Most of the exoplanets known today have been discovered by indirect techniques, based on the study of the host star radial velocity or photometric temporal variations. These detections allowed the study of the planet populations in the first 5–8 AU from the central stars and have provided precious information on the way planets form and evolve at such separations. Direct imaging on 8–10 m class telescopes allows the detection of giant planets at larger separations (currently typically more than 5–10 AU) complementing the indirect techniques. So far, only a few planets have been imaged around young stars, but each of them provides an opportunity for unique dedicated studies of their orbital, physical and atmospheric properties and sometimes also on the interaction with the ‘second-generation’, debris discs. These few detections already challenge formation theories. In this paper, I present the results of direct imaging surveys obtained so far, and what they already tell us about giant planet (GP) formation and evolution. Individual and emblematic cases are detailed; they illustrate what future instruments will routinely deliver for a much larger number of stars. I also point out the limitations of this approach, as well as the needs for further work in terms of planet formation modelling. I finally present the progress expected in direct imaging in the near future, thanks in particular to forthcoming planet imagers on 8–10 m class telescopes.

1. Planet imaging: interest and challenges

Exoplanet science aims at answering three main questions: (i) How do planets form and evolve? (ii) What is the diversity of planetary systems (planet orbital and physical characteristics, multiple systems architectures)? (iii) Can we identify planets suitable for the search of biosignatures?

Thanks to hundreds of discoveries (figure 1; http://exoplanet.eu/ [1]) for almost 20 years, mainly coming from radial velocity (RV) and transit surveys, our
knowledge on exoplanets has dramatically improved. We know that exoplanets are frequent solar-type stars: around \( \simeq 15\% \) of stars have planets with masses larger than 50 \( M_{\text{Earth}} \) and more than 50\% of that of planets (all masses [2]). There are indications that RV or transit planets were predominantly formed by the accretion of gas onto a solid core (‘core-accretion’ scenario; hereafter CA [3]), like our solar system giants, rather than by gaseous collapse within a gravitationally unstable (GI scenario [4,5]) disc. An unexpected diversity of planet orbital properties (separations, eccentricities, orbital motions, e.g. retrograde orbits) was revealed. One remarkable outcome of the studies is that dynamical evolution (owing e.g. to planet scattering during close encounters, the presence of the third body (secular models) or early disc–planet interactions (disc migration models)) is needed to explain close in, retrograde planets and/or high eccentricity planets; hence dynamical evolution plays an important role in the building of extrasolar planetary systems. Dynamics is now also known to have played a major role in the building of the final architecture of our solar system, as shown by the Nice models [6]. Finally, in a few cases, spectroscopic observations of transiting planets allowed the first explorations of the atmospheres of hot (\( \text{Teff} \simeq 2000 \text{ K} \)) Jupiters.

Direct imaging is mandatory to explore the outer content of planetary systems. RV techniques cannot, for instance, allow the characterization of the orbits of Saturn, Uranus and Neptune on reasonable timescales, given the planets’ periods. Direct imaging is also probably the most efficient technique to identify planets, as only two epochs separated by typically a few months are needed, instead of at least one planet orbital period in the indirect methods. The estimates of their masses, effective temperatures and gravities as well as atmosphere explorations can also be done rapidly. Another advantage of direct imaging is that, conversely to RV, there is no degeneracy owing to planet inclinations in the determination of their masses. However, as the observed separation between the star and planet is a projected separation, the determination of the actual planet separation requires either to know the inclination of the system (assuming, for instance, that the planet lies within the equatorial plane of the star, or within a disc) or to fully characterize its orbit, which requires monitoring the orbit over longer timescales.

The mass of imaged planets, as well as their effective temperature and gravity, is derived from the observed luminosities, using age-dependent, brightness–mass (or brightness–temperature/gravity) relationships given by evolution models; these relations are not yet well calibrated. Until recently, two types of models were proposed, the so-called ‘cold-start’ and ‘hot-start’ models, that were initially supposed to ‘describe’, respectively, the two main giant planet...
(GP) formation scenarios, that is ‘core-accretion’ and ‘gravitational instabilities’ in a disc or in a cloud. The models differ mainly from the assumptions made on the fate of the energy released from the accreting gas. Hot-start models assume that this energy is kept and transformed into heat, whereas cold-start models assume that this energy is lost. Hence, planets formed by cold-start models are much cooler than those formed by hot-start models at young ages. Also, planets of a given mass formed by cold-start models are predicted to be much fainter than that formed by hot-start models [7]. Very recently, intermediate situations were considered in ‘warm-start’ models [8] in which only a fraction of the accretion energy is radiated away (hence the initial entropy of the planet becomes a free parameter).

2. Surveys results

(a) Current capabilities

Direct imaging of planets is very challenging as one has to identify and characterize (astrometric, photometric measurements) the very faint planet signal, angularly very close to the much brighter, stellar signal. Detecting planets closer than typically 1" from their parent stars requires diffraction-limited images delivered by large apertures (10 m class telescopes). To remove the stellar light and artefacts caused by optical defects, different techniques and observing strategies have been used: coronagraphy, saturated imaging, using either comparisons stars or additional techniques, such as spectral differential imaging or angular differential imaging, to remove the slowly variable speckles owing to the imperfect optical elements.

Given today’s instrumental capabilities in terms of achievable contrasts, the observations are done in the near IR. Also, only self-luminous GPs in young systems can be detected, because they are much hotter and brighter than their older counterparts. Surveys have then mainly concentrated on young (less than or equal to 100 Myr) nearby (less than or equal to 100 pc) associations such as TW Hydra, β Pictoris moving group (MG), AB Doradus, η Chameleion, Carinae and Colombus. Identifying new members in these associations or finding new MGs is a challenge in itself and has been the object of huge efforts in the community for 10–20 years [9,10].

(b) Frequencies of giant planets on wide orbits

In a nutshell, a few hundreds of targets have been observed in high angular resolution and high-contrast direct imaging. Most of the surveys (for a detailed review, see [11]) have reported null detections, allowing thus to derive upper limits to planet occurrence, which was found to be less than typically 20% for planets with masses typically 5–13 M_Jup, and separations larger than typically 10 AU. For stars with spectral types FGKM in the range 0.5–13 M_Jup, and separations of 50–250 AU, an upper limit of 10% is found [12]. For A-type stars, taking into account the few detected planets around A-type stars (see below), a frequency in the range of 6–19% is found for 3–13 M_Jup GPs located 5–320 AU [13], while a range of 10–25% for planets more massive than 1 M_Jup and 1–1000 AU from AF stars is derived [11]. Finally, for a yet limited number of M-type stars, Delorme et al. [14] found a 50% probability to detect a 3 M_Jup companion at 10 AU or a 1.5 M_Jup companion at 20 AU.

To estimate these limits, most of the studies assume a flat (uniform) planet distribution or a distribution similar to that derived from RV surveys [15] and extrapolated to wider separations. Obviously, the last assumption is not justified because RV and most of the imaged planets did not form by the same mechanism. Recent analyses have started to include outputs of formation model simulations [11,16]. The latter showed that the observed frequency range is not compatible with the predictions of current GI models. This is probably because these GI simulations end up forming very massive clumps (brown dwarf precursors) rather than massive planets [8]. It is now crucial to further refine these models to see whether or not they can produce Jupiter mass planets (and with which configuration).
The surveys have revealed (see figure 1 for a visual summary) so far only few planetary-mass ($M \leq 13M_{\text{Jup}}$) companions: five orbiting low-mass stars (K to early M spectral types), all further than 200 AU, seven closer (8–120 AU) companions to higher mass stars (B-A-type stars) hosting moreover debris discs (see below for individual discussions) and three planetary-mass companions orbiting brown dwarfs at separations (3–50 AU). For the planetary-mass companions to A-type stars, the planet–star mass ratio ($q$) is smaller than 0.005, for K to early M type stars, $q$ is between 0.01 and 0.03, and for the brown dwarfs, $q$ is in the range of 0.15–0.37. Note that the surveys have in addition detected several substellar companions to stars and brown dwarfs (figure 1).

The imaging of the 4–8 $M_{\text{Jup}}$ mass 2Mass1207b around a 25 $M_{\text{Jup}}$ brown dwarf in 2004 (the first image planetary-mass-bound object; [17]) has raised questions of the nature of this object: is it a planet or a brown dwarf? and of its formation process. The planet–star mass ratio is more than or equal to 0.16, a value much larger than that of planets around stars. CA models do not predict such massive planets around very low-mass (VLM) stars. However, the mass ratio is also lower than that found until now, hence with limited capabilities in contrasts ($q \geq 0.4$) for companions to VLM; more importantly, cloud fragmentation simulations fail to produce a ratio lower than 0.6 for these types of objects ([18] and references therein). The formation mechanism of 2Mass 1207 is still unclear. Similar questions apply to other planetary mass objects detected around brown dwarfs.

Most of the planetary mass companions to stars are orbiting further than 200 AU. Core-accretion is not expected to be efficient enough a mechanism to form such big bodies in situ because the timescales to form the few Earth-mass solid cores required to trigger runaway accretion of gas are longer than the gas dispersal timescales and because the disc surface density is too low [19,20]. Close-in CA followed by outward migration [21] and/or planet scattering [22] could explain some of the detections but probably not all, and probably not the most massive planets. Gravitational instability [23] could be a viable mechanism at large separations (further than typically 20–40 AU, depending on the stars’ masses), as well as cloud fragmentation. Note however that it was shown recently that pebble accretion could allow CA up to much larger separations [24]; if confirmed, the present conclusions could change.

3. Emblematic cases

(a) Fomalhaut

A planet was reported based on a faint signal detected in optical Hubble Space Telescope (HST) images (figure 2), close to the inner edge of Fomalhaut’s dust ring [25]. Given this location, this body could be the one predicted earlier to explain this inner edge [26]. A mass of a few to a few tens of $M_{\text{Earth}}$ would be enough for such a sculpting. Because they did not detect a near-IR counterpart in Keck data, Kalas et al. [25] realized that the signal detected at optical wavelengths was not made of planetary photons; they attributed it to light scattered by dust (within a disc or rather a dust cloud) associated to a solid, light planetary body. Spitzer dataset direct constrains to the mass of this proposed planet, less than about 2 $M_{\text{Jup}}$ [27]. Later on, additional HST data indicated yet that Fomalhaut b projected orbit was in fact crossing the dust ring; in such a case, it is not responsible for the disc shaping; even more, there could be a possibility that the planet destroys the disc when it crosses it. Recently, it has been proposed that its orbit could in fact be inclined with respect to the disc, which could solve the disc stability problem. Much more data are needed to further test this possible planet and its orbit. Even though the planetary nature of the signal observed by HST is not totally proved yet and is sometimes questioned [27], the Fomalhaut system is very precious for studies of planet–debris disc or planet–planet interactions.
We detected with NaCo on the very large telescope (VLT) a GP orbiting β Pictoris (figure 2; [28, 31]), roughly along the edge-on dust disc position angle (PA), with a semi-major axis $a$ between 8 and 14 AU (note that the orbit determination is easier as the planet has a short period and its approximate inclination with respect to the line of sight as well as its rotation is known, if we assume that it shares approximately these properties with the disc). Its $L_p$ luminosity indicated a $\simeq 1700$ K, $7-11$ $M_{\text{Jup}}$ mass GP, assuming hot-start like conditions for its formation [29]. Follow-up observations at 4.05 $\mu$m [32] and at $K_s$ [33] confirmed these values. Recently, β Pictoris b was also detected with NICI on GEMINI, hence on another telescope than UT4 on the VLT [34]. A full analysis of β Pictoris b photometric data from J to M bands [30]. (Online version in colour.)

(b) β Pictoris

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β Pic b is so far the closest planet imaged around a star. Its relatively short orbital period (less than or equal to 20 yr) allows complete coverage of its orbit over a reasonable time scale. The first two sets of data allowed one to see the planet move from one side to the other side of the star. Additional astrometric data have been used to refine its semi-major axis, now in the range of 8–10 AU and its eccentricity less than 0.2 [35].

β Pictoris b’s young age ($12^{+5}_{-4}$ Myr) furthermore directly proves for the first time that GPs can form in million-year time scales in discs. Given its distance to the star, it is not expected to have formed in situ by gravitational instability within a disc [11]. Based on current model predictions [13], it could have formed instead via CA. However, its luminosity is not compatible with current cold-start models, supposedly reproducing core-accretion formation. Also, its dynamical mass, derived from RV data, is less than or equal to 14 $M_{\text{Jup}}$ if orbiting at 9 AU [36], a value that current cold-start models fail to explain. Warm-start models [7] may explain the β Pictoris b photometry akin to the initial conditions that are close to those adopted in hot-start models. The simulations recently developed by Mordasini et al. [37] to describe planets formed by CA also allow explanation of β Pictoris b properties [34]. In any case, this planet illustrates how critical evolution models are for the determination of the planet masses, and how direct constrains on masses (dynamical masses) are crucial to calibrate the derived brightness–mass relationships derived from these models.

β Pictoris b properties can nicely explain several of the disc characteristics, in particular the disc inner (80 AU) warp [38,39], and some outer asymmetries [40]. We attributed 15 years ago the warp to a massive body located on an inclined orbit and the outer asymmetries to the distribution of the small dust released by collisions among the perturbed planetesimals and submitted to the
star radiation pressure [38,41]. Our $K_s$ data show, after a careful calibration (required because the planet is so close to the star), that the planet is orbiting within the inner, warped disc [42], confirming the dynamical link between the disc and planet.

Finally, we remind the reader that $\beta$ Pictoris was the first star around which exocomets were evidenced in the late 1980s falling onto the star and evaporating. Such infalls were attributed to gravitational perturbation by a planet orbiting at about 10 AU that could be $\beta$ Pictoris b (for a review see [43]). It is not clear at the moment whether this planet could also be responsible for a short photometric eclipse that occurred in 1981 [44] but the orbit monitoring will answer this question in the coming years.

(c) HR8799

HR8799 (A-type) is today the only planetary system imaged, with three GPs detected in 2008, at projected separations ranging between 24 and 68 AU [45], and a fourth one, closer to the star (projected separation = 14 AU), was detected in 2010 [46]. This system is then unique for dynamical studies of multiple systems. Of course, the outcome of such studies depends on some still unknown planet orbital properties, in particular the inclination(s) and eccentricities, and on the age of the system. The age has been debated, as asteroseismology predicts an age of about 1 Gyr [47], while there are on the contrary several indicators of youth [48]. It appears that only combinations of given values of age, system inclinations, planet masses and eccentricities allow dynamical stability over timescales compatible with the system age. Models by Fabrycky & Murray-Clay [49] suggested that the system could be stable if the planets were locked in a 1d:2c:4b mutual mean motion resonance (MMR). There now seems to be a consensus that the three outer planets can be stable on tens of Myr time scales only if the system is young (less than or equal to several tens of AU), the planets have low inclinations (20–30°) from face-on and have masses less than $7-10^{-10}M_{\text{Jup}}$ (see [50] and references therein). However, it was shown recently that these conclusions could be significantly modified when taking into account the dynamical interaction of the planets with the debris disc, depending on its mass [51].

The formation mechanism of the HR8799 planets is still not clear. Given their separations, the three outer planets probably did not form in situ by core-accretion. Scenarios of inner formation followed by outward motion through e.g. planet–planet scattering have been proposed. Gravitational instability is another possibility; however, no detailed modelling has been done yet.

The HR8799 planets offer precious opportunities of detailed SED or spectroscopic studies, especially of planets b and c, which are angularly far enough (more than 1") from the star. Discrepancies with predictions from classical cloud-free atmosphere models are found from numerous studies (see e.g. [52] in the case of HR8799b and [53] for HR8799c). High-quality large binocular telescope images show that fitting the planets bcde SEDs requires fine-mixed clouds models (see figure 3; [54]). Also, a $K$ band spectrum shows that conversely to atmosphere model predictions no CH$_4$ absorption is detected towards HR8799c despite its temperature ($\simeq 1100\,\text{K}$); it also brings for the first time constrains on the C/O ratio in the planet atmosphere,
possibly favouring CA formation for this planet [55]. The HR8799 system illustrates the complexity of planet atmospheres and the need for both more refined models and high-quality spectroscopic data.

4. Future work

In recent years it has been demonstrated how precious planet direct imaging could be to make a full exploration of planetary systems, to constraint planet formation scenario, planet evolution and atmospheres, and to study planet–disc interactions. The data available have already allowed detection of planetary mass objects from a few to more than 2000 AU from stars or brown dwarfs, to constraint the frequency of GPs around young stars (a few tens to a few hundreds million years) and to study in detail the as yet very few planets imaged within 120 AU from their parent stars. Altogether the data bring evidence that different mechanisms have been at work to form planets around stars, in addition to cloud fragmentation at work to form planetary mass or brown dwarfs mass binaries. The few close planets found already challenge the simple, black-and-white approach 'cold-start' versus 'hot-start' models which were supposed to describe the core-accretion/gravitational instability scenarios as well as current atmosphere models.

The planets detected so far are only very few. In the near future, dedicated instruments using extreme adaptive optics will be available to extend the searches and studies in different directions [56,57]: towards lighter (down to sub Jupiter masses) planets, on closer (down to typically 5 AU) orbits and around stars aged up to 1 Gyr. This will in particular allow the detection of GPs in the same area as our solar system planets (figure 4). With these instruments, we can hope to get a full description of the typically 1 $M_{\text{Jup}}$ or more GP content of planetary systems further than 5 AU. Also, and very importantly, these instruments will provide near-IR spectra of these planets to perform detailed studies of their atmospheres. The James Webb Space Telescope will also allow light GP detection and spectral characterization up to the thermal domain. Later on, ELTs, and possibly also space-borne instruments (e.g. SPICES, [58]) will allow the detection and characterization of even lighter planets, orbiting even more mature stars.

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