

Direct Imaging of Exoplanets at the Era of the Extremely Large Telescopes

Gaël Chauvin^{1,2}

¹ Unidad Mixta Internacional Franco-Chilena de Astronomía, CNRS/INSU UMI 3386 and Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile,

² Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France.
email: gael.chauvin@univ-grenoble-alpes.fr

Abstract.

Within ten years, the era of large-scale systematics surveys will decay thanks to a complete census of exoplanetary systems within 200 pc from the Sun. With the first Lights foreseen between 2024 and 2028, the new generation of extremely large telescopes and planet imagers will arrive at a propitious time to exploit this manna of discoveries to characterize the formation, the evolution, and the physics of giant and telluric planets with the ultimate goal to search and discover bio-signatures. In that perspective, I will briefly summarize the main characteristics of the direct imaging instruments of the ELTs dedicated to the study of exoplanets, and I will review the key science cases (from the initial conditions of planetary formation, the architecture of planetary systems and the physics and atmospheres of giant and telluric planets) that they will address given their predicted performances.

Keywords. Exoplanets, Extremely Large Telescopes, Direct Imaging

1. Introduction

The young field of exoplanetary science has exploded in the past years. Two decades ago, the only planets we knew were the ones of our Solar System. Today, thousands of exoplanets have been discovered since the 51 Peg discovery (Mayor & Queloz 1995) and, with the diversity of systems found (Hot Jupiters, irradiated and evaporating planets, misaligned planets with stellar spin, planets in binaries, telluric planets in habitable zone, discovery of Mars-size planet...), the theories of planetary formation and evolution have drastically evolved to digest these observing constraints. Although on the timescale of a human Life, we may well be witnessing the first detection of bio-signatures in the atmosphere of a nearby exo-Earth at the horizon of 2030, we are still missing the full picture and some key fundamental questions lack answers regarding: i/ the existence of one or several mechanisms to form giant planets, ii/ the physics of accretion to form their gaseous atmospheres, iii/ the physical properties of young Jupiters and their time evolution, and iv/ the impact of dynamical evolution in crafting planetary system architectures. In that perspective, the upcoming decade is rich in terms of space missions and ground-based instrumentation dedicated to this young field of modern astronomy (see Fig. 1).

With the new generation of planet imagers (SPHERE, GPI, SCExAO), the direct imaging technique now represents a unique path to characterize true analogs of cool Jovian planets orbiting at more than 5-10 au (Chauvin 2018), a parameter space currently not explored by transit and radial velocity surveys. At sub-mm and centimetric wavelengths, ALMA in full capability now pursues the characterization of the cold dusty and gaseous component of young protoplanetary and debris disks with an exquisite spatial resolution

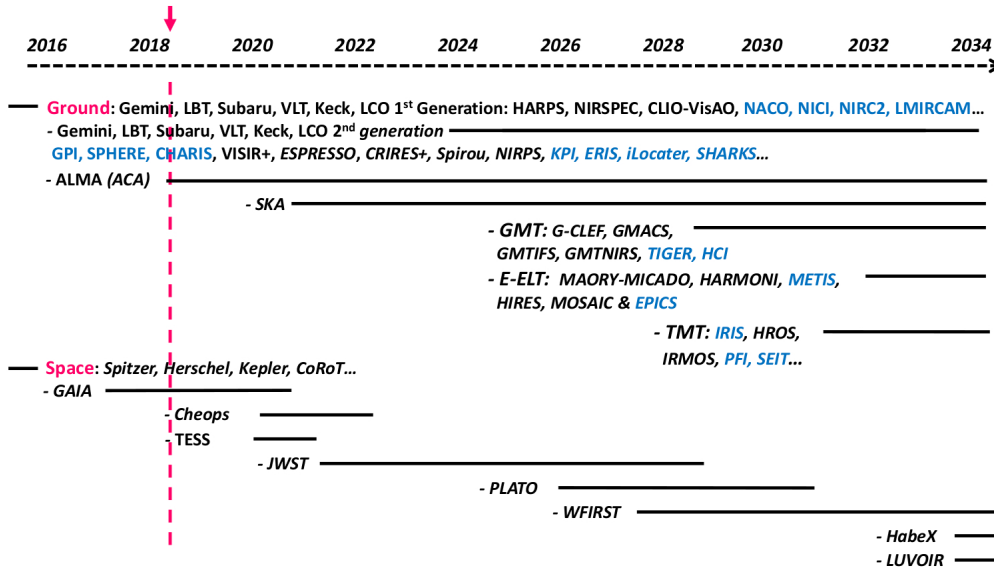


Figure 1. Timeline of current & future missions and instruments dedicated to exoplanets.

(down to 0.1") and will be soon completed by the Square-Kilometer Array (SKA) starting in 2020. The arrival of a new generation of high-resolution spectrographs, ESPRESSO at VLT, CARMENES at CAO, SPIROU at CFHT now in operation, CRIRES+ at VLT, NIRPS at the ESO3.6m Telescope, and iLocater at LBT soon, will extend the current NIRSPEC and HARPS horizon to the population of light telluric planets around solar and low-mass stars. In space, *Gaia*, launched end-2013, will achieve a final astrometric precision of 10 μ s in the context of a systematic survey of a billion of stars and therefore discover thousands of new planetary systems. The *Gaia* data release 4 in 2022 should give us a complete census of the giant planet population between 2 and 4 au for stars closer than 200 pc. The new transiting exoplanet survey satellite (*TESS*, Transiting Exoplanet Survey Satellite) just started operation going beyond the *Corot* and *Kepler* missions with its first discovery of a transiting planet around π Mensae (Huang et al. 2018). It is designed for a full-sky survey to reveal thousands of transiting exoplanet candidates with the size of Earth or larger and orbital periods of up to two months. This will be complemented by the *CHEOPS* (CHAracterising ExOPlanet Satellite) mission aimed at characterizing the structure of exoplanets with typical sizes ranging from Neptune down to Earth diameters orbiting bright stars (launch date in 2019). Finally, *PLATO* (Planetary Transits and Oscillations of Stars), foreseen for 2024, will extend our knowledge on the content of telluric planets at longer periods, up to several years, around relatively bright, nearby stars. Within 10 years, the era of large-scale systematics surveys will decay thanks to a complete census of exoplanetary systems within 100–200 pc from the Sun. A new Era fully dedicated to the characterization of known systems will rise. Already initiated with *Hubble*, *Spitzer* and the first generation of planet imagers and spectrographs, the characterization of the physics of giant and telluric planets will intensify with the operation of the James Webb Space Telescope (*JWST*), foreseen for the year 2021, which will address several key questions for the study of young circumstellar disks and exoplanetary atmospheres using direct imaging and transit and secondary eclipse spectroscopy.

Table 1. Instrumentation roadmap of the ELTs summarizing instruments and modes adapted for high contrast imaging and spectroscopy of exoplanets and disks. For AO flavors: seeing-limited (SL), single-conjugated AO with moderate-Strehl (SCAO) and extreme-AO with high-Strehl performances (XAO). Various observing modes are proposed: imaging (IMG), medium and high resolution spectroscopy (MRS, HRS), integral field spectrograph (IFS), combined with coronagraphy (corono) or polarimetry (polar).

Telescope (1 st Light)	Instrument	AO	Mode	λ (μm)	Spectral resolution	FoV ($''$)	Add.
E-ELT (2024)	MICADO	SCAO	IMG	0.8 – 2.4	BB, NB	53	corono
		SCAO	MRS	0.8 – 2.4	< 15000	3 – <i>slit</i>	
	HARMONI	SCAO	IFS	0.5 – 2.5	3500-20000	0.6	corono
		SCAO	IMG	3 – 19	BB, NB	18	corono
	METIS	SCAO	MRS	3 – 19	5000	18	
		SCAO	IFS	3 – 13	100000	0.4	corono
	HIRES	SCAO	IFS	0.33-2.4	< 150000	0.09	
	EPICS	XAO	IFS	0.95-1.65	125-20000	0.8	corono
		XAO	IMG	0.6-0.9	BB, NB, DBI	2	polar
GMT (2024)	G-CLEF	SCAO	HRS	0.4 – 1.0	20000-100000	7×0.23	corono
	GMTIFS	SCAO	IMG	1.0 – 2.5	BB, NB	20	
		SCAO	IFU	1.0 – 2.5	5000-10000	0.5×0.25	
	GMTNIRS	SCAO	HRS	1.1 – 2.5	65000	1.2 – <i>slit</i>	
		SCAO	HRS	3.0 – 5.0	85000	1.2 – <i>slit</i>	
	TIGER	SCAO	IMG	1.5 – 14.0	300	30	corono
		SCAO	LRS	1.5 – 14.0	300	30	corono
TMT (2028)	IRIS	SCAO	IMG	0.85 – 2.4	BB, NB	33	
		SCAO	IFS	0.85 – 2.4	4000-8000	0.06×0.5	
	MICH	SCAO	IMG	3 – 14	BB, NB	28	corono
		SCAO	LRS	3 – 14	600	28 – <i>slit</i>	corono
		SCAO	HRS	3 – 14	< 120000	2 – <i>slit</i>	corono
		SCAO	IFS	7 – 14	1000	0.18×0.07	corono
	NIRE	SCAO	HRS	1.0 – 2.4	20000-120000	2 – <i>slit</i>	
		XAO	IMG	1 – 2.5	BB, NB, DBI	1	corono
	PFI	XAO	IFS	1 – 2.5	100	1	corono

2. The era of ELTs

Despite a reduced sensitivity compared to *JWST*, the new generation of extremely large telescope (ELT), the Giant Magellan Telescope (GMT; Shectman & Johns 2010), the Thirty Meters Telescope (TMT; Simard et al. 2010) and the European Extremely Large Telescope (hereafter E-ELT; McPherson et al. 2012), will offer a unique spatial resolution and instrumentation. With the first Lights foreseen between 2024 and 2028, these ELTs will arrive at a propitious time to exploit discoveries of the upcoming generation of instruments and space missions owing to its capabilities in terms of sensitivity, spatial resolution and instrumental versatility. They will bring us a step further in the understanding of the physics of the early phases of stellar and planetary formation, the characterization of exoplanets, and the quest of extraterrestrial Life.

The three ELT projects (GMT, TMT and E-ELT) represent ones of the most challenging projects in modern astronomy with the realization of 30 to 40m-class Adaptive Telescopes designed for visible and infrared wavelengths and equipped with segmented primary mirrors (7 segments of 8.4 diameter for GMT, 492 segments of 1.44 m for TMT and 800 segments of 1.45 m for E-ELT). They will cover a large variety of scientific topics from the re-ionization of the early universe to the search for bio-signatures on nearby exoplanets. They will therefore rely on a diversity of dedicated instruments exploiting the

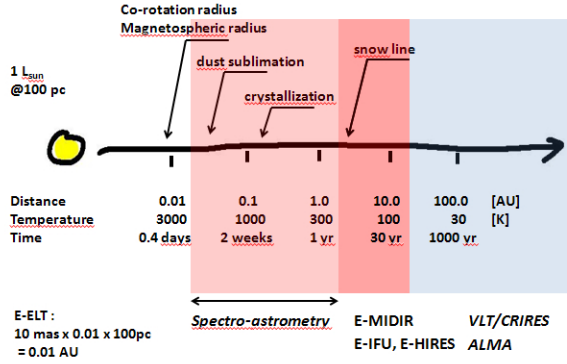


Figure 2. Exploration space of the planet-forming regions by the ELTs

telescope unprecedented sensitivity and spatial resolution with various observing modes: from integrated field spectroscopy, high-precision astrometry, simultaneous multi-object spectroscopy of hundred of targets, high resolution spectroscopy or high contrast imaging over a broad range of wavelengths (from 0.33 to 19.0 μm) together with a high operation efficiency. To respect these requirements, various flavors of AO systems will be used to ultimately provide the international community with diffraction limited images down to ~ 10 mas in K -band and/or to exploit the full patrol field of view of several arcminutes offered by these telescopes. These ELTs will undoubtedly open a new era for observers to address various unanswered fundamental questions of astronomy: accelerating expansion of the universe, fundamental constants, galaxy formation and evolution, stellar populations, and the study of exoplanets and bio-signatures. The Table 1 summarizes the main instruments and modes that will address this ultimate science case combining high-angular resolution with adaptive techniques and/or imaging and low to high-resolution spectroscopy.

3. Imaging and Characterizing Exoplanets with the ELTs

3.1. Initial conditions for planetary formation

The increased sensitivity and exquisite spatial resolution of the ELTs will offer an incredible opportunity to scrutinize and characterize the stellar environment from the inner regions of proto-planetary disks, the chemistry of planet-forming zones, to the characterization of recently formed giant planets in their birth environment. Fig. 2 illustrates for instance the synergy between current 10m-class telescope instrumentation, ALMA and the future instrumentation of the ELTs to characterize the spatial, temporal and chemical evolution of young proto-planetary disks. The combination of increased sensitivity, spatial resolution at the 10 mas scale and high spectral resolution will open a new observing window at the sub-au scale to study the physics of star-disk interactions. With the use of spectro-astrometric technique, a typical astrometric precision of 100 μas will be achieved for a star at 100 pc, enabling a characterization of the physical processes of accretion and ejection at a few solar radii ($1 R_{\odot} \sim 0.005$ au). This will place unique constraints on the star-disk interactions processes, the role of magnetic fields (reconfiguration and line reconnection) and the geometry of the accretion channels close to the star. At such a scale, we will also explore the properties of the inner circumstellar disks (asymmetries, warp, puffed-up inner rim...). We will directly probe the Jet-launching and stellar/disk winds regions (geometry and plasmas conditions), using various spectroscopic emission

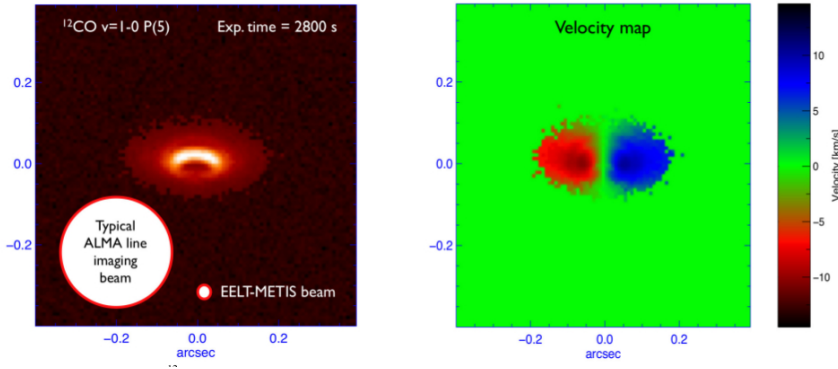


Figure 3. *Left:* Simulated ^{12}CO line emission at $4.7\mu\text{m}$ of a proto-planetary disk, reconstructed with METIS. The map is continuum-subtracted and the velocity channels are optimally co-added. Also indicated is typical ALMA beam for line imaging of disks, estimated from Semenov et al. 2008. *Right:* velocity map calculated as the first moment of the data cube. It shows that a resolving power of 100,000 (3 km.s^{-1}) is well matched to the spatial resolution of the E-ELT for a typical proto-planetary disk. Figure from Brandl et al. (2012).

and forbidden lines proxies of elements like Hydrogen, He, Ca, Mg, Fe, O, N or S. Moreover, accessing these close physical scales will enable short-term variability studies to explore the temporal dynamics of physical processes over a few hours and days timescale to witness in real time the evolution of the star-disk interactions including accretion and ejection processes with the magnetic field evolution.

Direct spectral imaging of the planet-forming regions will be achievable with the ELTs. For a typical young star at 100 pc, a 10 mas spatial resolution corresponds to physical separations of 1 au, i.e. to the exploration of the warm gas and dust spatial distribution down to the snow line, the disk evolution and dissipation to ultimately determine the initial conditions of planetary formation. Fig. 3 presents simulations of the young proto-planetary disk SR 21 (Ophiucus, 160pc, 1 Myr) seen in spectral imaging in the $^{12}\text{CO}(1-0)$ line at $4.7\mu\text{m}$ with the IFU mode of METIS (Brandl et al. 2012). The inner CO gaseous gap at 18 au is directly resolved. In addition to directly image the gas distribution, asymmetries and over densities in planet-forming zones, the spectral information with a resolving power of 100,000 will enable to directly map the gas dynamics with a velocity precision of 3 km.s^{-1} . Keplerian rotation will be distinguished from wind, accretion or Jet components. Deviation from Keplerian might also help to distinguish the presence of hidden planets as recently done with ALMA for HD 163296. The ELTs will therefore combine high angular resolution and high spectral resolution with instruments like METIS and HIRES at the E-ELT, G-CLEF and GMTNIRS at the GMT or HROS, MIRES and NIRES on the TMT to uniquely explore the inner planetary-forming regions ($\leq 20\text{ au}$). They will optimally complement ALMA or SKA observations, more sensitive to the characterization of the cold, outer dust and gas components of circumstellar environments (20 – 100 au).

In addition to the disk spatial structure and kinematics, these instruments will directly explore the inner disk chemistry, the disk atmospheres, the physical transport of volatile ices either vertically or radially, and the importance of non-thermal excitation processes in the planet-forming regions. They will offer a direct view of the distribution and the dynamics of water, playing a key role for the planetesimals formation and the disk cooling. It will also give clues on the organics content like CH_4 , C_2H_2 , HCN in the planet-forming regions and the prebiotic chemistry. The study of isotopic fractionation should also enable

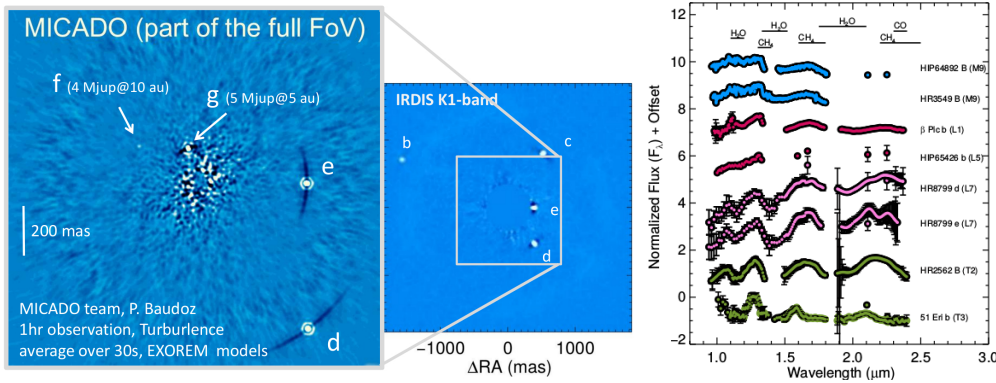


Figure 4. *Left:* MICADO simulations of Direct Imaging observations of the HR 8799 planetary systems leading to the detection of putative inner planets *f* and *g* to illustrate the contrast performances already offered with the first Light instruments of ELTs (Priv. comm. P. Baudoz, MICADO team). *Right:* Sequence of exoplanet's spectra characterized in the course of the SHINE and GPIES surveys (Priv. comm GPIES and SHINE teams).

to probe the chemical and physical conditions in the proto-planetary disks to improve our understanding of the transfer processes of water on telluric planets, including therefore the Earth itself. It represents of course a mandatory step to understand the formation of favorable conditions for life on telluric planets.

3.2. Architecture of planetary systems

With the first Light instruments, the combination of high angular resolution and moderate high contrast (10^{-6} at ~ 200 mas) will enable the detection of fine gaseous and dusty structures in proto-planetary and allows to directly detect giant planets recently formed in their birth environment. This will be particularly crucial to understand the physics of gas accretion determining the ultimate physical properties of giant planets, but also the physics of planet-disk interactions. It is now clear that planetary formation has a connection with the various spatial structures and asymmetries (warp, cavity, spiral, hole, vortex...) observed in young disks. Instruments like METIS, HIRES, EPICS at E-ELT or MICH, PFI at TMT and TIGER at GMT will ideally be probed with high-contrast imaging (contrast goals ranging from 10^{-6} at 200 mas to 10^{-9} at 20 mas), from visible to mid-IR, the existence of young giant (and potentially telluric) proto-planets down to the snow line around young stars together with the disk structures and physical properties (see Fig. 4, *Left*). At the more evolved stage of debris disk, the direct imaging of young solar system analogs, i.e. multi-belt architectures hosting imaged planets like HR 8799 bcde, β Pictoris b or more recently HD 95086 b, will be precious to understand the origin of our own solar system and test if giant planets might play a crucial dynamical role in the formation of telluric planets in stable habitable zones.

Ultimately, the synergy offered by the instrumentation of ELTs with other transit, radial velocity, astrometric and μ -lensing surveys will enable a global exploration of the planetary system architecture at all orbits (for the giant down to the telluric population; see Fig. 5). The complete overlap of these techniques will enable a systematical characterization of their frequency, multiplicity, distribution of mass and orbital parameters (period, eccentricity) for a broad range of stellar properties (mass, metallicity and age). Observables will be directly confronted to predictions of population synthesis models for various types of formation mechanisms (core accretion, gravitational instability or gravo-turbulent fragmentation). This will allow identifying the key mechanisms of formation

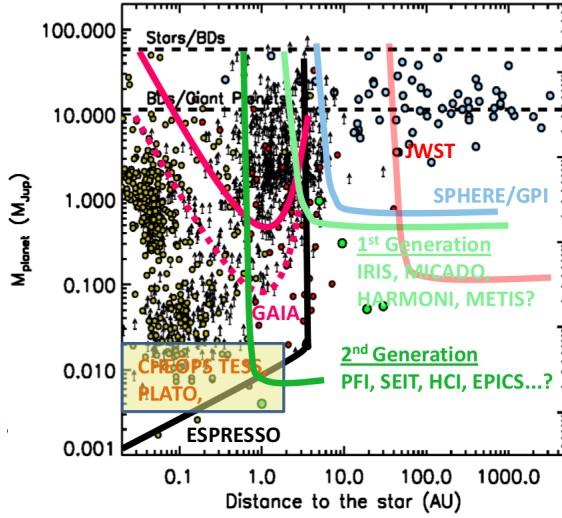


Figure 5. Confirmed exoplanets discovered today with the indicative detection limits of forthcoming planet hunting instruments and space missions together with the first and second generation of instruments of the ELT.

and dynamical evolution (planet-disk and planet-planet interactions) of planetary architectures. This is an essential step toward the understanding of the material redistribution in young planetary systems. This is directly connected with the transport of planetesimals from beyond the ice-line bringing water and organic molecules to the inner telluric planets (as proposed for Earth with the Late Heavy Bombardment of the young solar system).

3.3. Physics of exoplanets

Finally, first Lights of ELTs will arrive at a propitious time where thousand of new planetary systems will have been discovered and characterized by a large set of instruments or space missions, therefore covering a broad range of the parameter space in terms of physical properties (planetary masses, semi-major axis, radii, density, luminosity, atmospheric composition) and stellar host properties (age, mass, binarity, composition...). ELTs will therefore be mainly used for the fine characterization of known planetary systems and benefit from enhanced sensitivity, spatial resolution and instrumental versatility. The fact that observing techniques like direct imaging and radial velocity will overlap for the first time in the planetary mass regime will enable the simultaneous determination of the planet's mass and luminosity (see Fig. 6). It will therefore set fundamental constraints on the gas accretion history of giant planets, therefore their mechanisms of formation and evolution. It will also enable to characterize the atmosphere of giant exoplanets and potentially be sensitive enough to probe super-Earths and Exo-Earths.

The era of the characterization of exoplanets has already started a decade ago with the atmospheric characterization of hot and strongly irradiated Hot Jupiters like HD 209458 (Charbonneau et al. 2012). Such observations have been reported now for over 30 exoplanets to date, including hot Jupiters, hot Neptunes, and even super-Earths. The presence of water, carbon monoxide and methane molecules, of haze revealed by Rayleigh scattering, observation of day-night temperature gradients, constraints on vertical atmospheric structure and atmospheric escape have been evidenced in the past decade. More recently, VLT observations with CRIRES at high-spectral resolution (hereafter referred

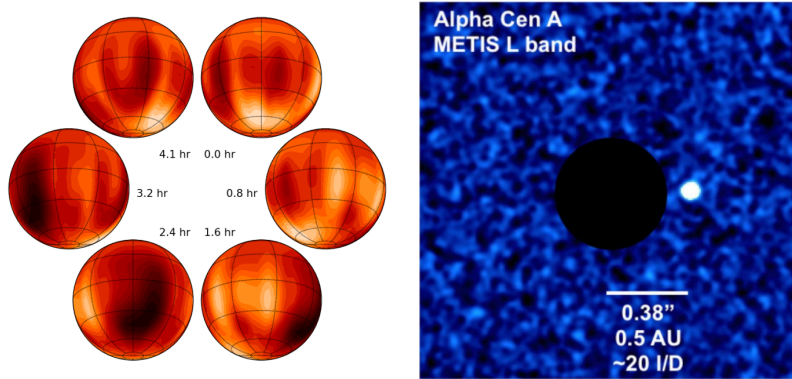


Figure 6. *Left*, a global cloud map of the nearest known brown dwarf Luhman 16 B. Figure from Crossfield et al. (2018). *Right*, HDS + XAO cross-correlation map of 30 hours of optical observations with METIS at the E-ELT of Alpha Cen A, 1.3 pc. An Earth twin, CO, CH₄ & H₂O-rich, is detected at 0.5 au. Figure adapted from Snellen et al. (2015).

as high-dispersed spectroscopy, HDS) showed that spectral features from planetary atmospheres can be disentangled from telluric and stellar lines making use of the radial velocity variations of the exoplanet. Planet to star contrast of 10^{-4} to 10^{-5} are typically expected for Hot Jupiters around solar-type stars. Such a contrast would be also sufficient to explore the atmosphere of a Earth-twin orbiting a small red dwarf (albeit such a star will be orders of magnitude fainter which imply decade of transit observations). In addition to classical transit and secondary eclipse low-resolution spectroscopy of exoplanets down to telluric masses, the use of HDS with instruments like HIRES, METIS, G-CLEF, GMTNIRS, MICHI or NIRES will enable to directly resolve the molecular lines (in transmission, emission but also reflection) of giant planets and to search for the signatures of CO, CO₂, H₂O, CH₄ and possibly NH₃, directly map their spatial distribution using Doppler imaging techniques (see Fig. 6, *Left*; Crossfield et al. 2014), and even constrain the planet's albedo. One might expect to get constraints on the structures and dynamics to characterize the processes of inversion, vertical mixing, circulation and evaporation of the planetary atmospheres of giant and telluric planets.

At longer periods, high-contrast low to medium-resolution spectroscopy in direct imaging already enabled to initiate the characterization of cool giant planets (see Fig. 4, *Right*). Exploiting that same technique, MICADO, HARMONI, METIS, TIGER, PFI, EPICS will offer a complementary view to directly resolve spatially and spectrally the photons of cool giant exoplanets from massive Super-Jupiter down to exo-Saturns and possibly Super-Earths. The study of their atmosphere composition and element abundances relative to the stellar ones will be precious to constrain the formation mechanisms of giant planets for instance. The ultimate goal will be to reach the necessary contrast of about 10^{-9} at angular separations of 20 mas around nearby M dwarfs (see Fig. 6, *Right*). It represents the very ambitious specification to meet to detect and characterize Super-Earths and Exo-Earths in the Habitable Zone (0.02 au at 10 pc around M dwarfs). Pushing this limit with ELTs is directly linked with the motivation to detect bio-clues like O₂, O₃, CH₄, CO₂ and H₂O in the atmospheres of telluric planets in habitable zones. A very promising approach arises from the synergy of XAO and HDS techniques Snellen et al. (2015). It represents a very exciting perspective in terms of future development in the view of future planet direct imagers like METIS, MICHI, PFI, EPICS that could lead to the first characterization of exo-earths and possibly the first probable discovery of exo-life, a scientific breakthrough of great philosophical value.



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Discussion

LYNNE HILLENBRAND: At wide separations, there is a rather large gap between the nominal sensitivity of the operating instruments SPHERE and GPI - Each of which have observed hundreds of stars - and the detect giant planets. Specifically, the gap appears between 0.7 and 7 M_{Jup} at separation larger than / au. Do you have any comment? Can it be concluded that the objects in this mass and separation range do not exist? Or is there perhaps some over-estimation of the current instrument sensitivity?

GAEL CHAUVIN: The SPHERE and GPI sensitivities presented in this talk (and in Fig. 4 of this proceeding) are rough estimation of the current mass and separation parameter space probed by current XAO imagers for comparison with other techniques. The goals are really to illustrate the complementary of the different techniques and to highlight the typical gains expected in separation and contrast with the first Light instruments and the 2nd generation of the ELTs. They actually aimed at reaching the ambitious contrast goals of 10^{-6} at 200 mas down to 10^{-9} at 20 mas. More accurate statistical determinations of the detection probabilities achieved by the SPHERE and GPI surveys are currently underway. They should soon provide us with the detection probability space explored, and, considering the number of discoveries, the frequency of giant planets found in the mass and separation domain. Results of the first generation of planet imagers (NaCo, NIRC2, NICI, HiCIAO...) on 10-m class telescopes were mostly sensitive to giant planets more massive than 5 M_{Jup} for semi-major axis between typically 30 to 300 au. Pushing that logic, the recent large meta-analysis of 384 unique and single young (5–300 Myr) stars spanning stellar masses between 0.1 and 3.0 M_{\odot} and combining several DI surveys (Bowler 2016) illustrates that the corresponding overall occurrence rate of 5 – 13 M_{Jup} companions at orbital distances of 30–300 au remains relatively low with frequencies of planets orbiting BA, FGK, and M stars of $2.8^{+3.7}_{-2.3}\%$, $< 4.1\%$, and $< 3.9\%$, respectively.

What are the Contributions of ELTs to Exoplanet Research?

How effective will ELTs be at detecting bio-clues in the atmospheres of telluric planets in habitable zones, and what innovations might these discoveries bring to the search for extraterrestrial life?