EPICS, a Planetary Camera-Spectrograph for OWL

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Abstract:

This paper presents the status of the EPICS project, an Earth-like Planets Imaging Camera Spectrograph for OWL. In a first part, we present the science case and the requirements for the the most challenging goal, the Earth-like planets. We describe the baseline of the Adaptive Optics system with optimized wave-front sensor for halo rejection in the field-of-view of interest. The instruments concepts for detection and characterization based on spectroscopy, differential imaging and polarimetry are briefly described. The Signal-to-Noise ratio estimation shows that Earth-like planets can be detected, by differential imaging, up to 25 pc in a reasonable amount of time.

Keywords: Earth-like planets, Extremely Large Telescopes, Adaptive Optics, Instrumentation

1. INTRODUCTION

The EPICS project (Earth-like Planet Imaging Camera Spectrograph) 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. After an overview of the science case, we derive the Top-Level Requirements and describe the implementation concept. 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. The Signal-to-Noise Ratio (SNR) for the detection of rocky planets and evolved gas giant planets is estimated and shows that Earth-like planets can be detected at 5σ up to 25 pc.

1.1. 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. 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 and Mars
- 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 and 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.

2. TOP-LEVEL REQUIREMENTS

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 to the host star. 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. This choice sets the limiting magnitude for adaptive optics as well as the minimum separation angle corresponding to the habitable zone (see table below).

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}

3. IMPLEMENTATION CONCEPT

EPICS concept is based on the experience of the VLT Planet Finder Phase A study. 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 [5] [4]. 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.

3.1. Overall concept

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 Jupiter-like 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 proposed for the VLT Planet Finder [4]. 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. 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.

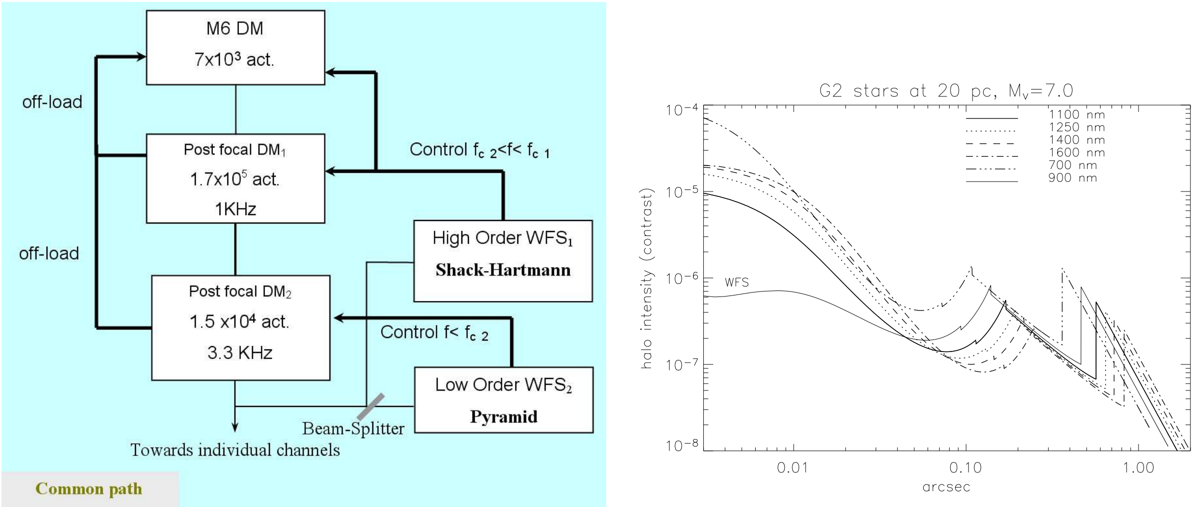

Figure 1. Left: EPICS XAO concept. Right: Halo intensity from AO residuals. Perfect coronagraph. Seeing: 0.5 arcsec. Coherence time: 4 ms.

3.2. Adaptive Optics and coronagraphy

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. This matter of fact calls for system specifications that are tremendously more stringent than for the VLT-PF project like a higher frame rate, extremely low residual static errors and very high sensitivity of the WFS for low to mid-spatial frequencies. 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 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 [2], 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. The corresponding theoretical residual haloes 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. A special coronagraph has been designed for OWL [1]. 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 [3].

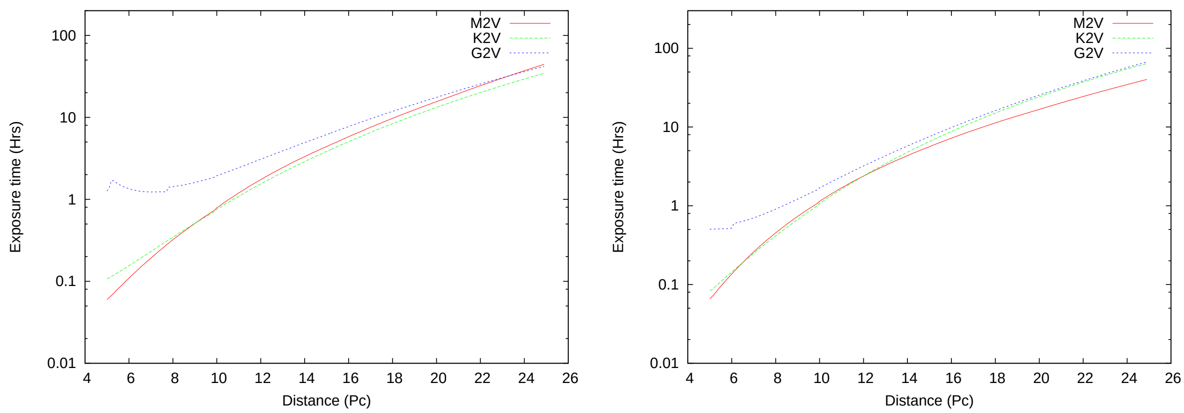

Figure 2. Integration times for a 5σ detection. Left: Earth-like planet, detection in water bands, R=15, $\lambda = 1400nm$. Right: CO_2 rich (10%) Earth-sized planet, R=15, $\lambda = 1600\ nm$.

4. 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 for the wave-length splitting instruments. The conditions of observations are: Differential detection with SNR=5, instrumental transmission: 16%, atmospheric transmission: altitude 4000-m, transmission in H_2O band (40%) and in O_2 band (80 %), seeing: 0.85 arcsec, $\tau_0 = 3\ ms$, AO residuals photon noise and speckle noise (perfect coronagraph). The integration times needed for a 5σ detection are displayed in Fig. 4. 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. Some other preliminary results in the visible have been obtained: detection of O_2 in a few tens of hours at 10 pc and a few hundreds of hours at 20 pc should be possible. Earth-like planets can also be detected by polarimetry in about 10 hours at 10 pc and 100 hours at 20 pc. Jupiter-like planets can be detected at 50σ up to 20 pc in the CH_4 bands in less than one night of observation opening the door to high resolution spectroscopy.

5. CONCLUSIONS

We have described a concept for a Planet Finder instrument for OWL. The performances show that, thanks to a very efficient AO system, 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 very high SNR.

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