

The Quest for Near-infrared Calibration Sources for E-ELT Instruments

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Extremely Large Telescopes (ELTs) and most of their instrumentation will be optimised for operation in the Near-InfraRed (NIR) because of the wavelength dependent performance of adaptive optics. Few established sources for wavelength calibration exist in this wavelength domain. A project is described which aims to provide the basic data to select the best calibration sources for NIR instruments at the European ELT (E-ELT) as a function of wavelength range and spectral resolution. This work directly supports the Phase A studies of E-ELT instruments; in addition its results will be highly valuable for future use in analysis of NIR science observations.

Since the focus of astronomy and laboratory atomic physics has been on ultraviolet and visible wavelengths for more than 100 years, a wealth of reliable atomic data exists in this wavelength range. In contrast, existing data for most elements are sparse at Near-InfraRed (NIR) wavelengths and a better knowledge of the spectral properties is clearly needed for both the analysis of astronomical spectra and for selecting possible calibration sources. No comprehensive database of NIR spectra is available. The European Southern Observatory (ESO) and the US National Institute of Standards and Technology (NIST) are collaborating on a project to provide the necessary basic data to help select the best calibration sources for the European Extremely Large Telescope (E-ELT) instruments. About 20 different hollow cathode lamps are chosen for this study. We are investigating their spectral and operational properties through laboratory measurements using a Fourier Transform (FT)

spectrometer at ESO. The most interesting sources will then be studied at atomic physics laboratories in order to produce accurate wavelength standards and calibration reference data directly applicable to operations of E-ELT instruments.

Requirements of E-ELT spectrographs

Instruments at ELTs will cover a variety of wavelength regions and spectral resolutions. The projected large size of E-ELT instruments will make it possible to deliver excellent calibration by combining optimised sets of calibration lamps, provided such lamps can be identified in advance.

Recent developments indicate that frequency-based systems such as the laser frequency comb (Araujo-Hauck et al., 2007) may provide wavelength calibration of unprecedented accuracy and stability for future high-resolution spectrographs such as CODEX. At lower resolution, and for instruments with less stringent calibration requirements, classical calibration sources such as hollow cathode lamps (HCLs) are expected to remain the preferred choice for many ELT instruments.

Currently, conceptual designs for six instruments suitable for the E-ELT are being made, with another two designs to start soon. Our project will directly support these studies by providing information on possible calibration sources for a given spectrograph. Figure 1 shows the parameter space of the suite of spectrographs currently under study. The values used in the diagram are very preliminary since both wavelength range and spectral resolution are parameters that

will be optimised during the conceptual design, based on the proposed science and technical feasibility. Nevertheless, it is obvious that the emphasis of E-ELT spectrographs will be in the NIR, and covering a large range of spectral resolution.

Hollow cathode lamps and their selection

Gas discharge sources such as hollow cathode lamps have been used as sources for wavelength calibration of astronomical spectrographs for many decades. HCLs are mass-produced for a commercial market and more than fifty elements are readily available from manufacturers. However, few have been studied for use in astronomy. The successful characterisation of a Th-Ar HCL (Kerber et al., 2008) – a joint ESO/NIST project – for CRILES has improved the calibration of NIR high-resolution spectrographs; while at lower resolution improved data for the noble gases have made it possible to model and quantitatively predict the IR performance of the calibration system for X-shooter (Kerber et al., 2007).

Ideally, existing databases of atomic spectra based on laboratory measurements would make it straightforward to select good calibration sources. The NIST Atomic Spectra Database (ASD) (Ralchenko et al., 2008) is probably the most extensive database of experimental data, and NIST is continually expanding the data volume by adding critically compiled data from various sources. For the NIR, the most recent comprehensive compilation of many elements dates back 30 years (Outred, 1978). A careful analysis has demonstrated that it is currently

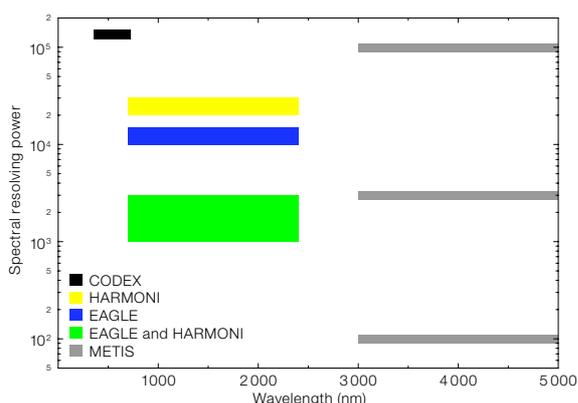


Figure 1. Parameter space covered by some of the projected E-ELT spectrographs. The numbers are preliminary since both wavelength range and spectral resolving power will be optimised during the initial design.

Metal	Al	Ti	Cr	Fe	Ni	Ge	Se	Zr	Ce	Ce	Dy	Ho	Tm	Hf
Atomic no.	13	22	24	26	28	32	34	40	58	58	66	67	69	72
Work function (eV)	4.28	4.33	4.5	4.7	5.15	5	5.9	4.05	2.84	2.84	–	–	–	3.9
First ionisation potential (eV)	5.99	6.29	6.77	7.90	7.64	7.90	9.75	6.84	5.54	5.54	5.94	6.02	6.18	6.65
Gas	Ne	Ar	Ne	Ne	Ne	Ar								

Table 1. Hollow cathode lamps selected so far for investigation of their properties.

not possible to select calibration sources in the NIR based on the existing databases, since these are not adequately populated with spectral data for many of the relevant elements.

Since HCLs are commercially available for more than 50 elements, it would be very convenient if their spectra could be predicted with some accuracy based on first principles. Unfortunately, reasonable accuracy can only be achieved with very considerable effort. We have used the freely available code by R. D. Cowan (Cowan, 1981) that calculates atomic energy levels, transition rates and spectra. For a more detailed description see Aldenius et al., 2008.

While the Cowan code can produce good results for many atomic systems, especially the light elements, the calculation of spectra for heavier species is greatly exacerbated by strong correlation effects resulting from a large number of overlapping low-excited configurations. Such correlations are especially important for atoms with open *d*- and *f*-shells that have rich NIR spectra of importance to the present work. A proper *ab initio* account of correlation effects would have to include an exceedingly large number of configurations. Any attempt to survey 20 or more elements in this manner would incur long-term computational efforts, and hence such an approach is impractical for our project.

In the absence of good line data or reliable calculations, we restricted ourselves to using some very basic and practical considerations to guide our selection of elements for procuring HCLs for laboratory measurements.

In the process of choosing suitable lamps, the properties of different metals have been considered in terms of e.g. availability, possible line structure, and possibility to produce a number of observable spectral lines in the wavelength region of interest. For calibration of high-resolution spectrographs, we have cho-

sen elements dominated by even isotopes, as hyperfine structure in odd isotopes may produce asymmetric spectral lines. For the calibration of low-resolution spectrographs, the line strengths are more important and any line structure will be negligible compared to instrument profiles. Theoretical calculations have also been made, in order to estimate the possible number of spectral lines. At the present time, 14 different lamps have been selected (see Table 1).

Fourier Transform spectrometry

Spectra of the HCLs are being recorded with the commercial Fourier Transform (FT) spectrometer at ESO. This type of spectrometer is mainly used for industrial applications using absorption spectroscopy, but it also provides a port for external sources. In order to duplicate the optical path used for internal sources, the light from the external source is collimated using an elliptical and a parabolic mirror (see Figure 2). Spectra are recorded in the spectral range between 3000 cm^{-1} and 14000 cm^{-1} (3.3 μm to 0.7 μm). For each lamp the spectrum is recorded at six different operating currents (4, 6, 8, 10, 12 and 14 mA) with a resolution of 0.125 cm^{-1} . Between 128 and 1200 scans (1 h to 10 h) are co-

added for each spectrum in order to increase the signal-to-noise of all lines. In order to further investigate the spectral properties of the lamps, spectra are also recorded with lower resolution (1, 4 and 8 cm^{-1}).

The spectral lines are identified using available compilations, databases, individual publications, and comparisons to Ritz wave numbers, that is wave numbers calculated from the difference in energy between published energy level values. Gaussian profiles are fitted to all observable spectral lines and the integrated intensity is studied as a function of lamp operating current. For each spectral line the ratio of the intensity of the line to the intensity of the same line in the 10-mA spectrum is calculated. The ratios are then averaged for all lines of the corresponding species at each current, showing a distinct difference between the behaviour of the gas and the metal lines. The average behaviour of line intensities as a function of current is displayed in Figure 3 where only resolved lines present at all currents are included.

This distinctive behaviour, which can be qualitatively explained in terms of the sputtering effect in HCLs (Kerber et al., 2006), provides a useful tool in distinguishing between gas and metal lines

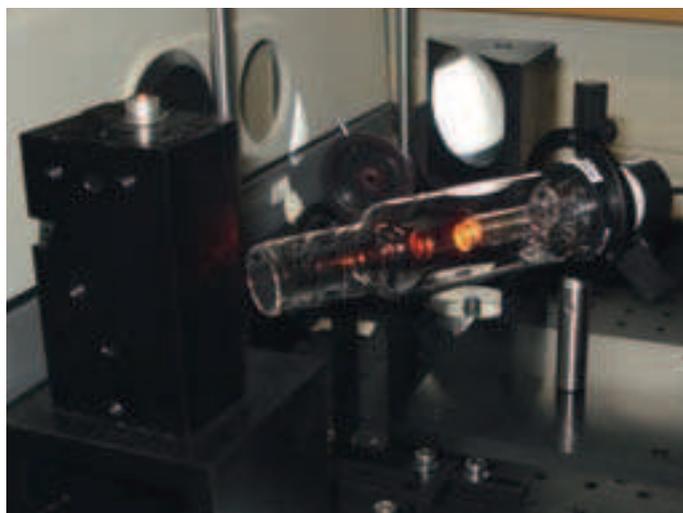


Figure 2. Set-up of a hollow cathode lamp and the Fourier Transform spectrometer.

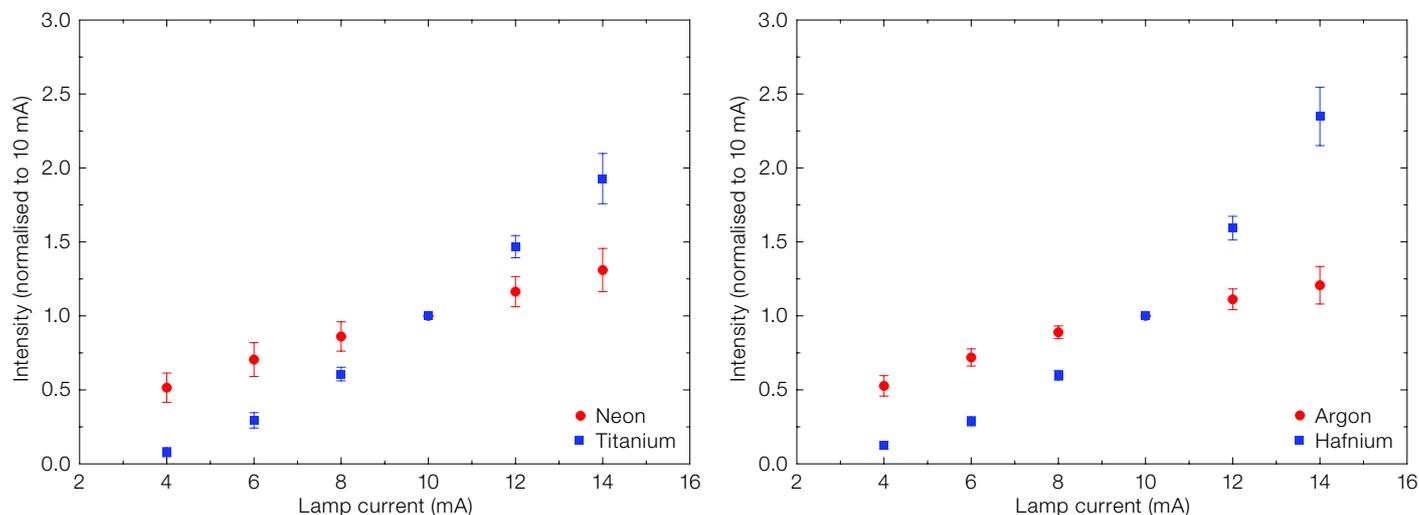


Figure 3. Line intensities as a function of operating current in the Ti-Ne and Hf-Ar HCLs. The intensities are normalised to the intensity at 10 mA and average values are calculated for identified lines from the car-

rier gas and the metal respectively. The error bars are statistical uncertainties and represent one standard deviation.

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when trying to identify the presently unidentified lines in the spectra. In addition to line identification, the results of the investigations of current dependence should also provide important information on how to optimise the operation of the calibration lamp.

Results and outlook

Five lamps have to date been thoroughly analysed resulting in solid knowledge about the number of lines available and their intensity ratios. Also the behaviour of line intensities as a function of lamp current has been well established. In general the spectra are dominated by lines from the carrier gas, but many metal lines are present as well. A small spectral region for the Ce-Ne, Zr-Ne and Ti-Ne lamps is displayed in Figure 4. The three lamps have the same carrier gas and the spectra are therefore similar, but significant differences are evident. Different metals produce lines in different spectral regions and lamps can thus be used in combination in order to optimise their utility.

Our laboratory project to conduct a preliminary survey of about 20 elements with a small commercial FT spectrometer forms the basis for developing a more robust understanding of the NIR spectra of elements suitable as wavelength cali-

bration sources. We focus our effort on the needs of currently planned spectrographs for the E-ELT, which will require good calibration sources for various resolutions across the NIR range. In a second phase we plan to establish the best qualified elements as wavelength standards by conducting dedicated laboratory measurements with high-precision FT spectrometers at qualified atomic spectroscopy laboratories.

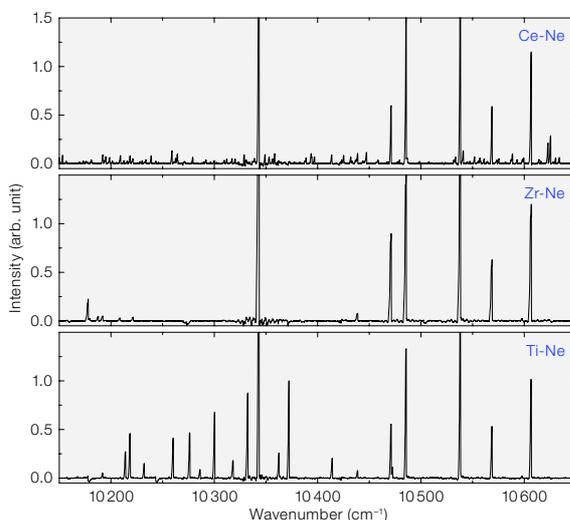


Figure 4. Observed spectra of the Ce-Ne, Zr-Ne and Ti-Ne lamps at operating current 10 mA in a small wave number range (0.99 μm to 0.94 μm). The spectra are dominated by lines from Ne (the lines common to all spectra), but metal lines contribute to significant differences.