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Using a 100-meter ELT (e.g., "OWL") for Extrasolar Planet and Extrasolar Life Detection

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Abstract. Several extremely large ground-based optical-IR telescopes (20m < D < 100-m) are now being proposed in several places. Here we outline one of the major attractions of the largest proposed aperture, that of the 100-m "OverWhelmingly Large telescope" (OWL) concept which has been studied at ESO. *Such a telescope appears capable of direct imaging of earth-like extrasolar planets out to tens of parsecs*, and, for many of the nearer ones, of securing atmospheric spectra, capable of revealing chemical signatures of photosynthetic life.

1. Introduction: an Outline of OWL

The realization that there are many critical astronomical observations which cannot be undertaken even with the largest existing telescopes (e.g., spectroscopy of the faintest objects in the Hubble Deep Fields, and even more so the fainter objects which will be detected by the JWST (neé NGST); cf. Mountain, 1996) has led to a number of proposals for "Extremely Large Telescopes" (ELTs) with apertures in the 20-m to 100-m range. In parallel has come close examination of the full science potential of the various apertures studied.

The extreme case is the "OverWhelmingly Large telescope" (OWL) a bold proposal which has been studied for several years at the European Southern Observatory (ESO) as a candidate design for a future European ELT (see Gilmozzi et al. 1998 and Dierickx et al. 2002, and references therein, for initial proposal and current status). OWL would employ $\sim$ 2000 - 6000 zerodur or SiC segments to form a spherical primary mirror (M1) 100-m in diameter. A flat secondary (M2) 34-m in diameter directs the light downwards to a spherical aberration corrector and thence to one of several instrument stations (cf. Dierickx et al. 2002 for details). Diffraction-limited optical performance over arcmin FOVs is offered, to be exploited by the application of multi-conjugate adaptive optics (cf., e.g., Rigaut, Ellerbroek & Flicker 2000) to achieve near diffraction-limited performance. Note that the diffraction limit is 1.0 milli-arcsec (mas) at V, 2.0 mas at J, 4.4 mas at K.

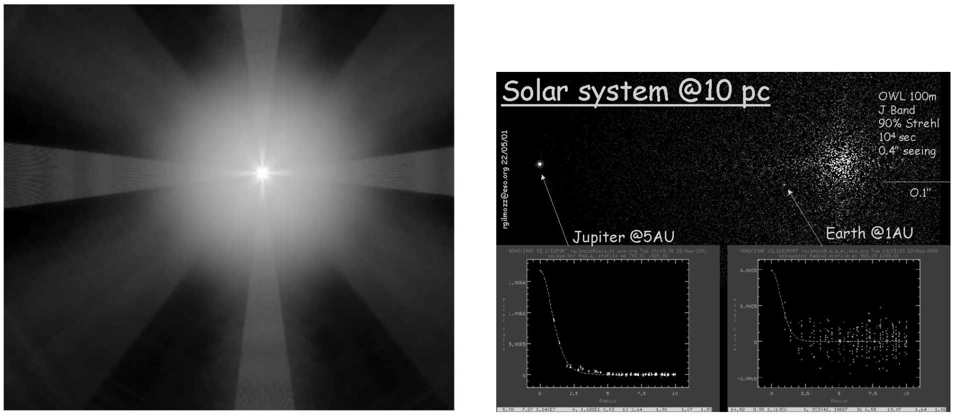

Figure 1. Left: Simulated PSF of OWL (log scale), showing diffraction from telescope structures, scattering, and the AO halo. Diffraction from the primary and secondary mirror segments is *not* included. Right: Simulation of a 10,000s exposure OWL image at $\lambda = 1.0\ \mu$m of a solar-type system 10 parsecs distant, comprising a sun, a jupiter (far left) and an earth (left). For reproduction, the light of the star has been removed, leaving only its noise signature. The extrasolar jupiter is detected at 100s of σ, the extrasolar earth at around 10σ.

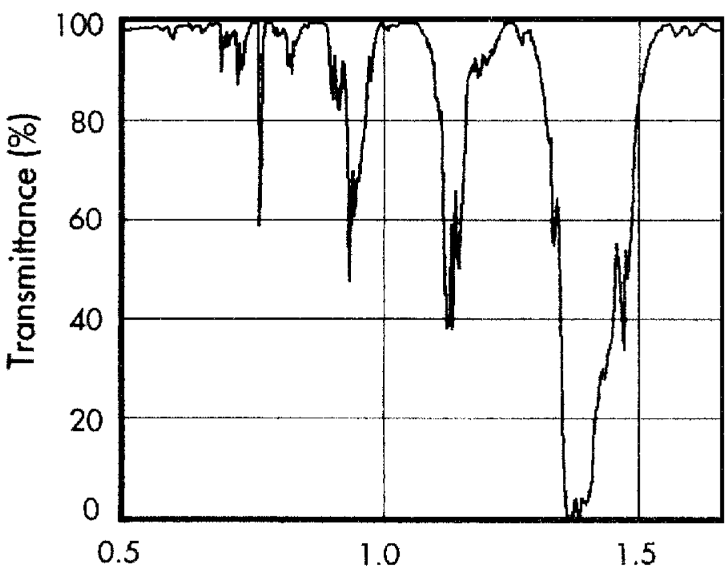

Figure 2. The optical and near-IR spectrum of the Earth's atmosphere. Wavelength is in μm. The left-most major absorption feature (around 0.76 μm) is of O_2, the rest are of H_2O.

At a workshop in Leiden, NL in May 2001 it was realized that a particularly exciting possibility for a 100-m telescope is the *direct imaging* of earth-like planets orbiting the nearer stars, enough of which should be accessible to allow a major study of such objects to be undertaken. This paper reports on that possibility and its potential.

2. Hunting Extrasolar Earths

At a wavelength of 1 μm we may reasonably expect to be able to achieve highly-corrected images by adaptive optics (AO), especially since observations will be centred on a bright star. At this wavelength the full width at half maximum (FWHM) of the central image spike of near-diffraction-limited point spread function (PSF) delivered by the telescope's AO system is only 2 mas.

At a distance of 10 pc an earth-like (terrestrial) planet orbiting a sun-like star in its habitable zone will lie around $0\overset{''}{.}1$, or 100 mas, from the star. The image of an earth-like extrasolar planet ten parsecs away would therefore lie at *100 times its radius* from the central spot. This is the key to the detection of such planets with OWL: the planet's image is well outside the bright structures of the image core.

The main background component with which the detection of an extrasolar earth must then contend is the "AO halo" produced by residual wavefront errors which remain uncorrected by the AO system. The halo resembles a seeing disk scaled to a total intensity 1-S of the star's signal (where S is the Strehl ratio of the AO-corrected image: the ratio of its central intensity to that which would occur in a perfect image). Like a seeing disk, it is composed of (rapidly) time-variable speckles and has a Lorentzian (Cauchy) profile (See Figure 1 (left)).

Complicating factors are the diffraction effects of segmentation of M1 and M2 and speckle effects associated with tip-tilt and piston errors (cf. Yaitskova, Dolan & Dierickx, 2002). For realistic inter-segment gap widths, diffractive effects produce an hexagonal array of peaks a few $\times 10^{-5}$ of the central peak, *much* brighter than the image of a terrestrial planet, but with regular and fixed spacing which should readily allow its identification, and probably its removal and the identification of real planetary images. Speckle effects will be slowly time-variable as tip-tilt and piston effects vary with active mirror setting, reinforcing and cancelling. These seem likely to add another halo with half the radius of the AO halo and about half its total intensity. These effects, not shown in Figure 1, are only starting to be studied and *may* set the ultimate limits to the planet-finding capabilities of segmented mirror telescopes.

Figure 1 (right) is a simulation of a 10,000s exposure OWL image at $\lambda = 1.0$ μm of a solar-type system 10 parsecs distant, comprising a sun, a jupiter (far left) and an earth (left), the starlight having been removed, leaving only its noise signature.

The rules governing the performance of an ELT for planetary detection can be set out quite simply. The effects of the performance of the telescope and its AO system, characterized by the aperture and the delivered Strehl ratio, and the influence of the properties of the extrasolar planetary system may be summarized:

The **Signal**: $I_{planet} \propto D_{tel}{}^2(SAd^2\phi)/(D^2r^2)$ where S = Delivered Strehl ratio of telescope and AO system; D_{tel} = telescope aperture; A = albedo, d = diameter, ϕ = phase function, r = orbital radius of the planet; and D = distance of extrasolar system.

The **Noise**: $N \propto [a_{image} D_{tel}{}^2 (1 - S)(s/\theta^2 + s/2)^2 + C]^{1/2}$

where a_{image} = solid angle of image $\sim (\lambda/D_{tel})^2$, s = seeing FWHM, $\theta = r/D$ = angular distance of planet from star and $s/(\theta^2 + s/2)^2$ = (Lorentzian) profile of the AO halo.

Because $D_{tel}{}^2$ cancels, N does not depend on D_{tel}. *Sensitivity (S/N) scales as $D_{tel}{}^2$*, strongly favouring large apertures: a 30-m will be *10 × less sensitive* than a 100-m, while the *speed* of a given observations *scales as D^4*, so a 100-m will be *100 times faster* than a 30-m.

The effects on such scaling laws of segmentation diffraction and speckle effects is expected to be minor.

3. Characterization of Extrasolar Earths, a Statistical Sample, and a Basic Question

The signal-to-noise ratio achieved in the observation modeled above is such that one could readily contemplate attempting low-resolution spectroscopy of the extrasolar earth, albeit with rather long exposures. The red-to-near-IR wavelength range offers a number of diagnostics to allow the characterization of the planetary atmosphere, in particular strong features of water and of oxygen (O_2) (Figure 2). These are of course also present in Earth's atmosphere, so moderate resolution spectroscopy using photon counting detectors and exploiting orbital Doppler shifts may be needed to disentangle the planetary spectrum from telluric features.

The detection of atmospheric oxygen in the presence of water vapour and CO_2 is considered to be a reliable indicator of the presence of photosynthetic life (Selsis, Despois & Parisot, 2002) as no other known process can maintain a high O_2 level for more than a few tens of millions of years.

OWL should be able to detect extrasolar earths out to $\sim$ 25 pc (in contrast to a 30-m, which is unlikely to reach beyond $\sim$ 5 pc); in a year it could sample the $\sim$ 2600 stars, including $\sim$ 360 solar-types, within this radius, yielding a crucial statistical sample. If terrestrial planets are reasonably common the number accessible to spectroscopy may allow a very fundamental question to be addressed: the time scale for the evolution of analogs to the terrestrial eukarya. Here this happened 2.7 Gy ago, with the end of the anaerobic era around 0.5 Gy later. OWL's sample should establish whether this time scale is typical or an aberration.

What seem sensible questions to pose now, may appear trivial in the face of the surprises which are likely to await us in this totally new field. But it is a field far too important to ignore, and OWL may be our most powerful tool for its exploration.

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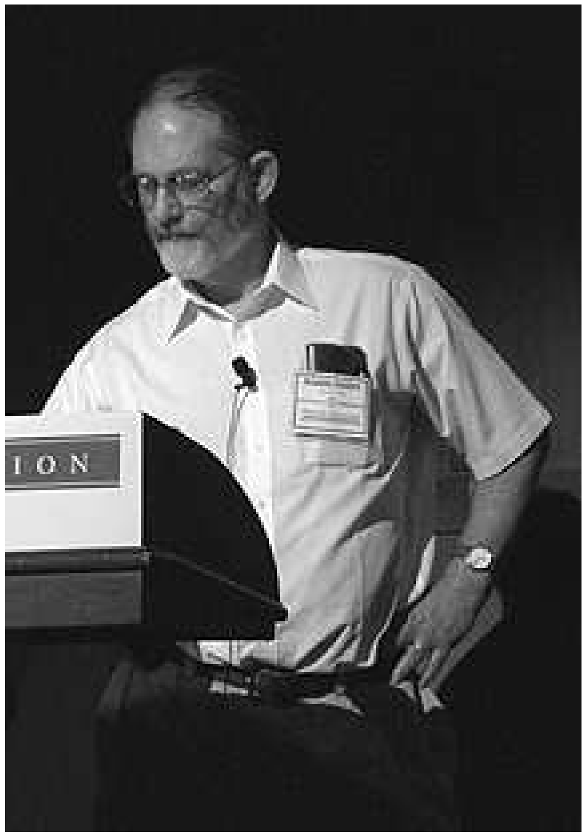

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