CRIRES–POP — A Library of High Resolution Spectra in the Near-infrared

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New instrumental capabilities and the wealth of astrophysical information extractable from the near-infrared wavelength region have led to a growing interest in the field of high resolution spectroscopy at 1–5 μm. A detailed knowledge of the resident spectral features is necessary to fully utilise the diagnostic power of this region of the spectrum. We report on our ongoing project of obtaining a high resolution, high signal-to-noise library of near-infrared spectra between 1 and 5 μm using the CRIRES spectrograph at the VLT. The library will be made public.

After the long domination of astrophysical observations by the visual spectral range, the past years have very clearly shown that the near- and mid-infrared (NIR and MIR) range will play a leading role in many prime areas of astronomical research for the coming decades. This part of the spectrum opens up a universe of "cool" phenomena, such as discs, planets or the extended atmospheres of evolved stars.

In order to understand the contents of the NIR spectral range better, high resolution spectroscopy is mandatory. Considerable progress has been achieved over the past twenty years concerning the sensitivity and size of infrared detectors, allowing efficient spectrographs for the near-infrared to be built for current astronomical use. However, to utilise this part of the spectrum fully, detailed knowledge of the range of spectral features is necessary. This requirement has not yet been reached: line lists, especially for the various molecules, are inaccurate and/or incomplete; many weak lines have not been identified or studied; and the widespread telluric absorption features are a source of confusion. The potential for important discoveries in spectra taken with ESO's CRyogenic Infra-Red Echelle Spectrograph (CRIRES) will not be realised until the spectral features can be identified and line data are made available.

A public library of high resolution NIR spectra of stars of various types throughout the Hertzsprung–Russell diagram (HRD) is needed to meet this challenge. Such a library would not only provide a database from which to select the wavelength range best-suited to a specific scientific question, but it would also be used to compare observations with a reference star, for example in order to measure abundance anomalies or to detect indicators of faint companions. Full coverage spectra of stars of different effective temperature and surface gravity will allow testing of not only atmospheric models with an unprecedented accuracy, but also the atomic and molecular line data used in these models, and determine where improvements are required.

Earlier work, such as the atlas of the solar spectrum (Wallace et al., 1996) or for the K giant Arcturus (Hinkle et al., 1995) illustrated the value of a stellar reference spectrum at high spectral resolution and high signal-to-noise (S/N). However, an inventory of complete NIR stellar spectra at such a resolution across the HRD is not yet available.

Against the background of this unsatisfactory situation, we have formed a team with research interests spread all across the HRD and with the common intention of optimising the usability of the NIR range for high spectral resolution studies, mainly focused on deriving element abundances in stellar atmospheres. As a consequence, we proposed to obtain high resolution spectra of the complete NIR wavelength range for a sample of bright stars of various luminosity, temperature, and chemical composition using CRIRES at the VLT (currently mounted on Unit Telescope 1, UT1). The CRIRES instrument is one of the current workhorses in the area of high resolution NIR spectroscopy[1]. A detailed description of this spectrograph can be found in Käufl et al. (2004).

Our proposal comes as a filler programme for UT1, as the brightness of the stars and the flexibility of the wavelength settings allow us to use almost any weather conditions. Our proposal was granted observing time both in semesters P84 and P85 to begin the collection of a CRIRES spectral library, which, in succession to the UVES Paranal Observatory Project (UVES–POP[2]), was named CRIRES–POP. A continuation of the programme in forthcoming semesters will be proposed.

Target selection

As a starting point for the target selection, we use the UVES–POP library (Bagnulo et al, 2003). Thus, a considerable fraction of the NIR spectra of the stars in our library will have continuous high resolution extension towards the visual and blue range. A further criterion for target selection is a low rotation velocity, to provide sharp-lined spectra. For stars at the extremes of the HRD, the UVES–POP targets are either too bright (at the cool end) or too faint (at the hot end) to be observed with CRIRES. Alternative targets were chosen in these cases. Whereas the UVES–POP library contains spectra of about 400 different stars, the CRIRES–POP will be significantly smaller. The CRIRES spectrograph can obtain only a comparably small part of the spectrum at each observation, thus a large number of wavelength settings is needed for a complete scan of the NIR range, even when omitting a few settings due to heavy telluric absorption.

Our aim is to obtain CRIRES spectra of 30 bright field stars, each of them composed from almost all of the 200 grating settings. With this number of targets, we cover a sufficient range of stellar parameters across the HRD for a reasonable investment of telescope time. Roughly five targets are foreseen for each semester. Proposed targets for P84 and P85 and their location in the spectral-type *vs.* luminosity plane are shown in Figure 1.

	O	B	A	F	G	K	M	S/C
I								
II			e Vel		HD 109379			X TrA (C)
III						HD 83240	YY Psc	NZ Gem (S)
IV				LHS 1515				
V		τ Sco					Barnard's star	
Deviating abundance pattern			HD 118022					

Figure 1. Spectral classification of the CRIRES–POP targets in the first two observing periods (P84 and P85). The final library will consist of 25–30 stars.

Science goals

The CRIRES–POP science goals are at least as diverse as the fields of interest of the team members. At the cool end of the target list, a major goal is to identify line transitions of the molecules forming in the atmospheres. Depending on the prevailing chemistry of the target, either line transitions of oxygen-bearing molecules (e.g., H_2O or SiO) or of carbon-bearing molecules (CN-, CH-, C_2-components) can be identified. Objects enriched in *s*-process elements (S-type stars) offer a unique opportunity to identify lines of these interesting elements, but also of iron-peak elements whose line lists are far from complete in the NIR. We expect that new diagnostic features for studying the chemical and physical properties of stellar atmospheres will be identified in this way. Both the study and identification of molecular and atomic lines requires collaboration with laboratory spectroscopists, who are among the members of our team. The CRIRES–POP library and the lines identified in the spectra will be important when setting priorities for the laboratory work.

Nearby M dwarfs have recently come into focus for precise radial velocity studies to search for the lowest mass planets. Their intrinsic faintness and variability in the optical makes them ideal candidates for search campaigns in the NIR. The first successful studies have just been launched (e.g., Bean et al., 2009), but the choice of the optimal wavelength region for these studies is still ongoing (e.g., Reiners et al., 2009) and no empirical high resolution atlas for M dwarfs at 1–5 μm exists to help evaluate other spectral features beyond the well known CO overtone spectrum at 2.3 μm. The CRIRES–POP programme will address this question and thus deliver an important input for the study of extrasolar planets.

A broad range of science goals related to understanding stars is directly met by the CRIRES–POP programme. However, stellar photospheric features can also be a source of systematic error, for example when seeking to detect a faint companion or gas emission line from a circumstellar disc. For example, Ramsay Howat & Greaves (2007) found that removal of the spectrum of the stellar continuum of the M3.25 star ECHAJ0843.3-1705 increased the accuracy of the detection of the signal from molecular hydrogen (v = 1–0 S(1)) at 2.122 μm by 10 %, with a corresponding effect on the estimated mass of gas in the disc. Therefore, it is also our intention to provide a library of template stars that may be used to calibrate, and remove, continuum features from stellar photospheres that may mask faint spectral features which are the subject of a science programme.

Hotter stars can also be used both as telluric standards and to address scientific questions. Most prominently, NIR spectroscopy at high resolution will allow us to study the early phases of hot stars when they are still enshrouded by the gas and dust of their parental clouds.

The CRIRES–POP data will play a crucial role in testing and improving model atmosphere techniques across the HRD. Quantitative analyses of NIR spectra can involve a non-trivial extension of classical work in the optical, in particular for the hotter stars. The challenge is to model non-local thermodynamic equilibrium effects in the correct way. Surprisingly, even in the simplest case of hydrogen, the atomic data were, until recently, shown to be of insufficient quality to achieve consistency from the optical and NIR analyses (Przybilla & Butler, 2004). CRIRES–POP data will guide the work on refining the modelling to facilitate unbiased stellar parameter and element abundance determinations at high accuracy in the NIR domain.

Data reduction and release

The CRIRES–POP library of high S/N 1–5 μm spectra will allow for improvements in the general extraction and calibration of CRIRES spectra, and will foster intensive interaction with the CRIRES pipeline developers at ESO. Key interest comes from a strong improvement in the removal of telluric lines, as it opens up the study of weak features, such as from circumstellar material or rare elements and isotopes. In our approach, we will not use individual observations of telluric reference stars, but instead use one of the CRIRES–POP spectra of an early-type star to produce an accurate model of the atmospheric spectrum. This in turn will then be the basis for the removal of telluric lines from the CRIRES–POP data (cf. Seifahrt et al., 2010; Smette et al., 2010).

All raw data obtained for this programme become immediately public in the ESO archive. At the time of writing, complete spectra from 1 to 5 µm exist for two stars, namely the M giant YY Psc and the F8 subgiant LHS 1515 (see Figure 1). Two parts of the spectrum of YY Psc are shown in Figures 2 and 3, illustrating both the high quality of the spectra and the good results achieved for fitting the telluric spectrum with our model.

As soon as the full wavelength coverage for a star is complete and a brief quality check has been done by our team, the raw data become — in a more user-friendly way — available also on our project website[3]. Once available, all reduced spectra will be placed there as well. All spectra will be reduced in the same consistent way to ensure easy comparability between stars with different stellar parameters. Usage of these data will be made freely available, but we ask that researchers make reference to this *Messenger* paper or our forthcoming paper in a refereed journal (Lebzelter et al., in preparation).

Conclusions

We believe that our high quality NIR spectral library will be an extremely useful tool, e.g., for proposal planning and evaluation. In fact, these spectra will be of considerable interest for a wide variety of scientific investigations not only by the proposers, but by many others in the astronomical and laboratory astrophysics communities. CRIRES–POP will be well suited to the testing of atmospheric models, and for a revision and extension of atomic and molecular line lists, as well as for discovering weak features imposed on the spectral background of a bright star (e.g., for discovering companions or discs).

The CRIRES–POP spectra will be used in conjunction with the UVES–POP spectra and available UV spectra from satellite observatories (HST, IUE) in order to provide wavelength coverage from the far ultraviolet to the NIR. The extent of these data will trigger new ideas by allowing the entire spectrum to be considered. In the absence of high resolution ultraviolet spectra in the post-HST/STIS era, it may be necessary to create infrared diagnostics to replace those at ultraviolet wavelengths. With the focus of major forthcoming astronomical facilities, such as the James Webb Space Telescope or the Extremely Large Telescope projects, on the NIR, we expect that the CRIRES–POP library will find wide use throughout stellar astrophysics.

Further details on CRIRES-POP can be found on the project website[3].

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Links

[1] The CRIRES instrument: http://www.eso.org/sci/facilities/ paranal/instruments/crires/
[2] UVES–POP page at ESO: http://www.eso.org/sci/observing/tools/uvespop/
[3] CRIRES–POP: http://www.univie.ac.at/crirespop/

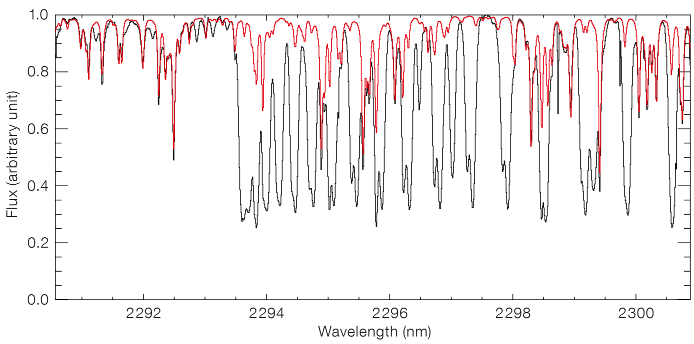

Figure 2. CRIRES spectrum of the M3 giant star YY Psc (black line) taken at the reference wavelength 2308.7 nm, showing the prominent 2–0 band head of CO. The red line shows the telluric model spectrum with lines mainly caused by water vapour and methane fitted to the observed spectrum.

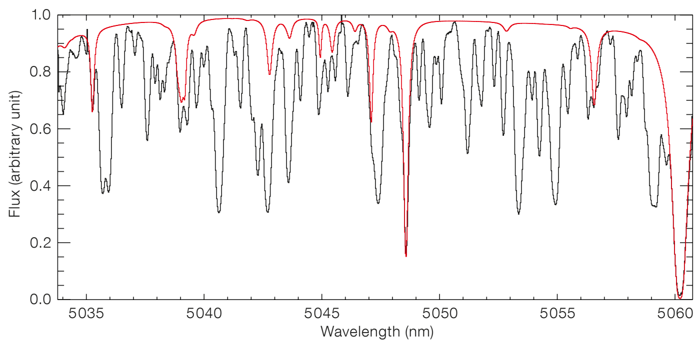

Figure 3. CRIRES spectrum (black line) of YY Psc taken at the reference wavelength 5114.0 nm. The spectrum is dominated by lines of CO and includes interesting low excitation lines of $^{13}C^{16}O$ and $^{12}C^{18}O$. The red line shows the telluric model spectrum with lines caused by water vapour fitted to the observed spectrum.