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Activity of OU6, PCS: E-ELT Planet Finder

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Abstract. We describe the activities of the T-Rex Operating Unit (OU) 6, related to the Planet Finder instrument PCS for the E-ELT. They included the update of the science case of PCS, and in particular the assessment of the detection capability of PCS using Monte Carlo simulations; the development and application of high contrast imaging techniques based on experience with SPHERE, the new high contrast imager for the VLT; the combination of high spatial and spectral resolution; and further acquisition of competence in the scientific design of High Contrast Imagers.

Key words. Instrumentation: high contrast imagers

1. Introduction

Search and characterization of extra-solar planets is a major topic of modern astrophysics. We would like to answer many important questions concerning planet formation (how planets form? Why planets have different masses and separation from the stars? What is the impact of disk-planet interactions? How the environment impacts planet formation?), their early evolution (What is the evolution of young planets? How are their atmospheres made and what are their chemical composition? What is the impact of planet-planet interactions?), and more in detail how many habitable planets do exist (How common are rocky planets in the habitable zone? What is the structure of small mass planets? What is the composition of their atmospheres? Are we able to detect biosignatures?). The E-ELT is expected to have a major role in this field.

Different techniques are expected to provide main contributions answering differing questions. For instance, masses for most planetary systems can only be obtained from indirect techniques such as radial velocities and astrometry. On the other hand, information about the planetary atmospheres can only be obtained through spectro-photometric techniques such as observations of transits or direct imaging of planets. In addition, explorations of various regions of the systems also require to use various approaches. Table 1 gives our view of the issue: we considered different kind of problems and for each of them we considered which technique is most likely to provide most information at different distances from the star. It should be remarked that the column subdivision in this Table is appropriate for solar-type stars. For less-luminous stars, (old, small-mass) planets are expected to be cooler at the same separation from the star so that techniques that for solar-type stars are mainly useful for hot planets becomes applicable also closer to the snow-line. The opposite holds for more luminous stars. With this caveat, Table 1 can be used to clarify where E-ELT imaging contribution to extra-solar planet science

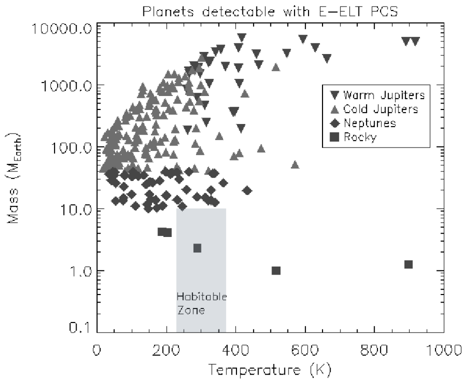

Fig. 1. Planets expected to be detected with E-ELT PCS according to the simulations with MESS in the mass vs. temperature plane. Different types of planets are marked with different symbols. The area of planets that can host life is shoen. For details, see Bonavita et al. (2014).

is expected to be more important: it mainly concerns the intermediate region close to or slighter inner than the snow-line. This is indeed a very interesting region of planetary systems because it is the region where we expect that life-friendly conditions are most likely.

2. Update of the science case of PCS

We used the MESS Monte Carlo program (Bonavita et al. 2012) to update the science case of PCS by re-considering its detection capability considering new estimates of the achievable contrast, as well as developments in our understanding of the planet frequency. MESS (Multi-purpose Exoplanet Simulation System) compares expected properties of a population of exoplanets with detection limits for different instruments, using various techniques (imaging, RV, astrometry, transits). MESS has been applied to different high-contrast imagers that are or will be available in the next future. Figure 1 shows an example of the results of these simulations for the case of the PCS. Table 2 summarizes the number of planets expected to be discovered by future instruments. Within this decade, we expect that high contrast imagers will provide mainly data on young giant planets, whose luminosity is mainly due to their young age and large mass. Discovery of planets shining through reflected stellar light, such as the Earth, should wait ELTs or space instruments. These results have been presented at various meetings (Exoplanets with the E-ELT, Garching, February 2014; Exoplanets, Biosignatures and Instruments, Tucson, March 2014: Bonavita et al. 2014).

3. Development and application of high contrast imaging techniques

A major activity has been the development of new high-contrast imaging techniques and their application to the case of SPHERE, the new high-contrast imager for the VLT (Beuzit et al. 2008). SPHERE has been commissioned during 2014 and is now available to the all ESO users. SPHERE is a complex instrument, including a common path providing very stable pupil and field imaging, a high-order AO system (SAXO: Fusco et al. 2006), various coronagraphs (Boccaletti et al. 2008), and three scientific instruments: two for the NIR (the dual band imager IRDIS: Dohlen et al. 2008; the integral field spectrograph IFS: Claudi et al. 2008) and one for visible wavelengths (the ZIMPOL system for dual band image polarization analysis; Schmidt et al. 2012). INAF has been responsible for the design and realization of the IFS, including the algorithms for calibration and data analysis to be included in the reduction pipeline, and for the instrument control software. The IFS allows use of various techniques for differential imaging (angular differential imaging, ADI; spectral differential imaging: SDI; speckle deconvolution: SD; principal component analysis: PCA), allowing a substantial boost in the contrast achievable with SPHERE. The relevant algorithms may readily apply to an IFS on the PCS, and this is then a preparatory activity for E-ELT.

While the basic concepts for these differential algorithms have been developed by other groups, our activity consisted in preparing software procedures that exploit them in the particular case of SPHERE. This included development of of calibration procedures and algorithms allowing a precise registering of the

Table 1. Schematic of methods goal

Issue	Hot planets (P~days)	<snow-line (P~1 yr)	>snow-line (P~several yr)
Discovery: detection and statistics	Radial Velocities Transits	Radial Velocities Space Astrometry Microlenses **E-ELT imaging**	8m imaging
Dynamical characterization and structure	Radial Velocities + Transits	Radial Velocities Space Astrometry **E-ELT imaging**	Coupling 8m imaging and Space Astrometry
Atmospheric characterization and search for biosignatures	Transits: Duration Transmission spectroscopy Secondary Transits	**E-ELT imaging**	8m imaging and JWST ELT Mid-IR

Table 2. Planets expect to be discovered in the next 15 years with foreseen imagers

Imagers	Year	Young	Reflected light planets			
		Giants	Giants	Neptunes	Rocky	Habitable
Ground Based 8 m	2013	tens	few			
JWST	2018	tens	few			
1.5m Space Coronagraphs	?	tens	tens	tens	few	??
ELTs	>2020	hundreds	hundreds	tens	few	??

datacubes that are then used in the differential imaging, and the writing of the routines. Also, several instrumental effects should be taken into account in order to obtain best data. Early work based on the test data acquired during assembly of the instrument in Europe is described in Zurlo et al. (2014) and Mesa et al. (2015). We continued this activity, with special attention to a proper handling of the cancellation effect inherent to differential imaging and to the transformation of instrumental signal into physical units during instrument commissioning. A large number of papers is being prepared from the early on-sky data obtained with SPHERE and will soon be published. SPHERE has been a very successful instrument: on-sky performances compares very well with the specifications defined in its top level requirements. In particular, SPHERE is able to achieve a contrast of better than 10^6 at a separation of 0.5 arcsec from bright stars. As expected, IFS allows better contrasts at short separations thanks to the large number of spectral channels that allows full exploitation of the various differential imaging techniques. In the E-ELT perspective, this represents an important step demonstrating the possibility to design and construct high-contrast imagers that fully compliant on-sky the performances expected from initial instrument modelling. The experience we are acquiring on SPHERE will be extremely precious for the design and implementation of the E-ELT PCS.

4. Other activities

Other activities within OU6 concerned mainly two issues. First, we are developing a collaboration with the group led by I. Snellen at Leiden Observatory to study the combination of high spatial and spectral resolution. Early results by that group showed that this is a very promising technique for bright targets (Brogi et al. 2012; Snellen et al. 2014, 2015) possibly achieving a contrast better than 10^7 on 8-meter telescopes. The study of the Leiden group started from simple consideration of the potential of high resolution spectroscopy for detecting the faint signal by planets (which have spectra dominated by multi-atomic molecules) over-imposed to the bright signal of the stars (whose spectra are dominated by atomic lines) using a cross-correlation technique. Multi-atomic molecules produce a very rich spectrum and the cross correlation technique allows to combine the signal from many lines to produce a detectable signal in spite of the high contrast. Noise in this technique is due to the very bright stellar background and there is then a substantial gain in applying this method to high-contrast images, where the stellar background can be suppressed by several orders of magnitude. We (V.D.) are then considering the implementation of a combined high contrast-high spectral resolution method to E-ELT where, in principle, contrasts up to 10^{10} could be reached, allowing to probe the habitable zones around late-type dwarfs. We are also considering the possibility to realize a prototype on an 8m telescope (in particular on LBT).

Another area where we are working is further acquisition of competence in the scientific design of high contrast imagers. The rationale behind this is to prepare young people having competence in this area, in consideration of the long timescale required for the realization of PCS. V.D. has become the instrument scientist for the near-IR arm of SHARK (System for coronagraphy and High-order Adaptive optics from R to K band: Farinato et al. 2014, 2015), the new visible and near-IR high contrast imager that is in course of advanced design for the LBT. By exploiting the outstanding extreme AO capability at LBT (and the forthcoming upgrades), SHARK will investigate several fundamental topics, such as e.g. direct imaging of planets in wide orbits around late-type stars in star forming regions and associations (e.g. Taurus), complementing information obtained in the southern hemisphere by SPHERE and GPI. Moreover, photometric and spectroscopic characterization will be carried out, allowing for instance to define the L/T transition from IR-colours. Finally, other science cases will be addressed, from the study of circumstellar disks and jets around young, pre-main sequence stars up to QSOs and AGNs.

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