EPICS: direct imaging of exoplanets with the E-ELT

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ABSTRACT

Presently, dedicated instruments at large telescopes (SPHERE for the VLT, GPI for Gemini) are about to discover and explore self-luminous giant planets by direct imaging and spectroscopy. The next generation of 30m-40m ground-based telescopes, the Extremely Large Telescopes (ELTs), have the potential to dramatically enlarge the discovery space towards older giant planets seen in reflected light and ultimately even a small number of rocky planets. EPICS is a proposed instrument for the European ELT, dedicated to the detection and characterization of Exoplanets by direct imaging, spectroscopy and polarimetry. ESO completed a phase-A study for EPICS with a large European consortium which - by simulations and demonstration experiments - investigated state-of-the-art diffraction and speckle suppression techniques to deliver highest contrasts. The paper presents the instrument concept and analysis as well as its main innovations and science capabilities. EPICS is capable of discovering hundreds of giant planets, and dozens of lower mass planets down to the rocky planets domain.

Keywords: E-ELT, high-contrast imaging, adaptive optics, exoplanets

1. INTRODUCTION

The Exoplanet Imaging Camera and Spectrograph (EPICS) is an instrument project for the direct imaging and characterization of extra-solar planets with the European ELT (E-ELT). EPICS will be optimized for observations in the visible and the near-IR and will have photometric, spectroscopic and polarimetric capabilities.

The E-ELT is currently going through a phase-B study which will result in a proposal for construction which will include an instrumentation plan with the list of first generation instruments. The choice of instruments will be guided by the high priority scientific objectives as described in “An expanded View of the Universe”[1]. The most prominent science cases selected by the SWG - Exoplanets among them - have been studied as part of the Design Reference Mission (DRM, http://www.eso.org/sci/facilities/eelt/science/drm/).

The EPICS phase-A study is one of these E-ELT instrument studies and has been kicked off in October 2007. Among the goals of the EPICS phase-A concluded in March 2010 are: demonstration of instrument feasibility, derivation of requirements to the E-ELT and its site, and provision of feedback to the DRM. The EPICS phase-A study was funded in parts by ESO and by the European Framework Programme 7 (FP7), E-ELT preparatory activities, through WP 9400 and WP 6003.

2. SCIENCE OBJECTIVES AND REQUIREMENTS

By about 2015, radial velocity surveys and the Kepler satellite will have provided a very good statistical answer to the crucial question of how frequent exoplanets in close orbits are around main sequence stars. These data will be complemented by the VLT SPHERE[2] and Gemini GPI[3] planet-finding instruments for self-luminous giant planets in outer orbits around young stars. Spectroscopic data are being obtained for transiting planets and additional data will be obtained for self-luminous giant planets. However, with the current and planned space instrumentation, the capability to study the physical properties of exoplanets comprehensively, and in particular their chemical composition, remains limited. The contribution of EPICS will be unique and transformational in various areas of exoplanet research:

- Detection of low-mass and wide orbit planets to explore the unknown regions of the mass-orbit function. EPICS is much more efficient in detecting Exoplanets at angular separations larger than several AU than other techniques (e.g. transits with Kepler and Plato; radial velocities with CODEX[4]) that need to follow an orbit.
- Characterization of Exoplanets down to rocky planets by direct imaging, spectroscopy and polarimetry. Virtually all nearby Exoplanets detected by radial velocity or astrometric techniques can only be characterized in larger numbers by direct imaging, since the probability for transits is low at large orbital separations and transit spectroscopy also needs a fairly low Expolanet/Star contrast of the order 10^{-5}, again limiting the method to rather tight orbits.
- Detection of very young planets (age ~10^7 yr or less) close to the ice-line to test planet formation and evolution models and to understand the processes driving planet formation. Only EPICS will provide access to the small angular separations (~30-50 mas) required to observe giant Exoplanets forming at the ice-line around pre-main sequence stars of the closest star forming regions and young associations. Space telescopes have too low angular resolution, RV suffers from stellar noise of the active young stars and from the long time frames needed to follow a 3-5 AU orbit at the ice-line, and the probability to catch a transit event of an object orbiting at the ice-line is virtually zero.

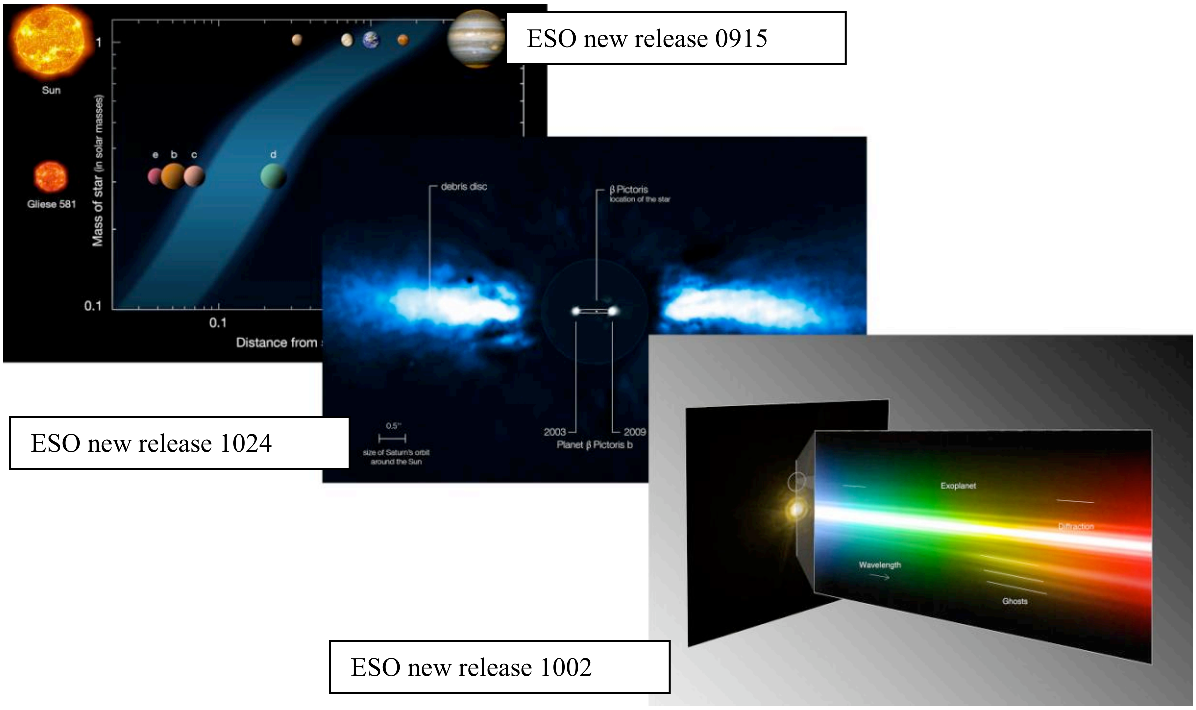


Figure 1. Upper left: Inner part of the Solar and Gl 581 planetary systems (eso0915 - News Release, GJ 581, Major et al.). Middle: Composite image of Beta Pic b and the disk (ESO Science Release 1024, Lagrange et al. 2010). Lower tight: Spectrum of the planet HR 8799c (ESO News Release 1002, Janson et al. 2010).

In addition, EPICS will make optimal use of the unique light collecting power and angular resolution provided by the E-ELT. Its spectroscopic and polarimetric capabilities, as well as the AO performance providing diffraction limited images even at optical wavelengths with angular resolution down to 5 mas, will have a substantial impact on a large variety of astrophysical fields from the solar system and disks to stellar astronomy and physics. Differential polarimetry at optical wavelengths will allow us to image circumstellar debris disks several orders of magnitudes fainter than the ones around βPic or HR 4796 at 10 mas resolution to study the dynamic interaction of the disk with embedded Exoplanets.

In order to deliver these science goals, EPICS fulfills the following main requirements:

- The systematic intensity contrast of the instrument is better than 10^{-8} at 30 mas and 10^{-9} beyond 100 mas angular separation.
- Spectroscopic and polarimetric imaging, as well as medium resolution spectroscopy (R~3000) for the spectral characterization of Exoplanet chemistry is provided.
- The spectral range covers the optical to the NIR between 600 and 1650 nm.

3. CONCEPT

3.1 Design drivers

The key to achieving highest imaging contrast and sensitivity from the ground is a superb correction of the dynamic and quasi-static wavefront aberrations introduced by Earth's atmosphere and the telescope/instrument, respectively.

In order to correct for dynamic aberrations and to suppress the atmospheric turbulence residual halo to about 10^{-5} at small angular separations and to better than 10^{-6} close to the AO correction radius, EPICS implements a SCAO wavefront sensor (WFS) driving the E-ELT M4 through its telescope control software (TCS) followed by an XAO system using a roof-Pyramid WFS.

All optics moving or rotating during an observation, such as atmospheric dispersion compensators or optical de-rotators, will be seen by XAO and instruments, i.e., they will be placed in the common path. Hence, EPICS will have excellent temporal stability of instrumental aberrations.

Non-common path optical aberrations will be calibrated by focal plane wavefront sensing techniques and off-loaded to the XAO system. The diffraction pattern will be suppressed by apodizers and coronagraphs. As a result EPICS will achieve a high quasi–static PSF contrast of better than 10^{-6}.

XAO and quasi-static PSF residuals are further calibrated and removed through instrumental and data analysis techniques such as spectral deconvolution with the NIR IFS and differential polarimetry with the optical polarimeter EPOL. These techniques will provide the required systematic contrast of the order 10^{-8} at 30 mas to better than 10^{-9} at larger angular separations. This last step of PSF residuals calibration will be made possible through an optimization of the instrument optics for maximum efficiency of the speckle calibration techniques:

i. A small and well-known speckle chromaticity is provided by minimizing amplitude aberrations introduced by the Fresnel propagation of optical errors, and
ii. A small instrumental polarization is provided by avoiding large angle reflections and a careful choice of coatings.

3.2 Optical-mechanical design

Figure 2 outlines the EPICS optical design. About 4.7 meters behind the Nasmyth focus, the beam is collimated by the M7 parabola. A gray beam-splitter (BS1) sends about 10% of the light to a first stage SCAO modulated Pyramid WFS which commands the telescope M4 through the telescope control software (TCS) and reduces turbulent aberrations to levels that the high order deformable mirror can cope with. The flat folding mirror TTM (M8) will be controlled by the XAO WFS and provide fast tip-tilt correction. The high order deformable mirror (M9) is a 211x211 actuator stacked piezo DM with 1.27 mm inter-actuator pitch and 3 μm mechanical stroke. EPICS will use a 3-glass ADC in the common path leaving very low chromatic residuals (< 1 mas PTV by design) over the operation bandwidth between 600 nm and 1650 nm. The dichroic BS2 reflects wavelengths shorter than 900 nm to the optical arm and transmits the NIR.

The NIR arm hosts an apodizer and zoom optics to provide an f/140 focus on the input of the IFS. The whole optical train up to the IFS input focus consists of optical components that are located in or close to the pupil plane to avoid mixing of phase into amplitude errors. Following this philosophy, diffraction suppression is achieved by amplitude apodization only. This solution is preferred over a coronagraph which would require a mask or some sort of re-imaging optics near the image plane. In order to attenuate the stellar light and to reduce problems with ghosting, stray light or detector saturation, a mask will be placed in the entrance image plane of the IFS.

Entering the optical arm, the light hits either a fully reflecting mirror for use with the IFS, or another gray beamsplitter (BS3) that reflects 15% of the light towards the XAO WFS and transmits the rest to the differential optical polarimeter EPOL. The EPOL measurement concept is intrinsically achromatic, so an apodized Lyot coronagraph efficiently suppresses diffraction. The EPICS optical design minimizes the number of reflective optics at large inclination angles introducing instrumental polarization and foresees calibration devices for those that cannot be avoided such as the telescope's M4 and M5 mirrors.

The major design guidelines (optics close to pupil plane and normal incidence) are hardly compatible with a K-mirror for optical de-rotation, so EPICS does not implement one. However, de-rotation of the IFS field will be needed for its pseudo long-slit high spectral resolution mode. Also the Lyot stops, the XAO DM, and the WFS implement de-rotation to keep them aligned with the E-ELT pupil.

A calibration unit near the Nasmyth focus will provide the means required for calibration of XAO and instruments.

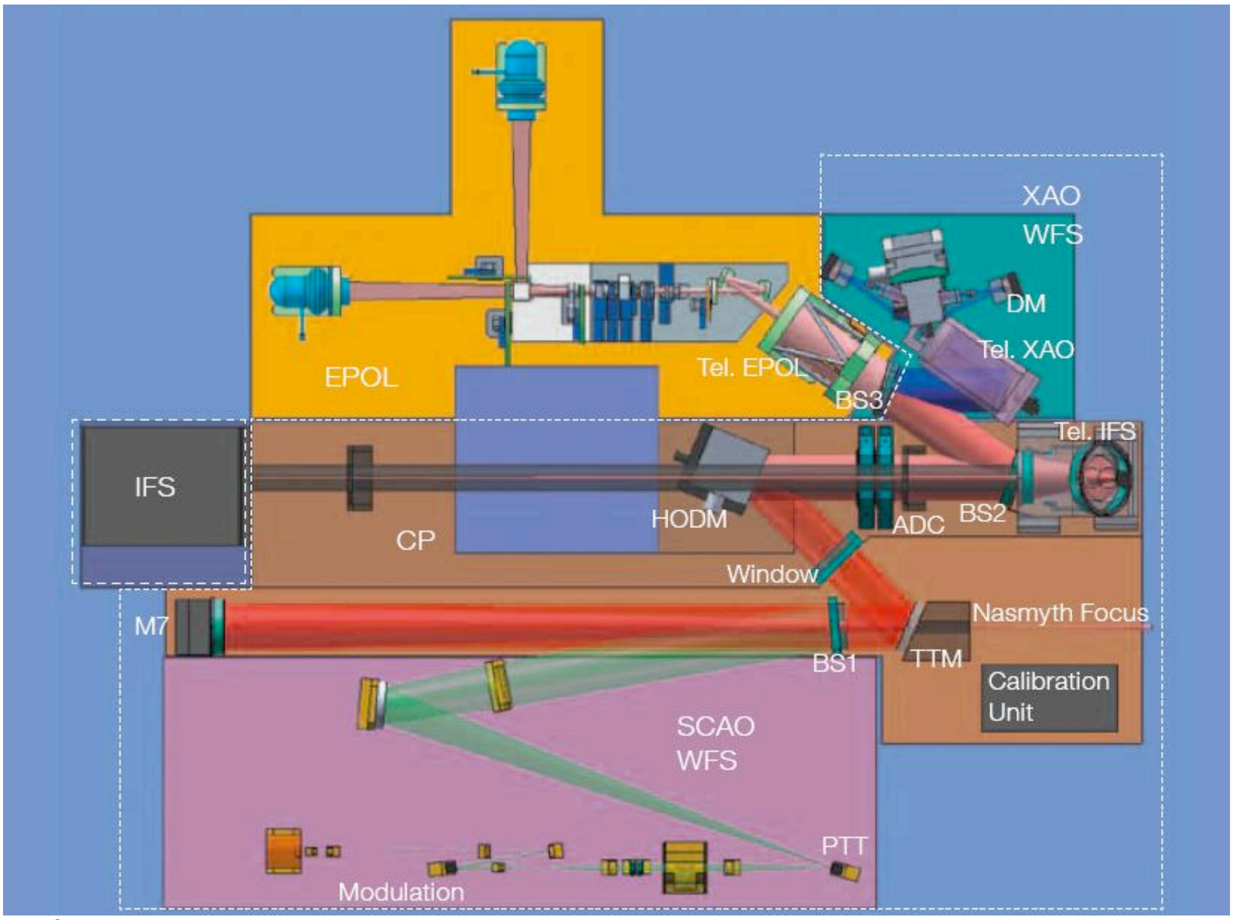


Figure 2. Top view of EPICS' opto-mechanical concept

3.3 Instruments

The baseline instrument suite for EPICS consists a lenslet-based NIR IFS and a differential optical polarimeter.

The IFS will provide a field of view (FoV) of 0.8″ x 0.8″ sampled by 2.33 mas SPAXELS at the diffraction limit ($\lambda/(2D)$ at 950 nm). The spectral range is 950-1650 nm, and the average 2-pixel spectral resolution is 124.6 in the main observing mode. In addition, the IFS offers two higher spectral resolution modes, one with R~1400 and one with R~20.000. These modes will provide only a smaller slit-like FoV of 0.8″ x 0.014″.

EPOL[13] is the visible-light (600-900 nm) coronagraphic imaging polarimeter in EPICS. A polarization modulator system converts the polarization signal into intensity modulation which is recorded by a demodulating detector system. The differential intensity measurement between the two modulator states then provides the polarization signal. Much of EPOL's design heritage comes from SPHERE/ZIMPOL[17] with the main difference that the driver behind the two-beam system is not photon-collection efficiency but the removal of differential aberrations by simultaneously observing both polarization states for each of the two polarization modulation phases. EPOL provides a FoV of 2″ x 2″ sampled by 1.5 mas SPAXELS at the diffraction limit ($\lambda/(2D)$ at 600 nm) and various astronomical filters.

4. PERFORMANCE AND SCIENCE ANALYSIS

In order to design EPICS and evaluate its performance considering as many as possible real-life error sources, the following tools were developed: i) an end-to-end model of the instrument called PESCA (Parallel EPICS Simulation Codes and Applications)[5] and ii) a Monte-Carlo code called MESS[6] to estimate the scientific output.

4.1 System performance

PESCA models the complete chain from atmospheric turbulence including AO error terms, over the telescope with its segmented primary and large M2 support structure, to the instrument with quasi-static aberrations and diffraction suppression systems and spectral deconvolution using a Fresnel propagation code.

Figure 3 shows the PSF contrast delivered by the XAO system together with the various contributors to the error budget. The error budget is well balanced providing a contrast level of 10^{-6} at 0.1″ separation for the conditions described in the caption.

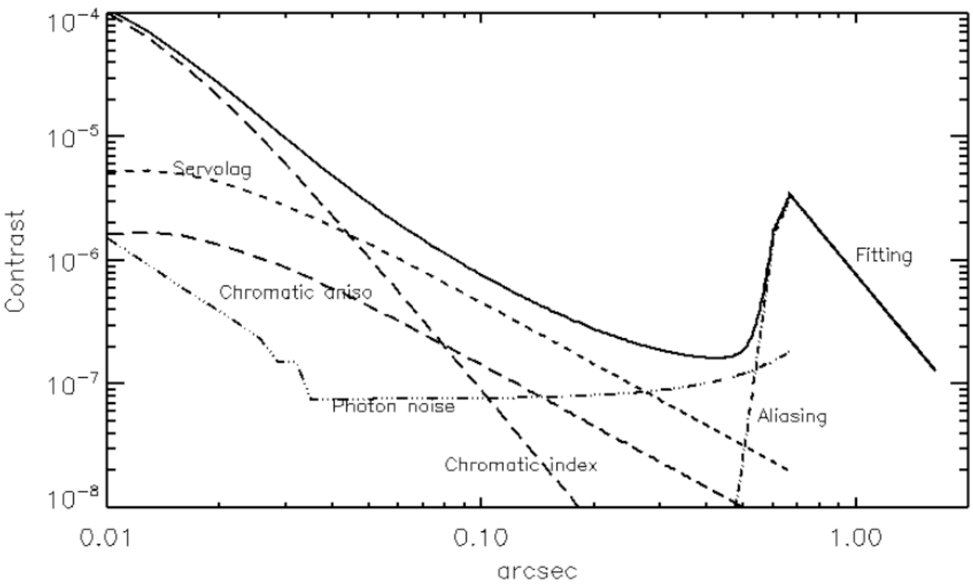


Figure 3. AO residual halo contrast. I=6, 0.85″ seeing, 30 deg zenith distance, λ = 1.3 μm.

Combining the XAO residuals with assumptions on object brightness, E-ELT wavefront and amplitude errors and pupil geometry as well as instrument aberrations, throughput, diffraction suppression systems and data analysis, PESCA provides final contrast curves such as the ones shown in Figure 4.

The PESCA results demonstrate that EPICS is pushing the systematic limits below the photon noise level for virtually all possible targets with the IFS and EPOL. It therefore achieves photon noise limited contrast levels of the order 10^{-9} at separations around 0.1″ required for the efficient detection of illuminated Exoplanets.

The lower number of photons available for EPOL when compared to the IFS (planet polarization <30%, smaller spectral bandwidth) and the higher AO residuals at optical wavelengths make EPOL less sensitive than the IFS at larger angular separations. The shorter wavelength and the efficient apodized Lyot coronagraph, however, allow EPOL to achieve high contrast at the smallest angular separations down to 10 mas.

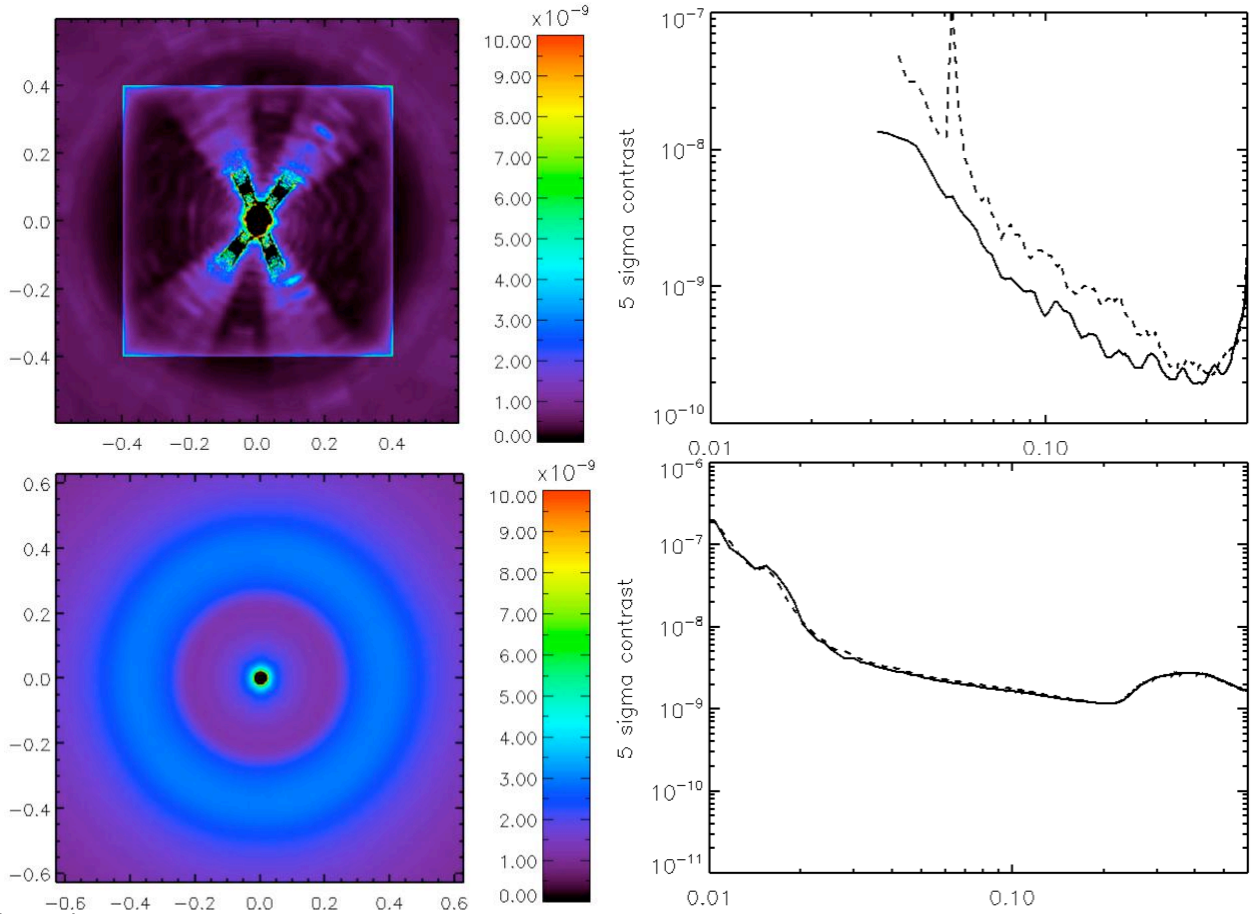


Figure 4. 2D contrast maps (contrast color coded, X- and Y-units are arcseconds) and cuts along x-y for I=2.3 G2 star (10H exposure, field rotation) for the IFS (top) and EPOL (bottom).

4.2 Science analysis

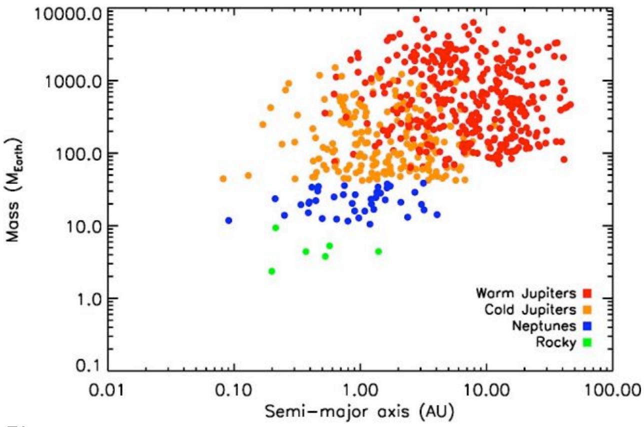
The PESCA contrast curves are then used to analyze the discovery space for EPICS using the Monte Carlo code MESS that compares expected properties of a population of Exoplanets with the detection limits. MESS models stellar parameters (mass, distance, age, etc.) from samples of real stars, and models planet populations using theoretical models and observational results.

Table 1 and Figure 5 show the EPICS detection rates predicted by MESS applied to a large sample of more than 1000 nearby or young stars. While the IFS generally achieves a better photon-noise limited contrast and has higher detection rates on Neptune-like and Giant Planets, the very small inner working angle of EPOL allows it to detect several rocky planets that cannot be accessed by the IFS.

Besides the detection capabilities of IFS and EPOL, the two instruments are also highly complementary in their characterization capabilities and offer a variety of secondary science cases, e.g. the observation of circumstellar debris disks with EPOL at highest angular resolutions. Moreover, an independent detection by the IFS and by EPOL virtually excludes false alarms such as background stars immediately and greatly increases the level of confidence.

Table 1. Expected number of planet detections with EPICS predicted by MESS.

Group	Expected detections				
	Mp>300 M_{Earth}	100<Mp<300 M_{Earth}	40<Mp<100 M_{Earth}	10<Mp<40 M_{Earth}	Mp<10 M_{Earth}
IFS	362	147	107	41	6
E-POL	79	50	55	55	19



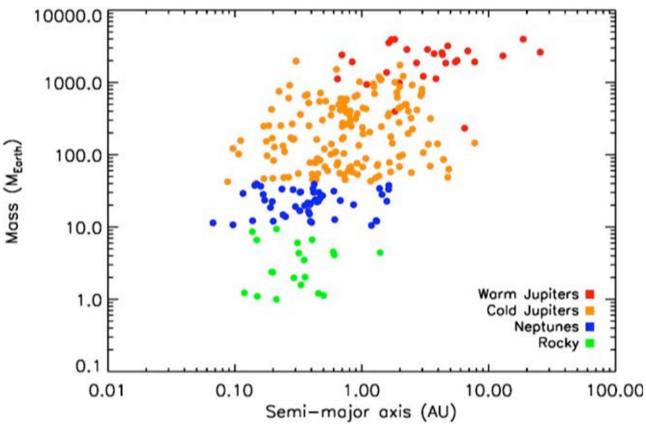


Figure 5. EPICS detections predicted by MESS for the IFS (left) and EPOL (right).

MESS is a versatile tool that is very valuable for evaluating the impact of instrument parameters on the scientific output. For instance, MESS can be used to prioritize targets and design reasonably small surveys tailored to a particular scientific question.

4.3 Rocky planets in the habitable zone – the case of Gliese 581d

Gliese 581 d is an Exoplanet orbiting the star Gliese 581 approximately 20 light-years away in the constellation of Libra. Because of its mass, between 7 and 14 times that of Earth, the planet is classified as a super-Earth. Gl 581d is probably a tidally locked habitable super-Earth near the outer edge of the habitable zone[7,8]. Despite the adverse conditions on this planet, at least some primitive forms of life may be able to exist on its surface.

Figure 6 demonstrates that Gliese 581 d, a rocky planet in the HZ with a separation of 35 mas and an approximate contrast ratio to the star of about 2.5 x 10^{-8}, would be readily observable with the EPICS IFS in about 20 hrs.

The EPICS contrasts shown in Figure 4 (top row) would in principle even allow for the detection of an Earth analog around a G2 star at 5pc (1AU corresponds to 0.2″ angular separation). However, there are only a handful of stars that are bright enough to be observed at ~2e-10 contrast, αCen being the most promising.

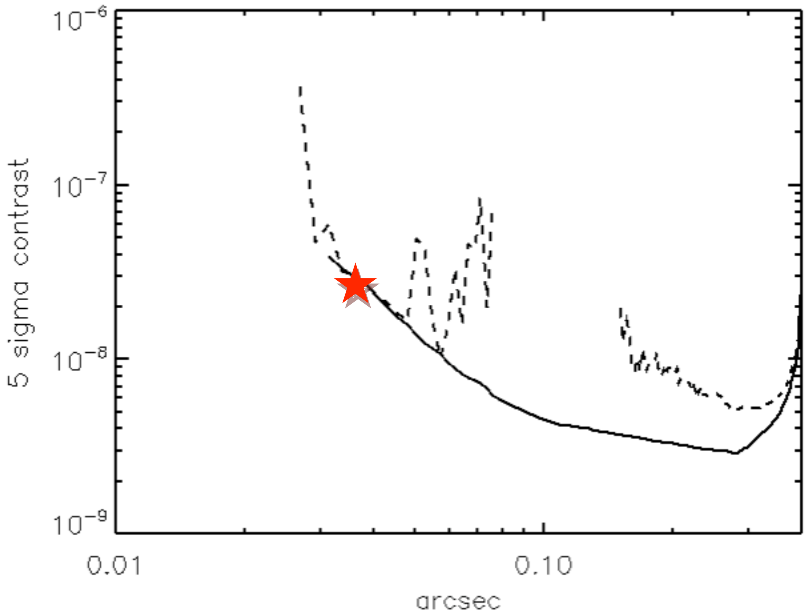


Figure 6. Contrast for an I=8 M3 star, representative of Gliese 581 (20h exposure, 1h field rotation). Angular separation and approximate contrast of Gliese 581 d are provided by the star.

5. CONCLUSION

Most concepts used for high-contrast XAO imagers have been tested successfully in the laboratory or on-sky. Integrated systems combining these concepts are currently being built for the VLT (SPHERE) and Gemini (GPI) and will see first light in 2011. For EPICS, the high-order DM and RTC present the main technological and cost risks. While there appears to exist a possible concept for the RTC[9], the DM requires an aggressive technological development program.

The EPICS phase-A study developed the science requirements and an instrument concept that fulfills those requirements. Very detailed modeling taking into account as many as possible real-life errors and expected telescope properties such as segment phasing and gaps confirmed the feasibility of the chosen approach. Within the EPICS phase-A study, plenty of activities aiming at the demonstration of the various concepts have been started and partially completed[10,11,12,14,15,16]. Further work is planned in the near future, mainly on wavefront control (XAO WFS and speckle nulling) using ESO's high-order testbench (HOT), as well as on technology developments of the deformable mirror and the RTC.

The time required to build EPICS is estimated to last 6-7 years, such that the instrument could be ready by the end of the coming decade assuming a project start some time in 2013.

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