E-ELT’S VIEW OF CIRCUMSTELLAR ENVIRONMENTS

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Abstract. Considering the fantastic perspective offered by the upcoming generation of instruments of the European Extremely Large Telescope (E-ELT), a new observing domain will be opened for the exploration of the circumstellar environment. After placing the E-ELT in the context of current and future instrumentation, I will briefly summarize the main properties and expected performances of the six currently known instruments. I then review the most interesting science cases from the disk-star interactions processes, the proto-planetary and debris disks, the characterization of exoplanets to the search for bio-signatures.

1 Introduction

1.1 The E-ELT project

The European Extremely Large Telescope (hereafter E-ELT) represents one of the most challenging project in modern astronomy with the realization of a 40m-class Telescope designed for visible and infrared wavelengths and equipped with a segmented primary mirrors of more than 800 elements actively controled. The E-ELT 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. It will therefore rely on a diversity of dedicated instruments exploiting the 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 0.4 to 16 µm) together with a high operation efficiency. To respect these requirements, various flavors of adaptive optics (AO hereafter) systems will be used to ultimately provide the community with diffraction limited images of 12 mas in K-band and/or to exploit the full patrol field of view of seven arcminutes offered by the telescope. The E-ELT 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, circumstellar environments and bio-signatures).

1.2 A rich decade before E-ELT

With the first Lights foreseen in 2023, the E-ELT 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 in

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Table 1. E-ELT instrumentation roadmap. Various AO flavors are used: single-conjugated AO (SCAO), multi-conjugated AO (MCAO), laser-tomography AO (LTAO), multi-object AO (MOAO), extreme-AO (XAO). Various observing modes are proposed: imaging (IMG), medium and high resolution spectroscopy (MRS, HRS), integral field unit (IFU), high multiplexing (HM) and high-definition (HD, for MOAO-assisted), differential polarimetric imaging with EPOL, but also coronography (corono), polarimetry (polar) and multiplexing capabilities (Mx).

<table>
<thead>
<tr>
<th>Instruments</th>
<th>AO</th>
<th>Mode</th>
<th>λ (µm)</th>
<th>Spectral resolutin</th>
<th>FoV (as)</th>
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<tbody>
<tr>
<td>E-CAM</td>
<td>SCAO</td>
<td>IMG</td>
<td>0.8 – 2.4</td>
<td>BB, NB</td>
<td>53.0/3</td>
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<tr>
<td>E-IFU</td>
<td>SCAO</td>
<td>MRS</td>
<td>0.5 – 2.4</td>
<td>4000, 10000</td>
<td>0.5 × 1.0/4.0</td>
<td>Corono</td>
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<td>E-MIDIR</td>
<td>SCAO</td>
<td>IFS</td>
<td>3 – 13</td>
<td>BB, NB</td>
<td>18.0/12</td>
<td>Corono</td>
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<td>E-HIRES</td>
<td>SCAO</td>
<td>HRS</td>
<td>0.37-0.71</td>
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<td>0.82</td>
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<td>E-MOS</td>
<td>MOAO</td>
<td>Slits, IMG</td>
<td>0.37-1.4</td>
<td>300-2500</td>
<td>6.8.1</td>
<td>Mₚ = 400</td>
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<td>E-POL</td>
<td>XAO</td>
<td>IFS</td>
<td>0.95-1.65</td>
<td>125-20000</td>
<td>0.8/1.5</td>
<td>Corono</td>
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order to 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. In the context of circumstellar environments studies, a plethora of new results are expected. Already in 2014, the planet imagers SPHERE at VLT (Beuzit et al. 2008) GPI at Gemini (Macintosh et al. 2008) will complete our view of planetary systems at wide orbits (≥ 5 AU), a parameter space currently not explored by transit and radial velocity surveys. ALMA in full capability will pursue the characterization of the cold dusty and gaseous component of young protoplanetary and debris disks with an exquisite spatial resolution (down to 0.1″) completed by the Square-Kilometer Array (SKA) starting 2016. The arrival of ESPRESSO at VLT will enable to extend the current ESO3.6m/HARPS horizon to the population of light telluric planets (Mégevand et al. 2012). In space, GAIA that will be launched end-2013 will achieve a final astrometric precision of 10 µas and therefore discover thousands of new planetary systems with a complete census of the giant planets content between 2 and 4 AU for stars closer than 200 pc (Sozzetti et al. 2011). The new transiting exoplanet survey satellite (TESS, launch date 2017, Ricker et al. 2010) will go beyond the Corot and Kepler missions is designed for a full-sky survey to reveal thousands of transiting exoplanet candidates which are Earth-sized or larger and orbital periods of up to two months. This will be complemented by the CHEOPS mission aimed to characterize the structure of exoplanets with typical sizes ranging from Neptune down to Earth diameters orbiting bright stars (launch date in 2017). Finally, the James Webb Space Telescope, foreseen for the year 2018, will address several key questions for the study of young circumstellar disks and exoplanetary atmospheres using direct imaging and transit and secondary eclipse spectroscopy (Clampin et al. 2010).
Despite a reduced sensitivity compared to JWST, the new generation of extremely large telescope, the GMT (Shectman et al. 2010), the TMT (Simard et al. 2010) and the E-ELT (McPherson et al. 2012), will offer a unique spatial resolution and instrumentation.

1.3 The E-ELT instrumentation roadmap

The E-ELT instrumentation roadmap currently includes 6 instruments (see Table 1; an additional call will be released for a seventh instrument in 2016). The two first Lights instruments are the near-IR imager E-CAM (Davies et al. 2010) and the visible-nearIR integral field spectrograph E-IFU (Thatte et al. 2010) foreseen for 2023, that will be followed by a second pool of equal scientific priority: the midIR spectro-imager E-MIDIR (Brandl et al. 2012), the visible-nearIR high resolution spectrograph E-HIRES (Pasquini et al. 2010; Origlia et al. 2010) and the multi-object spectrograph E-MOS (Evans et al. 2013; Le Fèvre et al. 2010), foreseen over 2024-2028. Finally, the high-priority planet imager E-PCS (Kasper et al. 2010), owing to a significant technological risk, is foreseen for 2027-2030. These instruments imply various favors of AO from single-conjugated AO (SCAO), to multi-conjugated AO (MCAO) with E-CAM with the requirement to achieve a 40 µas astrometric precion over a field of view of 53", laser tomographic AO to favor higher transmission and sky coverage, multi-object AO for the high definition mode of the E-MOS instrument to extreme-AO with E-PCS for an optimal control of the telescope PSF to achieve contrast up to 10⁹ at a few λ/Ds. The study of the circumstellar environment in the science cases of these six instruments is not equally ranked, and whereas the E-MIDIR, E-HIRES and E-PCS instruments devote a high-scientific priority to the study of disks and exoplanets, the E-MOS instrument is more dedicated to stellar population or extra-galactic studies. The priority is medium for the two first Lights and more generalist instruments that are E-CAM and E-IFU.

The increased sensitivity and exquisite spatial resolution of the E-ELT will offer an incredible opportunity to scrutinize the environment of stars, from young stars surrounded by accreting disk and outflows, proto-planetary and debris disks to mature planetary sys-
2 Circumstellar disks, Jets & Outflows

2.1 Star-disk interactions

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 with E-IFU and E-HIRES, 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 (see MHD simulation of accretion and star-disk interactions; Figure 2). 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 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 the evolution of the star-disk interactions including accretion and ejection processes with the magnetic field evolution.

2.2 Planet-forming regions

Pionier spectro-astrometric studies with VLT/CRIRES (Pontoppidan et al. 2008) initiated the study of gas spatial distribution at a few AU. Direct spectral imaging of the planet-forming regions will be achievable with the E-ELT (see Figure 1). For a typical young star at 100 pc, a 10 mas spatial resolution corresponds to physical separations of 1 AU,
Fig. 3. Left: Simulated $^{12}$CO line emission at 4.7m of a proto-planetary disk, reconstructed with E-MIDIR IFU. 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).

i.e. to the exploration of the warm gas and dust spatial distribution down to the snow kine, the disk evolution and dissipation to ultimately determine the initial conditions of planetary formation. Figure 2 presents simulations of the young proto-planetary disk SR 21 (Ophiucus, 160pc, 1 Myr) seen in spectral imaging in the $^{12}$CO(1-0) line at 4.7 µm with the IFU mode of E-MIDIR (Brandl et al. 2012). The inner CO gaseous gap at 18 AU is directly resolved. In addition to directly imaging 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. The E-ELT with E-HIRES and E-MIDIR will be unique to explore the inner planetary-forming regions ($\leq$ 20 AU) and 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).

2.3 Water & Organics

The detection of water and OH radicals in the terrestrial planet-forming zones of protoplanetary disks has been recently evidence using the Keck/NIRSPEC instrument with high-resolution spectroscopy at L-band (Salyk et al. 2008). The E-ELT will directly explore the inner disk chemistry, the disk atmospheres, the physical transport of volatile ices either vertically or radially, and the importance of nonthermal excitation processes in the planet-forming regions. An instrument like E-MIDIR will offer a direct view of the distribution and the dynamics of water, playing a key role for the planetsimals formation and the disk cooling. It will also give clues on the organics content like CH4, C2H2, HCN in the planet-forming regions and the prebiotic chemistry. The study of isotopic fractionation should also enable 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.
2.4 Signposts of planets

Finally, the spatial resolution of the E-ELT will enable the detection of fine gaseous and dusty structures in protoplanetary and allow to directly witness the formation of giant planets. Possible hints of young forming planets in LkCa 15 (Kraus et al. 2011), TCha (Huélamo et al. 2011), HD142527 (Casassus et al. 2013) or HD100546 (Quanz et al. 2013) have been suggested. Recent imaged planets like Fomalhaut b (Kalas et al. 2008), HR 8799 bcde (Marois et al. 2008, 2010), β Pictoris b (Lagrange et al. 2010) or more recently Hd 95086 b (Rameau et al. 2013) are unambiguously associated with the presence of circumstellar disks. It is therefore clear that planets are likely formed in disks and interacting with them creating warps like in the case of the β Pictoris b planets (see Lagrange et al. 2012) or gaps and inner and outer belts like for the exoplanetary systems HR 8799 (Patience et al. 2011) or HD 95086 (Moór et al. 2013). Instruments like E-CAM, E-MIDIR and E-PCS will ideally probed with high-contrast imaging (contrasts from 10-5 to 10-9 down to 20 mas), from visible to mid-IR, the existence of giant and possibly massive telluric planets down to the snow line around young stars together with the disk structures and physical properties.

3 Exoplanets

As mentioned before, the E-ELT first Lights will arrive at a time where thousand of new planetary systems will have been discovered and characterized by a large set of instruments or space missions using different techniques like VLT/SPHERE or Gemini/GPI, ESA/GAIA, VLT/ESPERSSO, ESA/CHEOPS, NASA/TESS, JWST, potentially ESA/EChO or PLATO, 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...). The E-ELT instrumentation will therefore be mainly used for the fine characterization of known planetary systems, to explore the physical and atmospheric properties of known
Fig. 5. Indicative detection limits of forthcoming planet hunting instruments (SPHERE, ESPRESSO) and space missions (GAIA, TESS, CHEOPS) together with the E-ELT instruments E-HIRES, E-IFU, E-MIDIR, E-PCS.

planets, to study of the system’s architectures and dynamical stability, finally to search for lighter planets and possibly bio-signatures in their atmospheres.

3.1 Toward twin-Earth discovery

With the development of more precised high-resolution spectrographs, hundreds of exoplanets have been discovered and confirmed down to a few Earth masses (Mayor et al. 2011). We know now that planets are frequent around stars, more than 50% have planets, mainly dominated by the population of telluric planets. More recently, a plethora of transiting planetary candidates have been revealed by Kepler (more than 2300 candidates known today, Batalha et al. 2013), confirming the abundance of telluric planets in agreement with Doppler surveys in terms of occurrence at less than 0.25 AU (Howard et al. 2012). The new generation of spectrographs like ESPRESSO at VLT or transit space missions will enable to extend our knowledge of the physical properties of the icy and telluric planets population. With a required radial velocity precision of 1 cm.s$^{-1}$, E-HIRES will be the ideal instrument of the E-ELT to search for Earth-like planets around low-mass and solar-type stars in the Habitable Zone (region where water is expected to be liquid). At this level of precision, the main limitation of radial velocity is not only related to the spectrograph but also to the stellar noise induced by the stellar activity (oscillation, granulation, convection; Lagrange et al. 2010). The discovery of twin-Earth with E-HIRES will therefore require both a well defined sample of bright, relatively quiet stars and a dedicated observing strategy to discriminate the planetary signals from the various sources of stellar activities.
3.2 Imaging New Worlds

The breakthrough discoveries of closer and/or lighter planetary mass companions like Fomalhaut b (Kalas et al. 2008), HR 8799 bcde (Marois et al. 2008, 2010), β Pictoris b (Lagrange et al. 2010) or more recently κ And b (Carson et al. 2012), HD 95086 b (Rameau et al. 2013) and GJ 504 b (Kuzuhara et al. 2013) confirmed that we are just initiating the characterization of the outer part of planetary systems between typically 5 – 100 AU (see Figures 5 and 6). In the coming decade, thousands of new planetary systems detected with SPHERE, GPI, GAIA and TESS offering a plethora of systems to be imaged with the E-ELT with a unique spatial resolution (10 mas at K-band). The E-ELT sensitivity will enable to detect the emitted and reflected light of close-in giant to super Earths planets to constrain albedos, luminosity, effective temperature, surface gravity, composition, cloud coverage in addition to the planets orbital properties. Observing techniques like direct imaging and radial velocity will probably overlap for the first time in the planetary mass regime to simultaneously determine the true mass and the luminosity of imaged planets. It will therefore set fundamental constraints on the gas accretion history of giant planets, therefore their mechanisms of formation and evolution.

3.3 Planetary Atmospheres

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 HD209458 (Charbonneau et al. 2002) or HD 189733 (see Figure 7, Left). Such observations have been reported now for over 30 exoplanets to date, including hot Jupiters, hot Neptunes (e.g. Stevenson et al. 2010), and even super-Earths (Demory et al. 2012). 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 (Seager & Deming 2010). More recently, VLT observations with CRIRES at high-spectral resolution 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 (Brogi et al. 2013). At wide orbits, high-contrast spectroscopy has also enabled to initiate the characterization of non-strongly irradiated giant planets like HR 8799bcd (Janson et al. 2010; Konopacky et al. 2013). In that perspective, E-HIRES and E-MIDIR will be perfectly adapted to acquire transit and secondary eclipse low-resolution spectroscopy of exoplanets down to telluric masses, i.e. to obtain spectra in transmission or emission of short-period exoplanets. The multiplexing capability of E-MOS might also help for correcting for atmospheric and instrumental biases with simultaneous observations of reference stars. The high spectral resolution of both E-HIRES and E-MIDIR will allow the application of spectral cross-dispersed technique to directly resolve the planetary lines and to search for the signatures of CO, CO2, H2O, CH4 and even even O2 or O3 molecules (see Figure 7, Right; Snellen et al. 2013). One might expect to get constraints on the structures and dynamics to constrain the processes of inversion, vertical mixing, circulation and evaporation of the planetary atmospheres of giant and telluric planets. At longer periods, instruments like E-CAM, E-IFU, E-MIDIR and ultimately E-PCS will offer a complementary view using high-contrast spectroscopy to directly resolve the photons of the non-strongly irradiated exoplanets, more similar to the giant planets of our own Solar system. The study of the atmosphere composition relative to the stellar one will be precious to constrain the formation mechanisms of these planets (currently debated). Finally, the ultimate and very challenging goal will be the detection of bio-signatures like O2 or O3 on telluric planets possibly with E-HIRES, E-MIDIR or E-PCS.

4 Conclusion

The E-ELT will be an incredible machine for the study of Jets, outflows, disks and exoplanets. A unique spatial resolution and sensitivity, combined with a versatile instrumentation,
will undoubtedly lead to breakthrough discoveries regarding the study of the star-disk interaction processes, the circumstellar disk structure, composition and chemistry, the study of the planet-forming zones, the giant and telluric exoplanets characterization to ultimately detect bio-signatures and unveil the favorable conditions for Life.

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