The EPICS project: Exoplanets detection with OWL

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Abstract. This paper presents the status of the EPICS project, an Earth-like Planets Imaging Camera Spectrograph for OWL. We present the Top-Level-Requirements of the instrument and we describe the baseline of the Adaptive Optics system with optimized wave-front sensor. The expected performance in rejection of starlight in the near infrared and in the visible is given. The instruments concepts for detection and characterization of exo-planets will be briefly described. The Signal-to-Noise ratio estimation shows that Earth-like planets can be detected up to 20 pc in a reasonable amount of time. The extremely challenging requirements in terms of static residual errors and differential aberrations are discussed.

Keywords. planetary systems, adaptive optics, high angular resolution.

1. Introduction

This paper describes the status of the Earth-like Planets Imaging Camera Spectrograph (EPICS) for OWL. The EPICS project started in mid-april 2005, after the completion of the phase A studies of the Planet Finder project for the ESO Very Large Telescope (VLT), and is the result of the cooperation between the two competitive consortia. The core of the project is composed of an extreme Adaptive Optics (AO) system coupled with coronagraphs. Three instruments directly inspired from the VLT-PF conceptual design are briefly described and the expected starlight halo rejection is estimated. The Signal-to-Noise Ratio (SNR) for the detection of rocky planets and evolved gas giant planets

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is estimated. We emphasize that to achieve the 10^{-10} contrast needed for the primary science goal, the requirements in terms of instrumental static and differential aberrations will be extremely challenging.

2. Science case

One of the most ambitious science objectives of OWL is the detection and characterization of extra-solar systems in an advanced evolutionary stage, the understanding of the mechanisms of formation and evolution of planets, and possibly the discovery of other planets able to host life.

Rocky planets. The main goal of EPICS is the detection and characterization of rocky planets in the habitable zone (Kasting 1997). For characterization, we mean observation of a statistically significant sample of rocky planets, to understand the relation between rocky and giant planets, and to understand the main features of rocky planets physics. Based on the variety of atmosphere composition observed in the Solar system, it is expected that also the planets targets of EPICS will possess a wide range of atmospheric properties. Essentially, we consider at least four different classes of planets:

• Planets without atmosphere, or with a very thin atmosphere that does not produce significant features, like Mars. These are likely planets of either small mass and/or very close to the central star.

• Planets with atmospheres dominated by methane, like the giant planets in the Solar System. These are likely either massive and/or cold planets, able to maintain a substantial amount of H in their atmosphere

  • Planets with atmospheres dominated by carbon dioxide, like Venus

  • Planets with atmospheres dominated by oxygen, like the Earth

The three last classes of planets cited above have quite different spectra, both in the Visible and Near-IR, as well as in the Mid-IR. In the Visible-Near IR spectral range selected for EPICS, features due to H_2O, O_2, CH_4, and CO_2 are well represented. This should allow appropriate classification of the detected planets into the various classes defined above even from low resolution (survey type) spectra.

Evolved giant planets. EPICS will also permit a significant breakthrough in the detection and characterization of cold gas giant planets. The better contrast (the contrast of Jupiter at 5 AU is 10^{-9}) and larger separation, permits an easier detection, and opens the door to high resolution spectroscopy. In particular, radial velocity measurements and the analysis of atmospheric composition and dynamics of close-in giant planets will be possible. The contrast between a Jupiter mass planet at 0.5 AU and its star is around 10^{-7}, so roughly corresponding to the stellar AO residuals. For 10 pc distance from Earth, assuming a G2 star, its magnitude would be around 22.5 and the photon flux at resolution 50.000 would be about 0.5 photons per second and spectral bin (16% overall quantum efficiency). Therefore, a reasonably high SNR for the high resolution spectroscopy appears feasible in observing times of a couple of hours.

3. Top-Level Requirements

The detection of rocky planets with possibly Earth-like features is an extremely challenging goal for EPICS. The direct detection of exo-planets is made very difficult by the very high relative flux ratio from the star and planets orbiting it and their small angular separation. The Top-level requirements for the detection of Earth-like planets in the habitable zone can be expressed in terms of contrast requirement in function of the separation. We chose to restrict the targets for terrestrial planets to three spectral types,

G, K, and M, and investigated out to what distance one can find at least 100 stars of each type (see table below, Paranal latitudes $Z < 30$ deg.). This choice sets the limiting magnitude for adaptive optics as well as the minimum separation angle corresponding to the habitable zone.

Spectral type	Distance	V magnitude	Angular separation	Contrast
G	25 pc	7	40 mas	2.10^{-10}
K	20 pc	8	25 mas	8.10^{-10}
M	15 pc	10	15 mas	8.10^{-9}

4. Implementation concept

The core of the instrument is based on an extreme AO system of high performance that feeds three main instruments: a wave-length splitting Differential Imager, an Integral Field Spectrograph, a Differential Polarimeter. This choice reflects the concepts that have been developed for VLT-Planet Finder (Mouillet *et al.* 2004) (Gisler *et al.* 2004). Due to science goals that are significantly different from VLT-Planet Finder, the EPICS concept is based on somewhat different choices on the system level.

The EPICS concept should be compatible with the detection of both gas giants and rocky planets. Due to different locations of the spectral and polarimetric features of these two groups of planets, different channels split in the spectral domain are needed. Each scientific channel will be equipped with its own coronagraph.

• **The R band** [600–800 nm] is dedicated to the **Polarimetric Differential Imager** for detecting rocky planets and to the follow-up observations for the **detection of O_2**. The Differential Polarimeter for EPICS is directly based on the ZIMPOL concept (Gisler *et al.* 2004) proposed for the VLT Planet Finder. The main requirement is that the telescope polarisation remains low and relatively stable so that a suitable place can be found for the polarisation switch essential for calibration. Different possibilities are still under investigations.

• **The J band** [1100–1430 nm] will be equipped with a **Differential Imager** that will be sensitive to both CH_4 and H_2O absorption bands on a 4x4 arcsec field. The baseline is a dichroic based differential imager which main advantage is the high throughput and the possibility to implement 4 wave-lengths simultaneously. The most critical issue of this concept is the optical quality of the dichoics that should permit typically less than one nanometer differential aberration for the primary science goal requirements.

• **The H band** [1380–1800 nm] will be equipped with an **Integral Field Spectrograph**. The main features that can be detected in this band are CH_4 and CO_2 and H_2O. The EPICS IFS will operate on a 2x2 arcsec field with spectral resolutions per pixel from 15 to 30. Square and hexagonal shapes are studied in order to find a compromise between cross-coupling and size of the detector. A Fourier Transform Spectrograph is also being studied. This concept could have a better performance in terms of differential aberrations but has some other complications due to time dependent effects. One important advantage is that the spectral resolution can be adjusted from low resolution to very high resolution.

• **The I band** [800-1000 nm] is reserved for **wave-front sensing**. This band has been chosen because of the lesser scientific interest for planet detection. Moreover its location, spectrally speaking, between the visible and NIR instruments, is optimal with respect to important atmospheric chromatic limitations for extreme AO on ELTs.
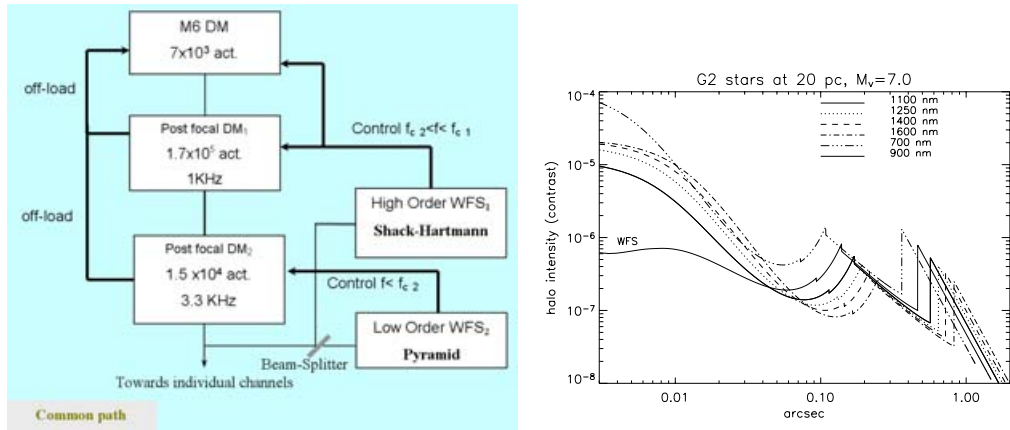
Figure 1. Left: EPICS XAO concept. Right: Halo intensity from AO residuals. Perfect coronagraph. Seeing:0.5 arcsec. Coherence time: 4 ms.

The EPICS ultimate contrast requirement is 4 orders of magnitude higher than the VLT-Planet Finder science goal of about 10^{-6} contrast at 0.1 arcsec. When scaling from a 10-m to a 100-m class telescope, the contrast naturally improves by a factor of 100 for a given rms value and power spectrum of the wave-front error. This means that the extreme AO system for EPICS should provide about 2 orders of magnitude better starlight halo rejection than a simply scaled version of the VLT Planet Finder system. This matter of fact calls for system specifications that are tremendously more stringent than for the VLT-PF project like a higher frame rate, low residual static errors and high sensitivity of the WFS for low to mid-spatial frequencies.

Adaptive optics. The EPICS XAO concept is displayed in Fig. 1. The OWL large adaptive mirror M6 is used for the correction of large amplitude and slow aberrations. The XAO system itself is based on a double stage. Two correctors in cascade each controlled by a WFS: a quad-cell Shack-Hartmann WFS controls a very high order adaptive mirror with 1.7×10^5 actuators (500x500 sub-apertures, $d_1 = 20$ *cm* inter-actuator distance as projected on OWL pupil) at 1 kHz. Using a fast Fourier reconstructor with modal control (Poyneer 2005), the correction is restricted only to the high spatial frequencies that are not corrected by the second stage. The latter is composed of a Pyramid WFS controlling a 1.5×10^4 adaptive mirror (150x150 sub-apertures, $d_2 = 65cm$) at 3 kHz. The main reason of this double stage comes from the computation time and CCD read-out time requirements and taking into account a projection at 10 years of future computing power availability. The advantages of this concept are the following:

• The Pyramid WFS is known to have a very low noise propagation for low spatial frequencies. Thus it favors a clean correction of the starlight halo at small angular separations (Verinaud 2005) where the most demanding contrast is required for rocky planets detection. A single stage with Pyramid sensor would have been ideal but revealed to be very demanding in terms of computing power required.

• The low number of sub-apertures of the Pyramid WFS (with respect to the SH WFS) permits a high frame rate for the read-out of the WFS CCD (300x300 pixels).

• Contrary to the Pyramid WFS, SH WFS-based systems can use fast algorithms for the reconstruction, allowing to control the high number of degrees of freedom of the first stage.

• The first stage SH-based system corrects only high spatial frequencies avoiding to propagate noise in the loop that would pollute the halo at small angular separations.

The corresponding theoretical Point Spread Functions for a perfect coronagraph at different wave-lengths are also represented in Fig. 1. One can notice three different regions: the innermost corrected by the Pyramid system, the intermediate corrected by the SH, and the outermost outside the corrected area. The main error sources affecting AO have been considered: servo-lag, photon noise, aliasing of pyramid sensor, static errors, anisoplanicity due to atmospheric differential refraction, chromatic seeing.

Coronagraphy. A special coronagraph has been designed for OWL (Yaitskova (2005)). It comprises a gaussian focal mask and several reticulated pupil stops that mimic the OWL segmentation gaps and follow their configuration during observation. The use of this system in double stage permits theoretically an almost perfect cancelation of the starlight. Micro-metric precision is needed for the alignment of the system. Apodized Lyot coronagraphs have also been considered (Soummer 2006).

5. Signal-to-noise ratio estimations

In this section the evaluation of the detection performance in terms of integration time needed to achieve a given SNR has been computed. The conditions of observations are :

• Differential detection, SNR=5, dual imaging either with DI or IFS and differential polarimetry (see also Schmid *et al.* (2006))

• Instrumental transmission 16%. Atmospheric transmission for altitude 4000-m: Transmission in H_2O band (40%) and in O_2 band (80 %).

• Seeing: 0.5 arcsec. $\tau_0 = 4\ ms$, AO residuals photon noise and speckle noise (perfect coronagraph).

The integration times needed for a 5σ detection are displayed in Fig. 2. H_2O (as in Earth-like planet) and CO_2 (10 % concentration) are detected in a couple of hours at 10 pc and in about one to two nights of observation at 15–20 pc. For the same amount of time Jupiter-like planets can be detected in CH_4 bands with a SNR of 50. Follow-up observations can be foreseen for O_2 detection in Earth-like planets (Fig. 2 bottom left) but require several tens of hours at 5–10 pc to several hundreds of hours at 20 pc. This amount of time, even if large, is probably not prohibitive regarding the philosophical impact such a detection could have. Planets without strong markers in CH_4, CO_2 and H_2O but with a high degree of polarisation could also be detected in the R band with the differential polarimeter (bottom right).

6. The challenge of systematic errors control

The instantaneous contrast delivered by the AO and the coronagraph will at best only be of about 5×10^{-8} at 0.1 arcsec separation (see Fig. 1). To attain the goal contrast of 10^{-10}, differential imaging and long exposures are needed. Differential imaging will permit to reject the residual atmospheric speckle noise but will inevitably introduce some new speckles that are due to systematic differential chromatic errors that can occur both before the coronagraph (because of atmospheric differential refraction) or after the coronagraph in the instrument itself (see Cavarroc 2005). Systematic errors for the future VLT-PF system are estimated to be of the order of several tens of nanometers. The requirements for EPICS will be of about a nanometer or less for some key optical elements. This kind of high precision control is comparable to what has already been achieved in the laboratory using very precise active mirrors (High Contrast Imaging Testbed (HCIT) experiment for the TPF-C mission, see http://planetquest.jpl.nasa.gov).
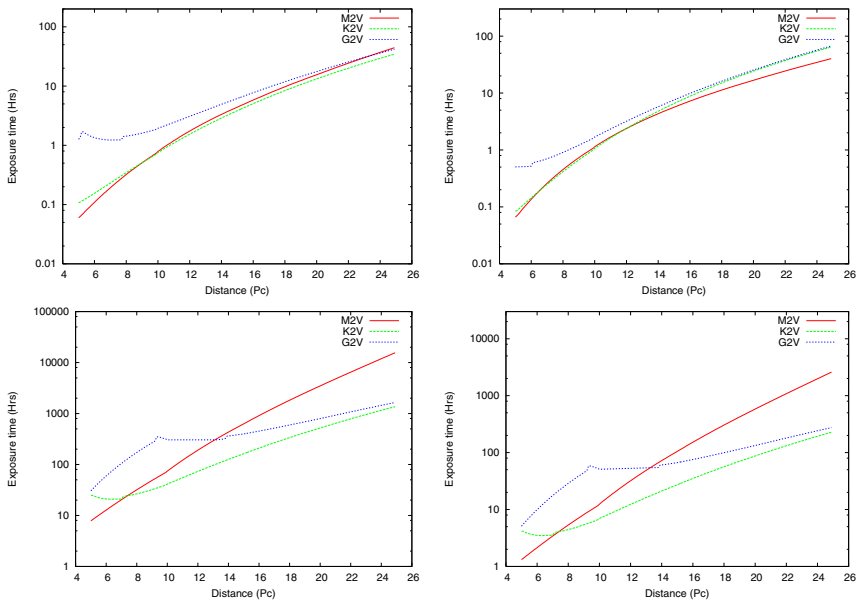
Figure 2. Integration times for a 5σ detection. Top-left: Earth-like planet, detection in water bands, R=15, $\lambda = 1400 nm$. Top right: CO_2 rich (10%) Earth-sized planet,R=15, $\lambda = 1600$ nm. Bottom left: detection of O_2 in Earth-like planet, R=150 $\lambda = 760$ nm.Bottom right: Detection of Earth-like planet by differential polarimetry (15% polarization), 600-800 nm.

7. Conclusions

We have described a concept for a Planet Finder instrument for OWL. The performances show that, thanks to an optimised AO system and coronagraph, a high rejection of the starlight halo in J and H band can be obtained permitting to detect H_2O and CO_2 (if abundant >10%) in Rocky planets in about one or two observation nights up to 20 pc. Detection by polarimetry will also be possible, as well as O_2 in Earth-like planets, however in follow-up observation only. Detection of Jupiter-like planets in CH_4 bands in J and H band can be done with high SNR opening the door to high resolution spectroscopy. The requirements on systematic errors control are very challenging but reachable with existing high performance active correctors.

Acknowledgements

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