proposed to explain the abnormally large radii of some transiting planets [167]. As mentioned earlier, however, these estimates of orbital decay timescales were ignoring the stellar tides, leading to incorrect tidal dissipation rates. As a consequence, eccentricity and tidal dissipation were found to be negligible at the age of the presently observed transiting planets, and hypothesis like continuous gravitational interactions from undetected companions had to be invoked to maintain a finite eccentricity. Only recently have correct tidal evolution calculations been conducted to quantify this effect [171–176, 186]. As mentioned earlier, the coupled tidal equations taking both star and planet tides into account yield significantly different timescales for the evolution of the orbital and rotational properties, with a non-monotonic evolution for the evolution of the eccentricity, semi-major axis and stellar spin, as well as for the tidal heating, and this latter can provide in some cases a significant enough source of energy to alter the cooling properties of the planet at a few Gyrs.

For tidal energy dissipation to significantly affect the contraction and thus the radius of the planet, however, tidal heat must be deposited deep in the convective layers. Turbulent viscosity (characteristic of what is usually referred to as ‘equilibrium tide’) may lead to dissipation of heat at depth [194]. However, for the planets of interest, the convection turnover time exceeds the tidal period, so that convective dissipation is probably too slow to be efficient in short-period planets as well as in their host stars [195, 196]. Excited short-wavelength g-modes (characteristic of ‘dynamical tides’) at the interface between convective and radiative zones [197] would dissipate within the radiative region, since g-modes do not propagate in isentropic regions, only affecting the outermost parts of irradiated planets. An interesting alternative mechanism in rapidly rotating planets might be short-wavelength, low-frequency inertial waves, restored by Coriolis rather than buoyancy forces, excited at the envelope-core boundary in the central parts of the planet. These waves can propagate and might dissipate in the convective inner regions and are thus more prone to affect the planet’s structure than the aforementioned gravity modes [198–200]. In that case, the tidal quality factor is found to depend on the orbital period and core size as \(Q' \propto R_p^{-5} P^2\) [200]. As discussed above after equation (7), the inferred age of the systems implies that \(Q'_p\) cannot be substantially smaller than the nominal values \(Q'_p \approx 10^5–10^6\). The same holds true for \(Q'_p\). Indeed, most of the transiting planets are predicted to have a core whose state remains uncertain (see section 4.1.2). A solid core implies a much lower quality factor, \(Q'_\text{core} \sim 10^{-3}\), than for a fluid or gaseous body, i.e. a more dissipative planetary interior, which in turn increases the expected tidal dissipation \(dE_{\text{tide}}/dt \propto 1/Q'_p\). The eccentricity of Io’s orbit, however, implies that \(6 \times 10^4 \lesssim Q_{\text{up}} \lesssim 2 \times 10^6\) [201]. Moreover, as mentioned above, if inertial waves are the main culprit for tidal energy dissipation, \(Q'_p\) is predicted to be of the order of \(\sim 10^6\) for Jupiter (Io’s orbital period is \(P = 1.77\) d) and \(\sim 10^{-3}–10^{-1}\) for hot Jupiters (\(P \sim 3–4\) d). This suggests that the Jovian planet cores may have melted, under the action of the violent accretion episodes during the formation or of tidal heating during the evolution.

Besides the gravitational tides mentioned in this section, it is worth mentioning the possibility for short-period, strongly irradiated planets to experience thermal tides [202]. Thermal tides arise from the torque exerted by the stellar gravitational field on the thermal bulge produced in the planet’s outer layers by the stellar time-dependent insolation. In that case, an equilibrium state in which gravitational and thermal tide effects balance each other can be reached, leading to asynchronous spin and/or possibly to finite eccentricity. This process, however, has been shown not to be valid in the case of gaseous bodies since, in the absence of a surface crust, the torque exerted on the thermal bulge vanishes [203].

8. Observational constraints

8.1. The radius anomaly of transiting exoplanets

As mentioned in section 2.2 a significant fraction of transiting exoplanets exhibits abnormally large radii (see figure 2). This puzzling property is one of the most titillating observational discoveries in this new field and still requires a robust explanation. Several ideas have been proposed, as described below, but none of them has yet received a consensus.

8.1.1. Atmospheric circulation. As mentioned in section 6.3, close-in planets receive a substantial amount of energy from the star. The resulting heating of the outer planet layers affects the vertical temperature stratification and, consequently, the
A correlation between the planet radius ‘excess’, defined as $R_{\text{th}} - R_{\text{obs}}$, is at play in all close-in planets, one expects this effect, however, is insufficient to explain observed radii $\gtrsim 1.2 R_{\text{int}}$. Irradiation can also modify the horizontal temperature profile. Indeed, if the planet is tidally locked and receives constantly the stellar flux on the same hemisphere, strong temperature contrasts can exist between the day- and night-sides of the planet, inducing rapid atmospheric circulation (see section 5). The resulting fast winds may produce a heating mechanism in the deep interior of the planet, slowing down its evolution and yielding a larger than expected radius. This suggestion was based on numerical simulations of atmospheric circulation by [117], which produce a downward flux of kinetic energy of about $\sim 1\%$ of the absorbed stellar flux. This heat flux is supposed to dissipate in the deep interior, producing an extra source of energy during the planet’s evolution. According to these simulations, this mechanism yields a typical heating rate of $10^{27}$ erg s$^{-1}$, which can explain the inflated radius of hot-Jupiters such as HD209458b [149, 204]. The validity of this scenario, however, is still debated. The substantial transport of kinetic energy found in the simulations of [117] strongly depends on the details of atmospheric circulation models and has not been confirmed by other simulations [118]. Although important efforts are devoted to the development of multi-D dynamical simulations of strongly irradiated atmospheres (see section 5), the various simulations so far yield very different results [127]. Furthermore, as demonstrated by [205], a proper description of the physical mechanisms responsible for energy dissipation and drag in the flow (e.g. shocks, turbulence) is mandatory to obtain reliable descriptions of heat redistribution and wind speeds across irradiated exoplanetary atmospheres.

Assuming this mechanism is at play in all close-in planets, and arbitrarily adding an extra source of energy corresponding to $0.5\% \times F_{\text{int}}$, Guillot et al [150] find a correlation between the mass of heavy elements required to fit the transit radii and the metallicity of the parent star. This result, however, is highly speculative, since it crucially depends on the aforementioned assumption of a constant fraction of $F_{\text{int}}$. If this wind-induced mechanism is at play in all close-in planets, one expects a correlation between the planet radius ‘excess’, defined as the relative difference between the observed radius $R_{\text{obs}}$ and the theoretical radius $R_{\text{th}}$ obtained with regular irradiated models, $(R_{\text{obs}} - R_{\text{th}})/R_{\text{th}}$, and the incident stellar flux $F_{\text{inc}}$, normalized to the planet’s intrinsic flux $F_{\text{int}} = L_{\text{int}}/(4\pi R_{\text{th}}^2)$, with $L_{\text{int}} = \int -T(dS/dt) \, dm$, where $S$ is the specific entropy of the irradiated planet. This relation is illustrated in figure 10 for a handful of transiting systems. Whether the expected trend exists or not is not clear, in particular when considering the fact that WASP-12’s large radius may be explained by tidal heating, as mentioned in section 8.1.2 below. Clearly, a more detailed analysis, extended to all transiting planets, is required to explore this issue.

To summarize, although atmospheric circulation remains an attractive possibility to explain the ‘hot-Jupiter’ radius anomaly, a robust confirmation of this mechanism, in particular of heat transport at deep enough levels to affect the internal adiabat, is needed, based on more sophisticated numerical simulations. It should also be noted that planets far enough from their host star ($\gtrsim 0.1$ AU) should not be affected by this mechanism, a diagnostic eventually testable with the Kepler mission.

8.1.2. Tidal effects. Following [167], several studies have suggested tidal heating as a possible mechanism to explain inflated transiting planets (see section 7.3). A heating rate of the order of $10^{27}$ erg s$^{-1}$, consistent with the tidal dissipation rate given in equation (13) and about 100 times the typical intrinsic energy flux of hot-Jupiters, dissipated in the planet’s convective interior over appropriate timescales could in principle explain the observed abnormally large radii for at least some coreless planets. The presence of a central core yields a smaller radius and thus requires a larger energy rate. As discussed in section 7.3, the first calculations [167] exploring the effect of tidal dissipation were based on incorrect tidal evolution timescales and assumed constant orbital properties over time. The correct impact of tidal dissipation on the planet radii from their supposed initial semi-major axis and eccentricity, taking into account the opposite effects of decreasing $a$ and $e$ on the tidal dissipation rate $\dot{E}$ along the evolution (see equation (13)) has been explored only recently [175, 176, 186], although under some restrictive conditions (see second footnote in section 7.2). In some cases, this heat source is found to be substantial at the age of the system, possibly affecting the planet’s contraction and helping solving the radius discrepancies, assuming tidal dissipation occurs deep in the convective interiors (see discussion in section 7.3). As shown in figure 11, WASP-12 experiences extreme tidal heating, which may explain its strikingly large radius (see [176]). Tidal heating due to finite eccentricity, however, does not seem to be the lacking dominant mechanism responsible for
and contribution (see equation (13)), assuming constant values for a transiting exoplanets as a function of the tidal dissipation. Tidal dissipation is calculated here assuming $a$ (measured or assumed) eccentricity $e$ planet’s tidal quality factor. Objects shown with a left arrow have $(\text{up to } 10 \text{ times solar})$. The combined effects of enhanced opacities, they assume super-solar atmospheric metallicities and including the rotational energy) tidal evolution equations remain to be done to fully address this issue.

An other source of tidal heating can arise if the orbit is inclined relative to the stellar quadrupole, so that the planet makes a vertical oscillation in the quadrupole field of the star once per orbit. This effect, however, has been shown to be utterly negligible [152]. Finally, as mentioned in section 7.3, thermal tides cannot be maintained in gaseous planets and thus cannot provide an extra source of heat [203].

8.1.3. Atmospheric enhanced opacities. A possibility to slow down the contraction of a self-gravitating body and to obtain a larger radius at a given age is to increase the atmospheric opacities. This solution was recently suggested by [151] to explain the puzzling large radii of some transiting planets. Alteration of atmospheric properties (chemistry, clouds, opacities) by strong optical and UV irradiation or enhanced atmospheric metallicities are suggested as the source of the increased opacities, although the authors do not work out the physical processes that could possibly lead to such an increase. In order to mimic the effect of enhanced opacities, they assume super-solar atmospheric metallicities (up to 10 times solar). The combined effects of enhanced opacities and of the presence of a dense core are found to reproduce the observed radius spread of transiting planets (see figure 2). Interestingly enough, [151] also finds the same correlation as suggested by [150] between planet core mass and stellar metallicity. Although enhancement of the atmospheric opacities of irradiated extra-solar planets is by no means excluded, given our limited knowledge of the various physical processes at play in such situations, the results obtained by [151], based on the increase in atmospheric metallicities, remain questionable. First of all, similar consistent calculations by [206] yield a smaller radius for the planet, as the larger mean molecular weight due to the increased metallicity counterbalances and even dominates the slower contraction due to the enhanced opacities. Second of all, although significant heavy element enrichment is observed in the atmosphere of our Solar System giant planets (see section 2.1), convective transport in these (cool) planets is predicted to occur all the way up to the atmosphere, constantly bringing up heavy material to the atmospheric layers. Irradiated planet atmospheres are radiatively stable down to deep levels. To maintain heavy elements high up in these stably stratified outer layers requires a (yet to be worked out) efficient mechanism to counteract gravitational settling. More importantly, a stratification with heavy elements on top of a (lighter) H/He envelope, as done in [151] has been shown to be unstable, leading to ‘salt-fingers’ instabilities [87]. The effect of strong irradiation, altering the chemistry and cloud properties requires additional work, as pointed out by the authors themselves [151]. Therefore, although enhanced atmospheric opacities in strongly irradiated planets are a possibility, it requires more robust physical foundations to be considered as the source of the abnormally large radii of irradiated planets. In any event, even such super-solar metallicity models cannot explain the most inflated transiting planets presently detected, such as Tres-4b and WASP-12, implying the need for one or several alternative mechanisms [151, 175].

8.1.4. Reduced interior heat transport. The idea of Stevenson that convection may not be as efficient as usually assumed in planetary interiors was resumed and applied to the case of exoplanets by [88]. These authors show that conditions prevailing in giant planet interiors could be favorable to the development of double-diffusive (layered) or oscillatory convection, if a molecular weight gradient is present (see section 4.3). With characteristic Prandtl number (i.e. the ratio of kinematic viscosity over thermal diffusivity), $Pr \sim 10^{-2}$–1, and inverse Lewis number, defined as the ratio of solute to thermal diffusivity, $Le^{-1} \sim 10^{-2}$, conditions in planets are not too different from those found on Earth. Indeed, double-diffusive convection, characterized by the formation of multiple thin diffusive layers surrounded by (small-scale) convective regions, is a well-known process in laboratory experiments, or in some parts of oceans and salty lakes, where the stabilizing gradient is due to salinity (the so-called thermohaline convection), with characteristic numbers $Pr = 7$ and $Le^{-1} = 10^{-2}$ for salty water [207]. The presence of a molecular weight gradient in the interior of giant planets

![Figure 11. Radius excess (same definition as in figure 10) of transiting exoplanets as a function of the tidal dissipation contribution (see equation (13)), assuming constant values for $a$ and $e$, at the age of the system. A value $Q_p = 10^6$ is assumed for the planet’s tidal quality factor. Objects shown with a left arrow have (measured or assumed) eccentricity $e < 0.01$, and their tidal dissipation is calculated here assuming $e = 0.01$.](image-url)
could be inherited from the formation process, during the accretion of gas and planetesimals, or due to core erosion. Assuming a molecular weight gradient in the inner parts of a Jupiter-like planet, Chabrier and Baraffe [88] show that if multiple layers can form, they might survive long enough to affect substantially the planet evolution. Heat transport by layered convection is indeed much less efficient than large-scale convection and the heat escape from the hot, deep parts of the planet is significantly reduced. The upshot is a larger planet at a given age than its homogeneous, adiabatic counterpart [88]. Depending on the number of layers and the steepness of the molecular weight, the presence of this process could explain the observed spread in transit planet radii. If confirmed, this scenario would bear important consequences on our general understanding of planetary internal structure. High spatial resolution multi-dimensional numerical simulations, which are progressing at a remarkable pace, might be able in a foreseeable future to confirm or to reject the existence of layered or oscillatory convection under planetary conditions. Note that, according to this scenario, one should not expect any correlation between the radius and the incident flux, contrarily to other suggested mechanisms such as the atmospheric circulation outlined in section 8.1.1.

8.2. Brown dwarfs versus massive giant planets

As underlined in section 1, brown dwarfs and planets overlap in mass. Observations of low mass stars and brown dwarfs in young clusters suggest a continuous mass function down to \( \sim 6 M_{\text{Jup}} \), indicating that very low-mass objects form as an extension of the star formation process [208]. There is indeed strong observational support for the brown dwarf formation process to be similar to the stellar one [209, 210], and analytical theories of star formation from the gravoturbulent collapse of a parent cloud do produce proto-brown dwarf cores in adequate numbers compared with the observationally determined mass spectrum [211–213]. In parallel, the discovery of ‘super’ Jupiter-mass objects \( > 10 M_{\text{Jup}} \) orbiting a central star (see figure 12) emphasizes the need for identification criteria enabling the distinction between a brown dwarf and a planet. Radii significantly smaller than predictions for solar or nearly solar metallicity objects would reveal the presence of a significant amount of heavy material, an unambiguous signature of planetary formation process. The case of the 8 Jupiter-mass transiting planet HAT-P-2b (or HD147506b, [214]) is interesting in this context, as its radius is consistent with the presence of a significant amount of heavy elements (\( \gtrsim 10\% \) in mass fraction) and cannot be reproduced by a solar metallicity brown dwarf model [216], as illustrated in figure 12. If confirmed, HAT-P-2b might be the illustration that planets can form by core accretion up to a least 8 times the mass of Jupiter. The nature of CoRoT-Exo-3b, a \( \sim 21 M_{\text{Jup}} \) object orbiting an F3V type star [215], however, remains ambiguous, given the present uncertainties on the radius determination [216]. Enhanced metallicity is also expected to leave its mark on the atmospheric properties of a planet and may provide signatures of its formation process in a protoplanetary disk. However, abundance patterns in the cool atmospheres of planets and brown dwarfs may be severely affected by different complex processes (non-equilibrium chemistry, cloud formation, photochemistry, see section 5). Predictions are thus uncertain and determination of clear spectral diagnostics requires much additional work before they can be used to distinguish a planet from a brown dwarf (see [28]).

8.3. Hot-Neptunes and evaporation process

About 20 planets with masses less than \( \sim 20 M_{\oplus} \) have been discovered by radial velocity surveys. Since these small planets are at the detection threshold, this number is relatively large, indicating that they should be rather common. Because of their low mass, their presence at close distance from their parent star raises the question about their origin. Observational evidence that close-in planets may undergo significant evaporation process [217] gave rise to the idea that hot-Neptunes may have formed from more massive progenitors and have lost a substantial amount of their gaseous envelope [218]. This idea and the interpretation, in terms of evaporation, of the observations of [217] are currently controversial [219]. Preliminary models of evaporation for hot-Jupiters induced by the stellar XUV radiation predicted large evaporation rates which could significantly affect the planet evolution [220]. More recent theoretical works based on improved treatment of atmospheric escape now reach different conclusions and find much smaller rates than predicted just after the observations of [217] (see [221] and references therein). Small evaporation rates are also consistent with the observed mass function of exoplanets [222]. Furthermore, formation models based on the core-accretion scenario can easily produce hot-Neptunes.
composed of a large core of heavy material without the accumulation of a substantial gaseous envelope [223–225]. Their existence can thus be explained without the need to invoke strong evaporation processes. Getting the final word requires (i) more statistics in the low planetary mass regime, (ii) confirmation of the observations and interpretation of [217] and (iii) improved models of evaporation of close-in planets.

Independently of these issues, the interior properties of hot-Neptune planets were recently revealed by the discovery of GJ 436b [226] and HAT-P-11b [227], two transiting planets of $\sim 22M_\oplus$ and $\sim 26M_\oplus$, respectively. They are remarkably analogous to Uranus and Neptune, in terms of heavy material content, with a radius indicating heavy element enrichment greater than 85%. For GJ 436b, models with $\sim 20M_\oplus$ core of ice or rock and a gaseous H/He envelope of $\sim 2M_\oplus$ reproduce its observed radius [19]. HAT-P-11b also appears to be a super-Neptune planet with $\sim 90\%$ heavy element and $\sim 10\%$ H/He envelope (see figure 14 of [227]). Given current uncertainties on the modeling of planetary interior structures, only their bulk composition can be inferred, and the total amount of heavy material, its composition and distribution within the planet cannot be accurately determined. As mentioned in section 4.1.2 and shown in [19], the thermal contribution of heavy elements to the cooling of Neptune-like planets significantly affects their evolution and thus radius at a given age. The discovery of GJ436b and HAT-P-11b confirms the large heavy element content that can be expected in planets, comforting our general understanding of planet formation through the core-accretion model. However, since there is no obvious signature of an evaporation process on the structure of a planet, current observations cannot certify whether or not these hot-Neptunes have undergone strong evaporation episodes during their evolution.

8.4. Light of extra-solar planets

So far, exoplanets have only been discovered by indirect techniques, without actually direct photon detection from the planet. Various claimed direct detections cannot unambiguously assess the very nature of the observed object, brown dwarf or planet. The recent detections of the $3M_{\text{Jup}}$ planet Fomalhaut-b [56] and of the young (30 to 160 Myr old) triple system orbiting HR 8799 [229], however, represent exciting discoveries and, if coplanarity of the system is clearly demonstrated for the second case, might indeed be the first genuine direct detections of exoplanets. Somewhat counter intuitively, the short-period hot-Jupiters were the first class of exoplanets to have their atmospheric properties measured, both photometrically and spectroscopically; a major contribution made possible with the Spitzer Space Telescope [230, 231]. The majority of Spitzer exoplanet observations target transiting EGPs orbiting nearby stars. As a transiting planet disappears behind its star, there is an observable drop in the total flux from the system as the planet’s contribution is temporarily absent. This event is often called the secondary eclipse, and the depth of the eclipse is a direct measure of the planet–star flux ratio (e.g. figure 13). The orbital phase coverage of these Spitzer data confines them to measuring the temperature and chemistry of a planet’s day-side only. Since the planet–star flux ratio is the quantity measured, secondary eclipses depths increase with increasing wavelength roughly in accordance with the Rayleigh–Jeans approximation, resulting in deep eclipse amplitudes even at wavelengths where the planet flux is quite small. Figure 14 compares the full set of secondary eclipse flux measurements for HD189733b with day-side model spectra with uniform global redistribution of absorbed stellar flux ($\alpha = 0.25$) and day-side-only redistribution ($\alpha = 0.5$). In this example, there is a transition between 2 and 3 $\mu$m from one case to the other, suggesting depth-dependent energy redistribution, probably caused by horizontal flows over a narrow range of pressures [104].

The anticipated diversity in hot-Jupiters is beginning to emerge from secondary eclipse observations with hints that some hot-Jupiters have temperature inversions across their photospheres (HD209458b and TrES-4) while others may not (HD189733b). Temperature inversions can be produced by a variety of processes, for example, the presence of a high-atmosphere opacity source could produce strong heating at low pressures. Plausible opacity sources could be the molecules TiO and VO which can play an important role in shaping the atmospheric structures [232, 233]. However, it has yet to be shown that an identifiable opacity source can produce a temperature inversion deep (high pressure) enough to reach the photosphere and impact the IR fluxes. Alternatively, strong horizontal currents could cool deeper layers while leaving layers above still quite hot resulting in a fairly deep inversion [104, 124]. The exact nature of the inversion and its cause will require observations of higher precision and across a broader range of hot-Jupiters. Spitzer flux measurements have also started to identify those planets that have strong or weak day-to-night redistribution of absorbed stellar energy leading to cold or warm night-side temperatures. Observations covering a large fraction of an orbital period can provide potential maps of the atmospheric temperatures allowing tests of global

![Figure 13. Secondary eclipse photometry of HD 189733 at 16 $\mu$m, as measured by the IRS instrument on board Spitzer [228].](image-url)
circulation models [234, 235]. In one example, HD189733b, the hottest location of the atmosphere (measured at 8 µm) is actually not located at the substellar point but instead leads the substellar point by 2 to 3 h (i.e. down wind by 20° to 60°)—as roughly predicted by global circulation models [122]. For a more comprehensive review of Spitzer exoplanet observations see [236].

Ground-based secondary eclipse observations at K- and L-bands are being attempted by several groups and, so far, only upper limits have been obtained [237, 241–243]. These near-IR flux upper limits, however, can be extremely useful for estimating the level of day-to-night redistribution since, in many cases, the peak of the energy distribution for hot-exoplanets is actually in the near-IR, rather than at wavelengths covered by Spitzer. As demonstrated by [104] the question of redistribution is fundamentally a bolometric argument and measuring the fluxes at multiple band passes including shorter wavelengths is critical for determining the true day-to-night flux redistribution.

As a transiting planet passes between Earth and the host star, the wavelength-dependent opacities in the planet’s atmosphere obscure stellar light at different planet radii, leading to a primary transit eclipse with a wavelength-dependent amplitude. Spectroscopic observations during primary transit (called transit spectroscopy) can measure planet radii across various absorption features from which atomic and molecular mole fractions can be inferred. There have been a number of models for EGP transmission spectra [244–250], all using 1D plane-parallel or spherically symmetric geometry and a single 1D temperature–pressure profile to represent the depth-dependent (radial) structure. The broad Na and K doublets in the optical were predicted to produce large radius variations [244]. Subsequent observations using the STIS instrument on board HST detected the Na doublet [251], though it was much weaker than predicted, prompting speculations about high clouds and photoionization [247, 248]. Following the Na detection, an extended hydrogen atmosphere surrounding HD209458b was discovered using transit spectroscopy in the UV at Lyman-α [217]. At Lyman-α wavelengths, HD209458b is ∼3 times larger than at optical wavelengths. The extended atmosphere may also contain carbon and oxygen as reported by [252]. Strong water absorption (figure 15) was identified in the HD 209458b STIS data [250] and later in emission on the day-side with secondary eclipse Spitzer observations [253]. A marginal detection of water in HD189733 b was made with Spitzer [254] in the IR and later detected at much higher confidence (along with methane) with NICMOS on board HST [255]. Ground-based observations have also successfully repeated the Na detection in HD209458 b [256], and have actually resolved the doublet into its two components for HD189733 b [257].

Higher up in the atmosphere, at lower pressures and densities, global circulation patterns become inefficient at redistributing heat and the temperatures are likely close to their radiative equilibrium values. Under radiative equilibrium, there will be significant horizontal temperature variations caused by different incident angles of incoming radiation from the host star. Furthermore, the photoionization of species such as sodium and potassium has been shown to be very important for modeling the transmitted spectrum [248,250]. Given the transparency of the upper limb, photoionization (and potentially more complicated photochemistry) may also spill over to the night-side. Consequently, independent of the global circulation, there will be horizontal structure that is not likely well reproduced in a 1D model of the transmitted spectrum. Efforts to model this region in three dimensions are underway and should greatly improve our ability to use transit spectroscopy to infer upper-atmospheric properties of hot-Jupiters.

9. The future

The coming decades promise a wealth of discoveries and new knowledge in the field of exoplanets. Our understanding of exoplanet properties will progress with expected developments on experimental and theoretical fronts. Ongoing and future high-pressure experiments in various national laboratories (Livermore and Sandia in the US, LIL and Laser Mega-Joule laser projects in France) and advancements of first principle N-body numerical methods (DFT, path-integral, quantum molecular dynamics) promise substantial progress on EOS in the critical pressure regime of 0.1–10 Mbar, characteristic of H and He pressure ionization, and at temperatures typical of planetary interiors. The question of internal heat transport, and its efficiency in the presence of molecular weight gradients, may receive an answer from current progress in high-resolution multi-D numerical simulations. Numerical tools, such as the one developed by [258] and devoted to high resolution stellar radiative hydrodynamical simulations, using grid refinement methods and high-order spatial schemes, offer promising techniques to handle this problem. The future study of exoplanet atmospheres is also poised for great progress in the coming years. Coupled multi-D radiation hydrodynamical simulations are in the works, and new and improved opacity

Figure 14. HD189733b energy distributions assuming full-redistribution (lower line, α = 0.5) along with a 1450 K blackbody spectrum (dotted line). Over plotted are IR ground and space-based flux measurements for HD189733b [228, 237–239]. The lower point (dotted line). Over plotted are IR ground and space-based flux measurements for HD189733b [228, 237–239]. The lower point at 8 µm is the night-side flux measurement from [240].
databases are emerging. Our understanding of clouds and chemistry (much of which comes from studying brown dwarf atmospheres) is steadily improving.

From the observational standpoint, a multitude of missions based on different techniques and wavelengths will provide a wealth of data. The combination of all these techniques defines efficient strategies for the detection and characterization of exoplanets, as highlighted by the impressive prospective work by [259]. Current and future space-based surveys, such as CoRoT and Kepler, will significantly increase the number of known transiting systems. These two space missions may soon answer the question of whether Earth analogs, in terms of mass and size, exist in the habitable zone. A large number of additional transiting planets will also emerge in the next years from ongoing ground-based wide-field surveys as HATnet, TrES or WASP. Increasing the number of detections will allow a more comprehensive study of exoplanet physical properties (mass–radius relationship, bulk composition, abnormal radii, etc) and will confirm (or not) current observed trends, placing them on firmer statistical footing. CoRoT is expected to find many tens of transiting giant planets and could discover a few tens (10–40) of super-Earths. CoRoT recently announced the detection of the very first transiting super-Earth candidate (still to be confirmed at the time of this writing), CoRoT-Exo-7b, with a radius of $1.7\,R_{\oplus}$ [260]. The Kepler mission, launched in March 2009, will observe hundreds of thousands of stars for transiting events and is expected to find about 1000 transiting gas giants. This mission will certainly provide the most reliable way to get a census of Earth-sized planets around solar-type stars. It is capable of detecting several hundreds of super-Earths in all orbits up to 1 yr and more than 50 Earth-sized planets ($1\,R_{\oplus}$) in all orbits, with about a dozen in $\sim1$ yr period orbits [76, 82, 261]. Kepler will thus be able to discover a large number of planets, but only a sub-sample of the most suitable ones will be followed-up with Doppler velocimetry from the ground (HARPS-NEF and possible future instruments). Reference [76] estimates that Kepler, limited only by available observing time for HARPS-NEF, could obtain, for dozens of super-Earths, their radius and mass with a precision of less than 5% and 10% respectively. Such an accuracy allows bulk estimates of composition for planets in the mass range 1–10$M_{\oplus}$ [76]. More details on observational uncertainties for both CoRoT and Kepler can be found in [261].

Also, Kepler and CoRoT promise optical phase curves of short-period planets, while a refurbished Hubble Space Telescope will bring new transmission spectra (from the UV to near-IR) and near-IR phase curves. Future missions such as JWST and SOFIA also promise new and exciting exoplanet atmosphere observations. As the successor of HST and Spitzer, JWST will open new avenues in transiting exoplanet science with the characterization of intermediate and low-mass exoplanets ($\lesssim M_{\text{Neptune}}$). Currently, about ten hot-Jupiters have been observed with Spitzer, allowing the analysis of their emergent spectra, and the Warm mission should double the number of detection [262]. Spitzer could in principle detect hot super-Earths in favorable cases, and JWST will extend these detections to ‘warm super-Earths’ ($\sim300\,\text{K}$). The latter mission is also capable of measuring the day–night temperature difference of warm Earth-like planets orbiting M-dwarfs, just as done by Spitzer for several hot-Jupiters [262]. JWST should be able to obtain light curves of primary and secondary eclipses of $1\,R_{\oplus}$ terrestrial planet around main sequence stars with a high precision, allowing basic characterization of the transiting exoplanet and the possibility to search for unseen planets [263].

From the ground, the recent discovery of the triple planetary mass system orbiting HR 8799 [229] has clearly demonstrated the potential of ground-based direct imaging campaigns. The development of a new generation of adaptive-optics (AO) systems, such as VLT-SPHERE or the Gemini Planet Imager (GPI), augurs well for direct imaging of planets orbiting solar-type stars, enabling direct detection of hundreds of warm Jovian planets in the next decade [264]. These systems, which are precursors for the next generation of extremely large telescopes with apertures around 30 m, attempt to reach in a near future contrasts up to $10^{8}$, allowing the detection of young Jupiters of less than 100 Myr around solar-type stars [265]. In the next years, AO coronagraphs should thus be sensitive to a broad range of self-luminous giant planets in the ranges 1–10$M_{\text{Jup}}$, 4–40 AU and 10–10 000 Myr [264]. High contrast imaging systems on extremely large telescopes (ELT) should achieve contrasts allowing the characterization of any self-luminous planet at high signal-to-noise ratio (SNR) and spectral resolution. Even mature planets in the inner part of solar systems ($<2\,\text{AU}$) should become detectable through reflected light [264].

![Figure 15. Model monochromatic transit radii for HD209458b. Horizontal bars correspond to mean radii across bins with λ-ranges indicated by the width of each bar. Observations are shown with 1–σ error bars [240, 250].](image-url)
Better characterization of our own solar system planets is also crucial to carry on with, for instance the Juno mission to Jupiter which should measure atmospheric abundances, in particular water, and accurately map its gravitational and magnetic fields. As stressed in this review, the understanding of exoplanet physical properties is strongly linked to the understanding of their formation process. On this front, our knowledge will greatly improve with the possibility to detect recently formed giant planets either directly, through their thermal or accretion luminosity using AO techniques as above mentioned, or indirectly by imaging the structures (e.g. gaps) they should produce in their disks with projects such as ALMA.

Finally, the possibility of identifying habitable planets, with the detection of water vapor and signs of chemical disequilibrium in their atmospheres, is given by projects such as DARWIN/TPF and JWST. This could be one of the most significant and stimulating achievements of science, as it may tell us that we are not alone in the universe.

Acknowledgments

The authors are grateful to their anonymous referee for valuable comments and appreciated contributions for improving the manuscript. The authors thank F Selsis, B Levrad, J Leconte and C Winisdoerffer for helpful discussions. They are also grateful to F Selsis and D Saumon for providing some of the figures presented in this review. IB and GC thank the astronomy department of the University of St Andrews, where part of this work was completed within the ‘Constellation’ network, for their warm hospitality. This work was supported by the Constellation European network MRTN-CT-2006-035890 and the French ANR ‘Magnetic Protostars and Planets’ MAPP project. TB acknowledges support form the NASA Origins of Solar Systems program along with the Hubble and Spitzer theory programs.

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