Scientific Requirements for Extremely Large Telescopes
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The case for a planetary spectrograph for ELTs: NOCTUA

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Abstract. Various projects to find planets or entire planetary systems around main sequence stars in the solar neighborhood are presently under way. When ELTs will be operational, there will be literally thousands of confirmed planetary systems including spectro-photometric detections. At this point it becomes inevitable to consider the *next logical step*: the spectroscopic analysis of the atmospheres of these planets. High-resolution spectroscopy, i.e. resolving $v \times \sin(i)$ of these planets, in the wavelength regime of 950-5500nm is a powerful and promising tool. In view of the obvious contrast problems in detecting such planets non-LTE features are specifically targeted. Sensitivity estimates for the detection of the non-thermal OH glow in oxygen-bearing atmospheres are given. With *8m*-class telescopes such a search is impossible, but a dedicated spectrograph, e.g. at the projected ESO *100m* OWL telescope could detect Earth-like planets at a distance of ≈10 parsec. A conceptual design for a dedicated spectrograph, NOCTUA, is presented. In case of ELTs of smaller size the science case changes and the instrument requirements have to be adjusted. Preparatory work with CRIRES, ESO's Cryogenic Infrared Echelle Spectrograph on the VLT at $\frac{\lambda}{\Delta\lambda} \approx 10^5$ as well as other science cases are shortly discussed.

Keywords. Stars: astero-seismology, atmospheres, individual (β-Pictoris); Planets: exo-planets, exo-earths; Gamma rays: bursts; Techniques: spectroscopy.

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1. Introduction

Since the discovery of the first extra-solar planet (Mayor & Queloz 1995) many more planets and even planetary systems have been reported. In addition to the now well established "workhorse" method, radial velocity searches, new technologies have been added, especially occultation searches with very high precision photometry, gravitational lensing surveys and extreme coronagraphy. All major observatories are now enlisted in the hunt for planets. Dedicated space missions are in various stages of development. Given that the first planet-detection was done at a *2m*-class telescope and today HARPS (Pepe *et al.* 2004) at ESO's 3.6m has entered the realm of exo-planet mass production, one can reasonably expect that in the era of ELTs the number count of bona-fide extra-solar planets including those with masses as low as few Earth-masses may well exceed 10^3. Telescopes in the 30-100 m will offer the chance to directly detect such planets and to approach the physical characterization of these largely, apart from their mass, unconstrained bodies (e.g. Käufl & Monnet 2000).

2. The power of high resolution spectroscopy

Once ELTs are operational *the next logical step*, the characterization of exo-planets becomes important. This is best done systematically using high-resolution spectroscopy. Target spectral features are rotational-vibrational transitions of infrared active molecules. Intrinsic line-widths of such lines in our solar system are of the order or $0.3 - 1\,\mathrm{km\,s^{-1}}$ to be convolved with the planet's rotation ($\approx 0\,\mathrm{km\,s^{-1}}$ for Venus and $\approx 20\,\mathrm{km\,s^{-1}}$ for Jupiter, to cover the two most extreme cases in our solar system). Geometrical effects like limb brightening or observations at *quadrature* will still produce spectral features closer to the "intrinsic" linewidths. Therefore the best signal-to-noise ratio for emission line detection is in any case most likely achieved with a spectrograph that just starts to resolve linewidths of the order of $1\,\mathrm{km\,s^{-1}}$. Thus the optimum instrument to detect emission lines from extra-solar planet atmospheres is a spectrograph, which has a resolving power equivalent to $0.3-1\,\mathrm{km\,s^{-1}}$. As a "by-product" such a spectrograph would also disperse (or dissolve) the stellar continuum of the star. The only technology with sufficient sensitivity **and** spectral resolution to tackle this subject is Echelle-Spectroscopy. To achieve best suppression of background and stray light only a single pass set-up is considered useful.

3. Choice of the best wavelength

Observing small rocky Earth-like extrasolar planets is challenging from the sensitivity as well as from the contrast point of view. The contrast issue is discussed elsewhere in this conference as part of the various proposals for coronagraphy at ELTs. These ideas should be recycled in any planetary spectrograph. However, longer wavelengths are generally advantageous, as scattering processes scale with $1/\lambda - 1/\lambda^4$. This holds for dust- aerosol- and all other scattering processes encountered. The best possible intensity contrast is achieved in the Rayleigh-Jeans-limit (long wavelength limit):

$$\frac{I_{planet}}{I_{star}} = D^2_{planet}/D^2_{star} \times \frac{T_{planet}}{T_{star}}$$

This ratio is of the order of 4×10^{-6} for our Earth relative to the Sun. This is indeed 4 orders of magnitude more favorable then trying to detect the Earth in visible light relative to the Sun. So both arguments tend to suggest that the obvious region to search and analyze exo-planets is the far infrared. However, there is also the issue of sufficient sensitivity. At least for the case of thermal infrared imaging with ELTs from ground one is limited to few parsecs to detect Earths (Käufl & Monnet 2000). In a similar sense, the diffraction limit tends to favor shorter wavelengths. So a strategic trade-off is necessary.

4. Suitable spectral features

4.1. *Non-LTE-effects*

From the considerations above, it is obvious that both for reasons of contrast enhancement and to get more photons non-LTE features should be targeted. From our local solar system it is well known that planetary atmospheres can show large non-thermal level-populations pumped by solar radiation: some of the strongest features are e.g. the CO_2 laser emission at 10.4μm (see e.g. Käufl *et al.* 1984 or the emission of C_2H_2 observed for Titan (Kunde *et al.* 1981). Both these features, however, are of little practical use, as they are either not observable through the atmospheric windows from the ground (C_2H_2), or effectively still not very bright (CO_2).

4.2. *OH-airglow*

Non-LTE populations in a planetary atmosphere can also be created by photo-chemical reactions. A very prominent process is the formation of the OH-radical (Black 2005) in our atmosphere at an altitude of ≈ 90 km via the reaction $O_3 + H \longrightarrow O_2 + OH^*$ creating the infamous infrared airglow via the excitation of the *Meinel*-bands. The line positions are extremely well known from laboratory spectroscopy (Abrams *et al.* 1994).

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4.3. *Other potential biomarkers*

Various spectral features are discussed as bio-markers, i.e. signatures of life on planets or at least of life supporting conditions, e.g. absorption lines of H_2O, CO_2 or O_3. All these searches have a common problem: due to the relatively small temperature gradient between the planetary surface ($\approx 290K$) and the atmosphere ($\approx 210-270K$), the resulting absorption features, even if the lines are saturated, are of the order of 10-20%. Moreover all these lines are also present in our atmosphere and lead, in the case of ground based observations, to obvious interferences. In addition, such observations would be plagued by the effects of anomalous dispersion which may in fact pose a severe fundamental limit to coronagraphy in combination with extreme adaptive optics as is proposed for ELTs. The OH-lines, however, are unique as they do not suffer from any interferences.

5. NOCTUA: preliminary design and potential

For the reasons above a study for a dedicated spectrograph to search for the OH-airglow from potential extra-solar oxygen bearing atmospheres was started: NOCTUA (Novel Census Testing Unknown Atmospheres). Table 1 summarizes the design features for such a spectrograph. Scaling these intensities in comparison to state of the art infrared instrumentation (e.g. Käufl *et al.* 2004) yields the following result: a dedicated spectrograph on a 100m-class telescope has the potential to detect OH-lines from an extra-solar Earth at a distance of 10 parsec at a level of 1σ per hour per line. It should be noted that there are more than 20 strong and hundreds of weaker transitions which could be searched for simultaneously with a dedicated spectrograph. To have sufficient pixels in

Table 1. NOCTUA: Summary of Requirements to Detect Planets with a 100m-Class ELT

spectral resolution	300 $\mathrm{m\,s^{-1}}$
spectral sampling	100 $\mathrm{m\,s^{-1}}$ per pixel
primary wavelength range	1400-2000 nm
effective # of pixels	10^6
optical quality	diffraction limited at 1600nm (= 4mas for ESO 100m OWL)
slit-length in cross dispersion	$\approx 0.5-1$ arcsec

dispersion direction a prism cross-dispersed spectrograph has been studied recording the spectrum in typically 12-24 orders. This would need a focal plane array with nominally 20-40 $4K \times 4K$ detectors. While the acquisition electronics for such a mosaic is well within the extrapolation limit of ESO's present controller IRACE, the price for the detectors is not. The latter, however, seems to be a general problem of most ELT-instruments. Fig. 1 gives the approximate lay-out and a calculated PSF.

6. Other science cases for NOCTUA/NOCTUA-light

For ELTs with $\approx 80-100$m diameter the focus should be on the characterisation of extrasolar planets. If, however, the next generation telescopes are more in the region of $30-50$m diameter, then the secondary science targets of NOCTUA should become the primary targets and consequently the spectrograph should be designed slightly differently (*NOCTUA-light*). There is a wide range of other science cases for a high resolution NIR spectrograph at an ELT, e.g.:

• **Falling Evaporating Bodies:** In high dispersion spectra of metal absorption lines around β-Pictoris time variable redshifted narrow absorption features have been observed. These lines are attributed to the evaporation of falling bodies (comets? (Lagrange

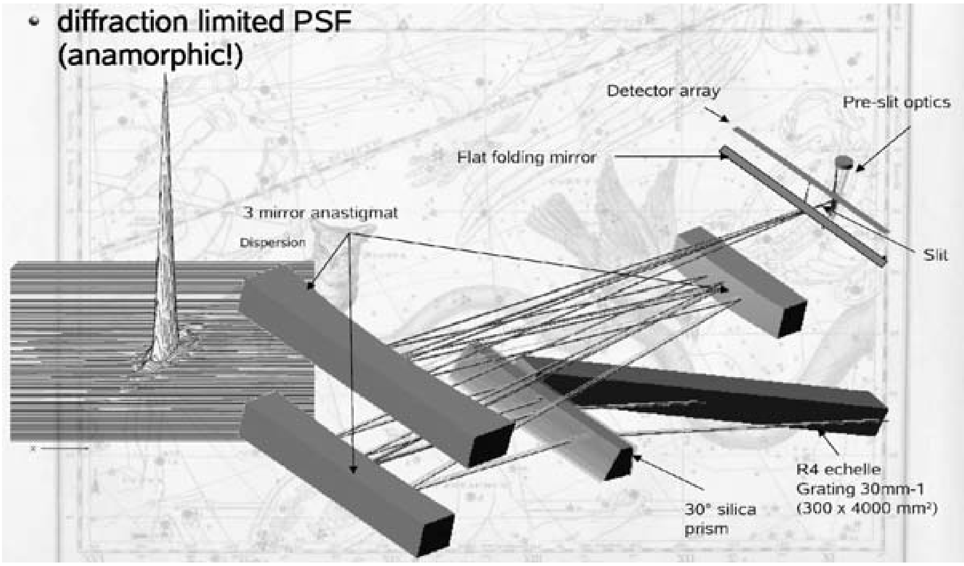

Figure 1. Lay-Out and PSF of a high resolution planetary spectrograph for extremely large telescopes. The fore-optics, matched to the ESO-OWL f/6-beam, includes a cold pupil stop, an optical de-rotator and an anamorphic pupil compression. This allows to keep the grating at a "moderate" size of $4000 \times 300\text{mm}^2$. While the fore-optics is well within the dimensions of metal optics for present ESO-VLT instruments, the 3-mirror anastigmat for the main spectrograph as well as the grating will require some R&D. The cross-dispersion prism appears uncritical and can be assembled as a mosaic. The anamorphic effect on the PSF is obvious: in slit direction there is an elongation by a factor of three, which may indeed be advantageous for disentangling the planetary signal from that of its mother star. The design allows to add cryogenic coronographic masks and dedicated AO if not provided by the telescope.

et al. 1996)). However, β-Pictoris has remained the only example. NOCTUA at an ELT would allow to do a systematic survey around hundreds of younger stars with IR-excess. Combination with a suitable IR-imager would allow to do this truly well targeted. Observations with NOCTUA in the near-infrared would allow to search both for metal line systems (e.g. the Na-doublet in the K-band) or real organic cometary lines such as H_2CO at 3.3μm. Thus the quest for extra-solar planets could be complemented searching extra-solar comets.

• **AGB-Stars beyond the local group:** Atmospheric features of AGB-stars are best observed in the near-infrared. Research on AGB-stars beyond the members of the local group with 8m-class telescopes is strongly brightness limited. NOCTUA at an ELT could move the frontier in this field of research to 1-3Mpc while adding operational advantages: a large infrared focal plane and systematic cross dispersion to be able to record typically 30-50% of the spectrum.

• **Asteroseismology in the infrared:** The power of high spectral resolution in combination with the collecting power of a 50-100m telescope is obvious. However, infrared lines forming in the chromosphere can give a completely different picture than the metal (*Fraunhofer*) lines forming in the photosphere (e.g. Deming *et al.* 1986). In addition there is a large potential for synergies with space observatories.

• **Comets:** The unprecedented combination of spectral with spatial resolution and spectral coverage would allow to tackle many up to now enigmatic processes associated with the jet-like gas-vents found to emerge from cometary nuclei. Thanks to the high spatial resolution (of the order of 1-5 km at the comet) cometary material can be studied within seconds after leaving the nucleus: this allows to understand the interaction of the gas with the solar radiation field and to measure the gas composition and its thermodynamic properties immediately when the material leaves the vents. Outflow velocities and intrinsic linewidths require a spectral resolution equivalent to $200 - 500 m\,s{-}1$.

• **Gamma Ray Bursts:** Recently a photometric redshift of 6.3 was reported for GRB 050904 (Tagliaferri *et al.* 2005). With the next generation of satellites, GRBs will be detectable up to much higher redshifts. The afterglows are long-lived and bright enough to use them as back-illuminators of clouds in the early universe. UV-metal lines longwards of restframe $Ly\alpha$, red-shifted into the near-infrared, will allow to study the "dark ages".

Beyond these few examples there exist many more scientific applications for high or very-high resolution infrared spectroscopy in astronomy (Käufl *et al.* 2005). The combination of NOCTUA with an ELT/OWL will provide for sensitivity and spatial resolution, parameters often limiting the work with today's 8m-class telescopes.

7. Conclusions and future work

It has been demonstrated that a very-high resolution spectrograph, NOCTUA, has the potential to detect signatures of oxygen-bearing atmospheres of extra-solar Earth-like planets for a *100m*-class ELT. With smaller telescopes, this science case will not persist. The design presented here can easily be rescaled for a somewhat more moderate instrument fitting better the general science case. NOCTUA-light should have a spectral resolution of $\approx 1\,\mathrm{km\,s^{-1}}$ and Nyquist sampling. This would reduce the size of the optics by a factor of ≈ 3 and the size and cost of the focal plane array by a similar amount. This simplification will be a bit offset by the requirement of a full implementation of operations up to $\lambda \approx 5\mu m$ (e.g. the cross dispersion becomes more ambitious). With the quasi-precursor CRIRES at ESO's VLT (Käufl *et al.* 2004) preparatory work will be started, ranging from calibration issues to a systematic preparation of OH-searches. The latter will encompass measurements of the integrated telluric OH-signal in scattered light from the Moon and systematic scans of the Martian and the Jovian atmosphere for signatures of OH to establish the uniqueness of the feature. Moreover, CRIRES will be used to explore the possibilities of the direct detection of hot Jupiters (hydrocarbonates).

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Discussion

DRAVINS: The star-exoplanet contrast in molecular lines (such as OH) should be higher for stars that are hot enough to have dissociated such molecules. Is this a reason for preferring stars hotter than the Sun, say?

KÄUFL: We checked the solar ITS data base (McMath). We found no obvious lines which would interfere. Moreover, the stellar lines would always be ~ 10 times wider and at a different Doppler-shift. In conclusion, no interference is expected even at later spectral types.

HOMEIER: At 10^6 resolution the gain in sensitivity may be limited by over-resolving the intrinsic line profiles (Doppler profiles for Earth temperature, damping profiles at over a few mbar). Could this effect your sensitivity estimates?

KÄUFL: In principle we expect the sensitivity to be background noise limited for $\lambda > 1.8\mu$m. Then S/N ratio scales only with $\sqrt{IR}$ and can be recovered by numerical rebining.

MCCAUGHREAN: You use the relative velocities of the star and Earth to separate telluric and exo-earth OH airglow. But if the required integration time is very long, then changes in the Earth's relative velocity (as it orbits the sun) will mean that some velocity shifting will be required before co-adding. What are your predicted integration times for exo-earth detections?

KÄUFL: Tools to stack observations spanning longer periods (weeks or more) are already implemented for CRIRES/VLT.