Young Stars & Planets Near the Sun
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Direct Imaging of Exoplanets Living an Exciting Life

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Abstract. With the development of high contrast imaging techniques and instruments, vast efforts have been devoted during the past decades to detect and characterize lighter, cooler and closer companions to nearby stars, and ultimately image new planetary systems. Complementary to other planet-hunting techniques, this approach has opened a new astrophysical window to study the physical properties and the formation mechanisms of brown dwarfs and planets. In this review, I will briefly describe the different observing techniques and strategies used, the main samples of targeted nearby stars, finally the main results obtained so far about exoplanet discoveries characterization of their physical properties, and study of their occurrence and possible formation and evolution mechanisms.

Keywords. planets and satellites: detection, formation, dynamical evolution and stability, atmospheres; techniques: image processing, spectroscopic, high angular resolution

1. Introduction

With two decades of exoplanet studies, observations regularly obtained key successes with the discovery of the Hot-Jupiters family, the detection and confirmation of about 2000 exoplanets today, the first glimpse of planetary atmopsheres and internal structures, the direct images of Super-Jupiters revolving around their host star as well as the determination of their rotating period, the discovery of Super-Earths in the Habitable Zone (where water is expected to be liquid) or the discovery Earth-mass planets. The five main hunting techniques currently used (radial velocity, transit, mirco-lensing, direct imaghing and astrometry) are complementary and can be combined to further constrain planet properties like density (using radial velocity and transit) or internal entropy (radial velocity and imaging). Radial velocity, transit, micro-lensing and astrometry enables the internal part study of exoplanetary systems, at less than 5–10 AU. Direct Imaging (DI) is here unique to explore the outer part at more than 10 AU to complete our view of the systems's architecture. In addition to the orbital properties, exoplanet's photons can be resolved and dispersed to probe the atmospheric properties of the imaged exoplanets. Being easier to detect at young ages, their atmospheres show low-gravity features, as well as the presence of clouds, and non-equilibrium chemistry processes. Moreover, DI enables to directly probe the presence of planets in their birth environment. Planet characteristics and disk spatial structures can then be linked to study the planet – disk interactions and system's stability.

In this review, I will briefly describe: i/ the observing challenges of DI, ii/ the samples of stars observed, iii/ the main surveys and discoveries published sofar, finally iv/ key results about the physics of exoplanets, the mass determination and accretion history, the orbit and architecture and the occurence and formation.

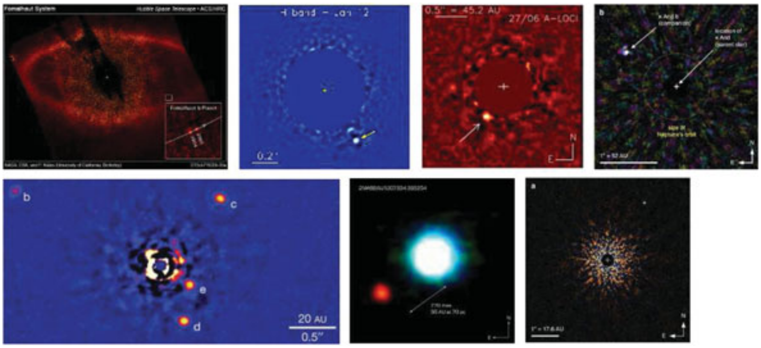

Figure 1. DI key discoveries: Fomalhaut b (Kalas *et al.* 2008), β Pictoris b (Lagrange *et al.* 2009), HD 95086 b (Rameau et al. 2013a), κ And b (Carson *et al.* 2013), HR 8799 bcde (Marois *et al.* 2010), 2M1207 b (Chauvin *et al.* 2005) and Gl504 b (Kuzuhara *et al.* 2013).

2. Observing challenges and techniques

To reach high contrast of $10^{-6}-10^{-7}$ at separation as close as 200 mas for the discovery of young jupiters at $\sim$ 10 AU (for a young star at 50 pc), current planet imagers are designed with a 3-stages implemenation (four if we include the post-processing analysis):

(*a*) *High angular resolution.* From the ground, Extreme-Adaptive Optics (XAO) systems are used to to compensate for atmospheric, telescope and common path defects. The main impact is to access the diffraction limit of the telescope (40 mas in H-band), to concentrate the stellar flux in the coherent core of the PSF, then to boost the detection signal. Current XAO instruments like SPHERE (Beuzit *et al.* 2008) and GPI (Macintosh *et al.* 2008) rely on high-order deformable mirror, high temporal sampling frequency at more than 1.0 kHz, spatial filtering of the wavefront before sensing to achieve Strehl correction of 90% in H-band on bright stars.

(*b*) *Stellar-light attenuation.* Coronagraphy is the second stage to reduce by a factor $\sim$ 100 the intensity of the stellar diffracted-limited core, and to eliminate the diffraction features due to the pupil edges. Various coronagraphic concepts are currently implemented to optimize the access to small separations, the transmission throughput and the chromaticity-dependency. The most common ones are the classical and apodized Lyot coronographs and the phase-masks coronographs like the four-quadran-phase mask and the vortex coronographs (see Mawet *et al.* 2012).

(*c*) *Speckles subtraction.* After the first two stages, boiling atmospheric speckles and instrumental quasi-statics speckles still remain an important source of limitation. Differential techniques have been developped to correct either: i/ residual atmospheric speckles using spectral or polarimetric differential techniques (simultaneous calibration of the PSF) or ii/ quasi-static instrumental speckles using angular differential imaging technique (Marois *et al.* 2006).

(*d*) *Post-processing tools.* Finally, important progress in the past years has been made to develop innovative algorithms to optimally calibrate the PSF temporally and spectrally in order to suppress the stellar contribution and recover faint planetary signals as close as possible to the star (LOCI, Lafrenière et al. 2007; PCA, Soummer *et al.* 2012).

3. Targets, surveys & main discoveries

Young ($\leqslant$ 500 Myr), nearby ($\leqslant$ 100 pc) stars are very favourable targets for the direct detection of the lowest mass companions (see Zuckerman & Song 2004; Torres *et al.* 2008). The first planetary mass companions were detected at large distances ($\geqslant$ 100 AU) and/or

Table 1. Deep imaging surveys of young (< 100 Myr) and intermediate-old to old (0.1 − 5 Gyr), nearby (< 100 pc) stars. Imaging modes are indicated as: Cor-I (coronagraphic imaging), Sat-I (saturated imaging), SDI (spectral differential imaging), ADI (angular differential imaging), ASDI (angular and spectral differential imaging).

Reference	Telescope	Instr.	Mode	Filter	FoV ($''\times''$)	#	SpT	Age (Myr)
Chauvin+03	ESO3.6m	ADONIS	Cor-I	H, K	13×13	29	GKM	$\lesssim 50$
Neuhäuser+03	NTT	Sharp	Sat-I	K	11×11	23	AFGKM	$\lesssim 50$
	NTT	Sofi	Sat-I	H	13×13	10	AFGKM	$\lesssim 50$
Lowrance+05	HST	NICMOS	Cor-I	H	19×19	45	AFGKM	$10 - 600$
Masciadri+05	VLT	NaCo	Sat-I	H, K	14×14	28	KM	$\lesssim 200$
Biller+07	VLT	NaCo	SDI	H	5×5	45	GKM	$\lesssim 300$
	MMT		SDI	H	5×5	-	-	-
Kasper+07	VLT	NaCo	Sat-I	L'	28×28	22	GKM	$\lesssim 50$
Lafrenière+07	Gemini-N	NIRI	ADI	H	22×22	85		10-5000
Apai+08[a]	VLT	NaCo	SDI	H	3×3	8	FG	12-500
Metchev+09	Palomar	PHARO	Cor-I	K	25.2×25.2	266	FK	3-3000
	Keck-II	NIRC2	Cor-I	K	40.6×40.6	-	-	-
Chauvin+10	VLT	NaCo	Cor-I	H, K	28×28	88	BAFGKM	$\lesssim 100$
Heinze+10ab	MMT	Clio	ADI	L', M	15.5×12.4	54	FGK	100-5000
Janson+11	Gemini-N	NIRI	ADI	H, K	22×22	15	BA	20-700
Vigan+12	Gemini-N	NIRI	ADI	H, K	22×22	42	AF	10-400
	VLT	NaCo	ADI	H, K	14×14	-	-	-
Delorme+12	VLT	NaCo	ADI	L'	28×28	16	M	$\lesssim 200$
Rameau+13c	VLT	NaCo	ADI	L'	28×28	59	AF	$\lesssim 200$
Yamamoto+13	Subaru	HiCIAO	ADI	H, K	20×20	20	FG	125 ± 8
Biller+13	Gemini-S	NICI	Cor-ASDI	H	18×18	80	BAFGKM	$\lesssim 200$
Nielsen+13	Gemini-S	NICI	Cor-ASDI	H	18×18	70	BA	50-500
Wahhaj+13	Gemini-S	NICI	Cor-ASDI	H	18×18	57	AFGKM	~ 100
Janson+13	Subaru	HiCIAO	ADI	H	20×20	50	AFGKM	$\lesssim 1000$
Brandt+14	Subaru	HiCIAO	ADI	H	20×20	63	AFGKM	$\lesssim 500$
Chauvin+15	VLT	NaCo	ADI	H	14×14	86	FGK	$\lesssim 200$

with small mass ratio with their primaries, indicating a probable star-like or gravitational disk instability formation mechanism. The breakthrough discoveries of closer and/or lighter planetary mass companions like Fomalhaut b (< 1 M_{Jup} at 177 AU; Kalas et al. 2008), HR 8799 bcde (10, 10, 10 and 7 M_{Jup} at respectively 14, 24, 38 and 68 AU; Marois *et al.* 2010), β Pictoris b (8 M_{Jup} at 8 AU; Lagrange *et al.* 2009) or more recently κ And b (14^{+25}_{-2} M_{Jup} at 55 AU; Carson *et al.* 2013), HD 95086 b ($4-5$ M_{Jup} at 56 AU; Rameau *et al.* 2013a,b) and GJ 504 b ($4^{+4.5}_{-1}$ M_{Jup} at 43.5 AU; Kuzuhara *et al.* 2013) indicate that we are just initiating the characterization of the outer part of planetary systems between typically $5-100$ AU (see Fig. 1). Vast efforts are now devoted to systematic searches of exoplanets in DI with an increasing number of large scale surveys (see Table 1; eight new surveys published between 2013 and 2015) and this will accelerate with the new generation of planet imagers.

4. Key astrophysical results

(a) *Physics of imaged planets.* Once an exoplanet is discovered and confirmed in DI (usually after a proper+parallactic motion test), the mass is derived from evolutionary models predictions. DI only enables to measure the photometry and luminosity of exoplanets, and not the mass. A key problem is that these models are not well calibrated at

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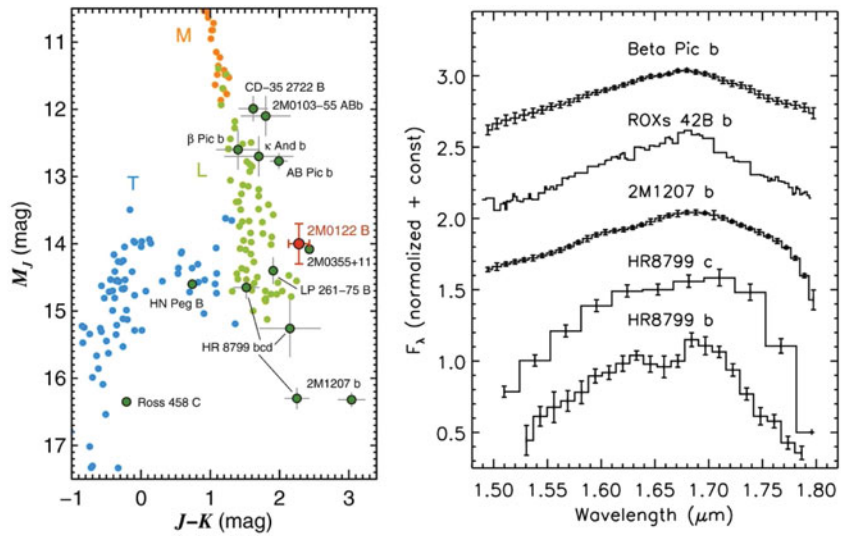

Figure 2. Left: M_J vs. $J - K$ diagram for field M (orange), L (light green), and T (blue) dwarfs. Dark green circles show substellar companions with parallactic distances (either to the primaries or the secondaries themselves). For comparison are overplotted the measurements for young imaged planets and brown dwarfs. From Bowler *et al.* (2013). Right: H-band spectra of young, directly imaged planets. From Chilcote *et al.* (2015).

young ages. In addition to the system age, the predictions highly depend on the formation mechanisms and the gas-accretion phase that will form the exoplanetary atmosphere (see Chabrier *et al.* 2014 for review). In the ideal case of multi-wavelengths photometric study, the spectral energy distribution of the exoplanet can be constrained. In the case of β Pic b, it shows atmospheric properties compatible with a young (low-gravity), dusty and early-L type and a planet's luminosity $log(L/L_\odot) = -3.90 \pm 0.07$ (see Bonnefoy et al. 2013; Fig. 6). Synthetic models give in addition a spectrum reproduced for $T_{eff} = 1650 \pm 150$ K and a $log(g) \leqslant 4.7$ dex and evolutionary models (hot-start) a mass between 8 and 13 M_{Jup}. Today, most imaged exoplanets are young, late-M or L-type exoplanets with dusty atmospheres. A striking feature is that some of them (2M1207 b, HR8799 b) appear redder and underluminous compared to field dwarfs of the same spectral type (see Fig. 2, Left). Methane absorption is also inhibited in some cases. The effect of low-gravity actually shifts the classical T_{eff}–SpT classification as highlighted by compartive studies between planets/young brown dwarfs and field brown dwarfs. Low-gravity conditions could also favour the formation of thick clouds causing photometric variability (Metchev *et al.* 2015).

(b) *Mass and accretion history.* As mentioned earlier, DI does not allow to measure the mass of exoplanets, but the luminosity. The so-called hot-, warm- and cold-start models of planetary formation and evolution, that describe different states of the gas-accretion shock during the planetary atmosphere formation, predict luminosities that are spread over several order of magnitudes for young, massive giants (see Marley *et al.* 2007, Mordasini *et al.* 2012). The combination of DI with radial velocity is here extremely precious to derive the dynamical mass of imaged planets. Such a combination between HARPS and NACO/GPI observations is illustrated for the case of β Pic b (Bonnefoy *et al.* 2014) and showed that the planet evolutive state may result from an inefficient accretion shock and/or a planetesimal density at formation higher than in the classical core-accretion model. Future systematic simultaneous determination of mass and

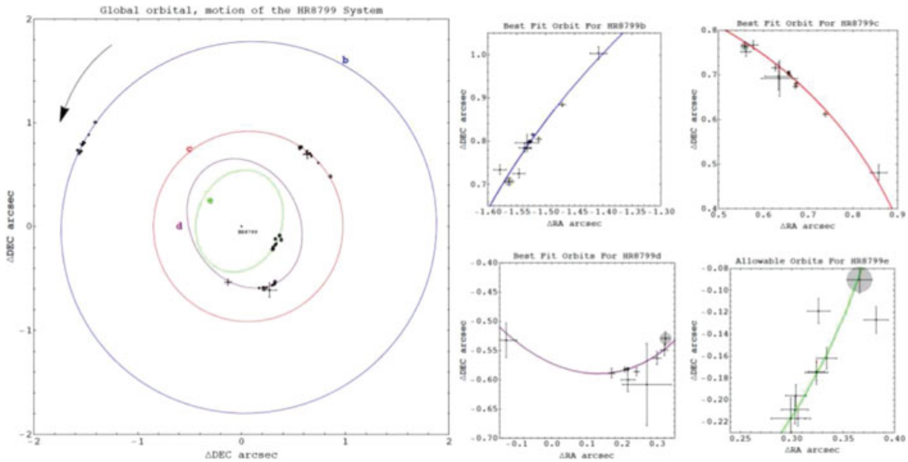

Figure 3. On-sky projection of the best fit orbits for HR8799 bcde (Pueyo *et al.* 2015).

luminosity will help calibrating the models. Much can be expected from the synergy between GAIA and SPHERE/GPI.

(*c*) *Orbit and architecture.* The third interesting question addressed by DI studies concerns the architecture of exoplanetary systems. In the case of multiple planetary system like HR 8799, a long-term astrometric monitoring enabled to characterize the planet orbits, to check for coplanarity, and ultimately to verify the dynamical stability of the whole system. Pueyo *et al.* (2015) recently showed that the HR 8799 d planet seems to be misaligned by 15–20 degrees and more eccentric (~ 0.3) than the other planets in the system, suggesting remaining imprints of dynamical interactions (see Fig. 3). They also confirm that mean motion resonances are likely to be present to stabilize the system. For HR 8799 and HD 95086, the planet location(s) can be compared to the dust spatial distribution and architecture, i.e for both cases with the presence of an inner warm belt and an outer cold belt surrounding the planets. The case of β Pic is even more striking in terms of planet–disk interactions, as the simultaneous characterization of the planet orbit and peculiar disk geometry confirm that the planet is responsible for the inner warped disk morphology, and that the orbital parameters are consistent with the transit-like event observed in November 1981, and the cometary activity observed for decades in that system (Chauvin *et al.* 2012; Lagrange *et al.* 2012).

(*d*) *Occurrence and formation.* Theories of planetary formation have drastically transformed in the last two decades and now favor the formation of planets within a proto-planetary disk by accretion of solids, building up a 10 to 15 $M_\oplus$ core followed by rapid agglomeration of gas. Whereas physical conditions and timescales favor core accretion in the inner disk ($\leqslant 10$ AU), gravitational instability or gravo-turbulent fragmentation could be alternative solutions to form massive planetary mass companions at wider separations ($\geqslant 10$ AU) in the earliest phase of the disk's lifetime (Boley 2009). The planets could either migrate inward, toward or outward, from the star by disk-planet interactions or during planet-planet interactions, which will alter the original semi-major axis distribution. One key element addressed by DI surveys concerns the occurence of giant planets beyond 10 AU to actually test these theories (Nielsen *et al.* 2013; Rameau *et al.* 2013b). Observed occurrences tend to reject gravitational instability or gravo-turbulent fragmentation as a dominant mechanism to form wide-orbit giant planets (Janson *et al.* 2013). For what concerns core accretion, the bulk of this population is probably still not explored by DI. However, SPHERE and GPI systematic surveys sensitive to physical

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separations as close as 5–10 AU (compared to 20–40 AU with previous instruments like NaCo, NICI, HiCIAO, NIRC2) will probably reach that bulk and allow a more significant overlap with other techniques.

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Discussion

QUESTION-1: Can we make any difference between imaged planets and imaged brown dwarfs?

ANSWER-1: Currently, no. We cannot access the formation history.

QUESTION-2: In addition to core accretion and gravitational instability, we should also consider stellar formation mechanism such as core fragmentation to form planetary mass objects (isolated or as companion).

ANSWER-2: Yes, I fully agree. It was refered as gravo-turbulent fragmentation in the slides.