Exploring the Near-Infrared at High Spatial and Spectral Resolution: First Results from CRIRES Science Verification

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The VLT cryogenic high-resolution infrared echelle spectrograph CRIRES offers high spatial, spectral and temporal resolution spectroscopy from 1 to 5 μm. Highlights from among the 29 pilot studies of the CRIRES science verification (SV) runs are summarised.

The VLT cryogenic high-resolution infrared echelle spectrograph CRIRES (Käufl et al. 2004) is located at the Nasmyth focus A of UT1 (Antu). It provides a resolving power of up to 100000 in the spectral range from 1 to 5 μm. CRIRES can boost all scientific applications aiming at fainter objects, higher spatial resolution (for extended sources), spectral and temporal resolution. Spectral coverage is maximised through a mosaic of four Aladdin III InSb arrays providing an effective 4096 × 512 detector array in the focal plane. A MACAO (Multi-Applications Curvature Adaptive Optics) system can be used to increase both spatial resolution and signal-to-noise ratio.

The scientific potential of the CRIRES instrument is demonstrated by the many results obtained during three science verification observing campaigns which have been performed in August, October 2006 and in February 2007. Twenty-nine pilot studies were granted observing time totaling 20000 s integration time. The principal investigators (PI) and project titles of the successfully executed SV programmes are given in Table 1. Individual projects range from studies of the Earth's atmosphere, disc structure around young stars, brown dwarfs (BD), extrasolar planets to pulsation and wind properties of massive stars, asymptotic giant branch stars (AGB), structure of the Galaxy and astroseismology. In this article some of the highlights are presented in a sequence beginning with young stars, brown dwarf stars and planets,

Tabel 1: CRIRES science verification runs: principal investigator (PI) and project title is given for each programme.

ID	PI	Title
1	Amado	NIR spectroscopy of pulsating stars?
2	Bik	Circumstellar discs around massive young stellar objects
3	Carmona	Probing the gas in the inner 50 AU of proto-planetary discs
4	Foellmi	Distances to late-type stars
5	Goto	H_3^+ and CO observation toward Superantennae
6	Günther	CRIRES for high precision RV of late-type stars
7	Gustaffson	CNO abundances in Bulge giants
8	Käufl	Search for OH in the disc around HD 163296
9	Kerber	Determining the atmospheric precipitable water vapour content
10	Kjaer	High resolution infrared spectrum of SN 1987A
11	Kurtz	High time-resolution precision radial velocities of peculiar A stars
12	Lidman	A high-resolution spectral atlas of the night sky
13	Linz	Disc winds and envelopes associated with BN-type objects
14	Martins	The most massive stars in the GC: binarity and metallicity
15	Melnick and Gredel	Molecular hydrogen in Doradus 30
16	Moutou	Transmission spectroscopy of transiting extrasolar planets
17	Nissen	The abundance of sulfur in metal-poor stars
18	Nürnberger	Weighing a high mass protostellar candidate
19	Reiners	FeH spectroscopy in ultra-cool dwarfs – CRIRES or UVES?
20	Sana	Can IR solve the wind clumping question?
21	Seifahrt	Effective temperatures and gravities of low-mass stars and BD
22	Siebenmorgen	Astrochemistry in dust formation regions
23	Siebenmorgen	Roadmap of astrochemistry during massive star formation
24	Siebenmorgen	Bound on time dependency of the fine structure constant
25	Smette	Na I D and Ca II in a $z \sim 2$ damped Lyα system
26	van Dishoeck	CO emission from transitional protoplanetary discs
27	Uttenthaler	The C/O and $C^{12}/C1^{3}$ ratios and three dredge-up in bulge AGB stars
28	Uttenthaler	Titanium Oxide band heads in the *J*-band
29	Valenti	Chemical composition of evolved populations in LMC and NGC 1866

followed by massive and Asymptotic Giant Branch stars to targets outside the Galaxy. Finally CRIRES calibration issues are mentioned.

Discs around massive young stellar objects and extrasolar planets

The known circumstellar discs around massive young stellar objects T Cha and IRAS 16164–5046 were studied by van Dishoeck [ID 26] and by Bik [ID 2], respectively. The CO first-overtone emission in the *K*-band probes high-temperature gas (T = 3 000 K) and the velocity profile of IRAS 16164–5046 suggests that the hot gas is located in a rotating disc within 10 AU of the central star. The CO-fundamental transitions in the *M*-band probe lower-temperature gas (T = 50–500 K) and therefore different regions in the circumstellar material. Figure 1 shows three transitions of the ^{12}CO spectrum of IRAS 16164–5046. The R(7) line is more sensitive to higher temperature compared to R(0). The spectra reveal two absorption components; a saturated blue component which could be caused by an outflow or wind, and a red, unsaturated component which changes in intensity from the higher to the lower energy level. This extra red absorption could be a cold envelope surrounding this object.

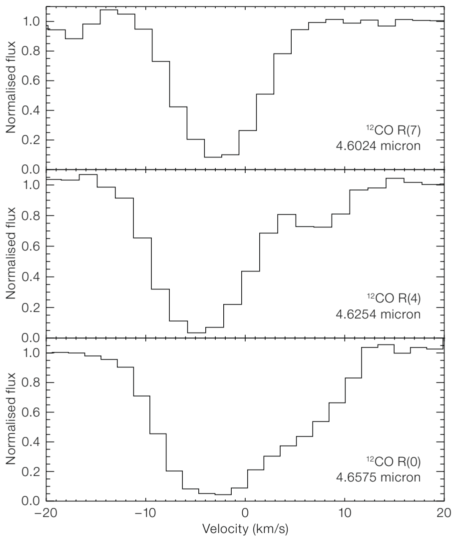

Figure 1: ^{12}CO profile of the massive young stellar object IRAS 16164-5046. From top to bottom, lines R(7), R(4) and R(0) are plotted. The R(0) line is more sensitive to cold material than the other two. Two components can be identified, one belonging to the cold envelope and the other component caused by a wind or outflow (Bik et al.).

A full *L*- and *M*-band (3 600–5 100 nm) wavelength scan of the spectrum of the extremely red and massive protostar W33A was performed, aiming to achieve a first road map of the astrochemistry occurring during the formation process of massive stars. A section of it, corresponding to the spectral region near 4 200 nm, is shown by Käufl et al (2007). Figure 2 compares the rich CO line system (near 4 730 nm) to the broad Brα and Pfγ lines. Derived radial velocities (RV) for CO, Brα and Pfγ lines are ~ 31 km/s confirming earlier estimates (Roueff et al. 2006).

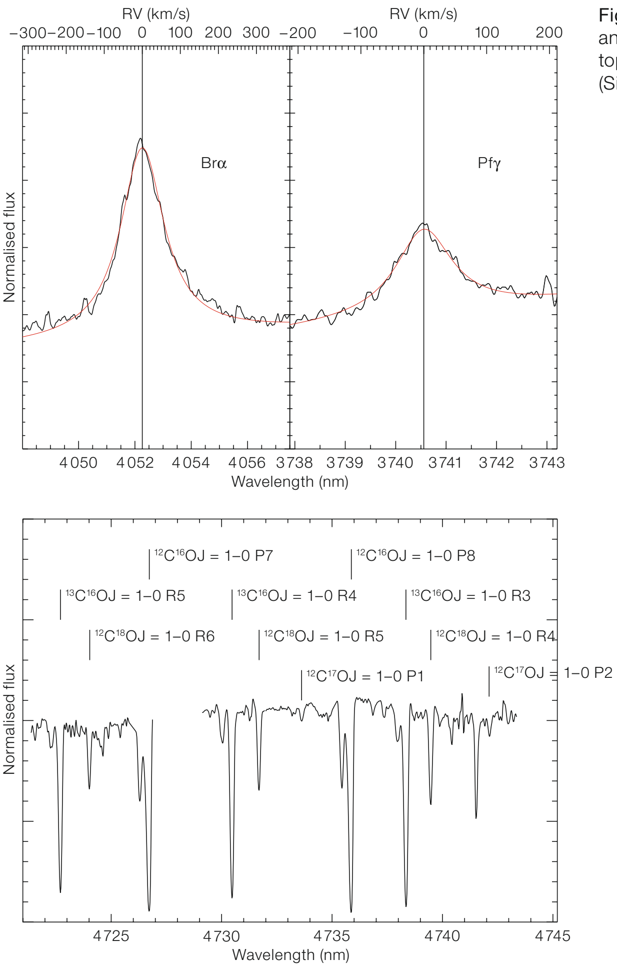

Figure 2: Line flux and RV of the Brα and Pfγ (top) and various CO isotopes (bottom) of the protostar W33a (Siebenmorgen et al.).

Carmona [ID 3] obtained *K*-band spectra of the classical T Tauri star LkHα 264. They confirm the previous discovery of the ro-vibrational ν = 1–0 S(1) H_2 line. In addition, thanks to the enhanced sensitivity of CRIRES, they detect at 2 223.3 nm the ν = 1–0 S(0) H_2 transition. However, the spectra do not reveal the ν = 2–1 S(1) H_2 line. The line ratios of 1–0 S(0)/1–0 S(1)

= 0.33 ± 0.1 and 2–1 S(1)/1–0 S(1) < 0.2 indicate that the H_2 emitting gas is at temperature below 2000 K and most likely thermally excited by UV photons. Both detected lines have a FWHM of ~ 20 km/s and are spatially unresolved. The mean FWHM of the PSF in the continuum is ~ 0.36″ in the H_2 1–0 S(1) spectrum, constraining the H_2 emitting region to the inner 50 AU of the disc at an assumed distance of 300 pc. The ν = 1–0 S(1) and the ν = 1–0 S(0) H_2 lines in LkHα 264 are single peaked. Modelling of the ν = 1–0 S(1) line shape indicates that the disc has a relatively small inclination. The best model fit suggests that the disc surrounding LkHα 264 is inclined by 20° relative to the line of sight (Figure 3).

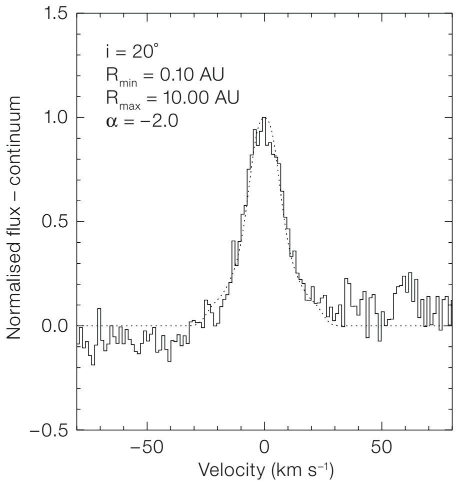

Figure 3: H_2 ν = 1–0 S(1) line detected in LkHα 264 at 2121.8 nm and model (dashed) assuming that the emission originates in a circumstellar disc. The fit parameters R_{min} and R_{max}, the inner and outer radius of the emitting region, α, the power law exponent of the intensity ($I(R) \propto R^{\alpha}$) and i, the inclination angle (Carmona et al.), are listed.

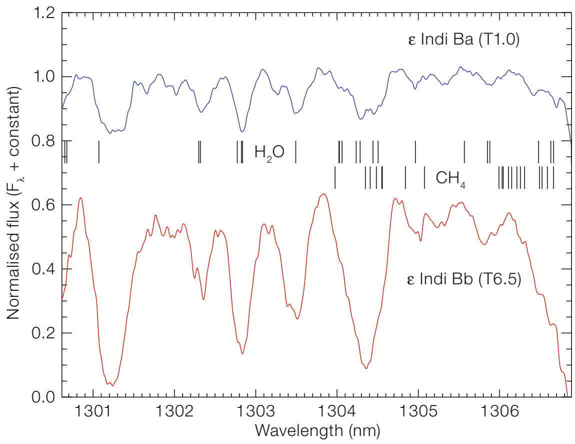

Figure 4: Cut–out of the high-resolution spectrum of the binary components ε Ind Ba (top) and Bb (bottom). Lines of water vapour (H_2O) and methane (CH_4) are marked. Note the increase in line strength for both species between the T1 dwarf (Ba) and the T6.5 dwarf (Bb) and the strong line broadening by the high projected rotational velocity *v* sin *i* ~ 28 km/s (Seifahrt et al.).

Late-type objects of spectral type M and later exhibit extremely interesting absorption bands. In particular, the molecular band of FeH shows sharp absorption lines that can be used for precision spectroscopy, a rare feature for late-type stars and brown dwarfs. These lines appear in the spectral range close to ≈ 1000 nm, at the red end of the UVES spectral coverage and at the blue one of CRIRES. A performance test of both instruments in this overlapping region was carried out by Reiners [ID 19] on GJ 2005A, a M5.5 star, observed with CRIRES and MACAO, while Gl 406, a star of the same spectral type, was observed with UVES. The FeH absorption of both stars resembles each other very closely. The UVES data were taken at a resolution of 50000, and for comparison CRIRES data were rebinned to match this lower resolution. The UVES exposure of Gl 406 (V = 13.54) yielded a SNR of 60 after 200s whereas the CRIRES spectrum on the much fainter star GJ 2005 A (V = 15.42) gives a SNR of 50 after 480 s. Therefore, in this overlapping wavelength region, UVES requires roughly twice the observing time of CRIRES to reach the same SNR for similar flux levels and spectral resolution.

The closest T dwarf to the Sun (3.26 pc), ε Ind B, is an ideal system to improve our understanding of substellar objects by detailed spectral measurements. The two members of this extreme cool brown dwarf binary have spectral type T1 and T6.5 and masses of ~ 47 and 28 M_{Jup}, respectively. The CRIRES spectroscopy campaign by Seifahrt [ID 21] concentrated on a K I line at 1252.5 nm, water vapour and methane (CH_4) features at wavelengths close to the peak flux of T dwarfs. For the first time in natural-seeing observations, spectra of both binary components, separated by ~ 0.9″, have been obtained with spectral resolution of R ~ 50000 (Figure 4). The S/N of the spectra are between 20–60 (per pixel) which is in close match to the predictions of the CRIRES exposure time calculator (ETC). Detailed comparison of the spectra to synthetic atmospheric models as well as to existing T dwarf models are in progress. In particular, the relative radial velocity of ε Indi Ba-Bb will improve their orbital parameters.

Precise radial velocity (RV) measurements are important in many astrophysical objects. In particular, they have led to the discovery of more than 200 extrasolar planets. Carrying out equivalent measurements at infrared wavelengths has several advantages: indeed, late-type stars and brown dwarfs are much brighter at infrared wavelengths while the RV-jitter caused by stellar activity is about one order of magnitude smaller in the infrared than in the optical regime (Martins et al. 2006). Günther [ID 6] observed the M0V star GJ9847 in two different nights, obtaining spectra with the N_2O-absorption cell, as well as template spectra without. Simulations predict that the simultaneous wavelength reference allows a radial velocity precision of better than 30 m/s to be achieved. Even though improvements in the data analysis are still possible this accuracy is already achieved. The basic idea of the procedure is the same as for the I_2-cell method in the optical, which has been used for many years for planet detection. The main difference is that the influence of the telluric absorption lines has to be carefully removed. This is achieved by dividing the spectrum by a reference star free of absorption features, e.g. a B-type star. This technique is illustrated in Figure 5 for the M0V star GJ 9847.

The SV programme by Moutou [ID 16] aimed at detecting the absorption signature of a planetary atmosphere, during a transit of the extrasolar planet in front of its parent star. This requires high spectral resolution to deblend the planetary features from the stellar ones at a certain epoch. For such transiting systems, one expects to detect a K I absorption feature in the near-IR. Unfortunately during the execution of the programme, the CRIRES observing sequence could not fully meet the time critical window that lasted a little more than two hours. The data however show differences from one spectrum to the other and a longer lasting sequence is allocated in P79.

Massive stars, Asymptotic Giant Branch stars and Galactic structure

The Pistol star, located close to the Galactic Centre, is the most luminous star in the Galaxy. Unless it is actually made up of various components, it is also the best candidate to be the most massive star. The very high resolving power of CRIRES was used by Martins [ID 14] to investigate the presence of a spectroscopic companion, as well as to constrain the abundance of a few key elements (Si, Mg and Fe). Data were obtained during the February run and are currently being analysed with atmospheric models. They will reveal whether the Pistol star is truly a very massive star, and will provide the ratio of alpha elements to Fe, a quantity which critically depends on the chemical enrichment history and the IMF in the Galactic Centre.

Information on star interiors can be obtained through the determination of the frequencies of pulsation modes as they emerge at the stellar surface, a technique known as astroseismology. Amado et al. [ID 1] tested the feasibility of astroseismology in the NIR. For 3.5 hours, they continuously observed the strongly photometric δ Scuti variable star, 1 Mon and searched for the presence of line profile or equivalent width variations due to the pulsations.

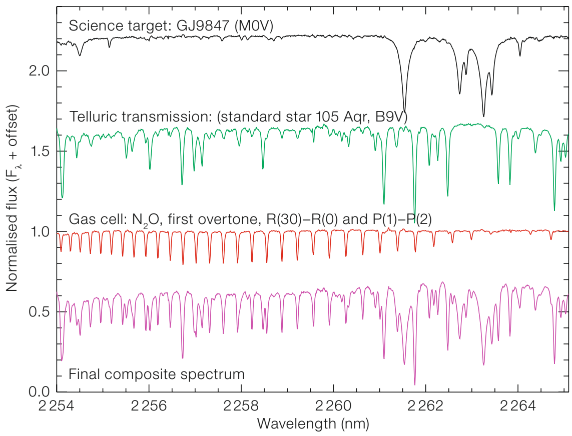

Figure 5: From top to bottom and shown as indicated: the normalised spectrum of GJ9847; the telluric standard star; the N_2O gas cell; and the final composite spectrum (Günther et al.).

O-type stars are among the brightest and most luminous stellar components of a galaxy. Through their radiation and wind momentum, they largely influence their surroundings as well as their host galaxies. However, our knowledge of these objects is still fragmentary. One of the currently most critical questions is related to the exact properties of their stellar winds, which determine their mass-loss rates, and thus their evolution to become supernovae. CRIRES allows to significantly increase the number of accessible diagnostic lines. Sana [ID 20] acquired a high S/N ratio spectrum of ζ Pup, an O4 supergiant and one of the closest O-type stars. The comparison of the observed line profile with the one predicted from atmospheric models should provide tight constraints on its wind properties and, more specifically, on its clumping factor. Using ESO and IUE archives, a multi-wavelength analysis covering the whole spectral range from the UV to the near-IR domain is foreseen. The complementarity of the diagnostic lines in these various wavelength ranges should help to obtain a self-consistent view of the atmosphere of this massive star.

Nissen [ID 17] choose extreme metal-poor stars in the Galactic halo to study the abundance of Sulphur, an α-element, considered an important diagnostic for galactic chemical evolution (see the article by Nissen et al. on page 38). Infrared observations of atomic lines in the near-infrared are an important complement to visible (UVES) spectra, as they can be less sensitive to details of the atmospheric models and may have substantially larger oscillator strengths. An impressive spectrum with a S/N of 330 was achieved (Nissen et al. 2007 – the first published refereed paper from CRIRES).

The infrared absorption spectra of H_3^+ and CO were observed by Goto [ID 5] toward the luminous infrared source in the Quintuplet cluster GCS 3-2 and is shown in Figure 6. Note the distinct absorption profiles of H_3^+ $R(1,1)^l$ and CO R(1) along the same line of sight. While CO mostly probes the gas in molecular clouds in the Galactic arms along the line of sight, the H_3^+, responsible for $R(1,1)^l$, occurs both in arm clouds and in the gas at the Galactic Centre region. The pedestal component of $R(1,1)^l$ is almost indentical with the broad absorption band of $R(3,3)^l$ obtained at Subaru and Gemini South. $R(3,3)^l$ however exclusively samples the gas in the Galactic Centre. The population of H_3^+ in the metastable state (J,K) = (3,3), 361 K above the ground state, attests to the presence of warm (T ~ 250 K) and diffuse gas (N_H ~ 100/cm^3) in the central molecular zone, which was unknown before (Oka et al. 2005).

Uttenthaler [ID 27] obtained *H*- and *K*-band spectra of a handful of bulge AGB stars to determine the C/O and $^{12}C/^{13}C$ ratios. These ratios are influenced by a deep mixing event called the third dredge-up (3DUP) which occurs on the AGB. If 3DUP has occurred in a given star, the $^{12}C/^{13}C$ ratio should be high (compared to the solar value of ~ 89), otherwise it should be low (< 10). As an example the CRIRES spectrum of M794 reveals a strong ^{12}CO 4–2 band head but weak ^{13}CO lines (e.g. at 2354.25 and 2355.1 nm), so that this star has a rather low $^{12}C/^{13}C$ ratio. Further support that

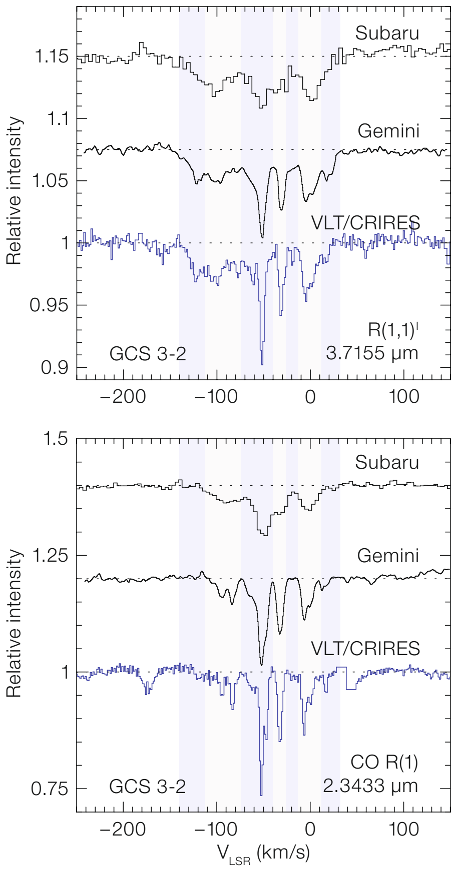

Figure 6: Infrared absorption spectra of H_3^+ R(1,1)^l and CO R(1) towards the Quintuplet cluster GCS 3-2 observed with three different high-resolution spectrographs. The performance of IRCS at the Subaru telescope (with spectral resolving power R = 20 000) and Phoenix at Gemini South (R = 75 000) is compared to that of CRIRES at the VLT (R = 100 000). The higher velocity resolution of CRIRES is the obvious advantage among the other instruments on 8-m-class telescopes.

M794 has not experienced a 3DUP is given by the non-detection of Technetium, a radioactive indicator for this process. Interestingly, as determined from UVES spectra, this star shows Lithium in its atmosphere, which is rather surprising for a previously classified low-mass AGB star. Most probably another mixing process – called cool bottom processing – is at work in this star, reducing the $^{12}C/^{13}C$ ratio almost down to its equilibrium value.

Gustaffson [ID 7] studied the CNO abundances in bulge giants, first, as a SV trial run and subsequently in an allocated programme in period P79. The team is a large international collaboration including members from Australia, Brazil, Chile, France, Germany and Italy. Studying the Milky Way Bulge is particularly important and, as an ultimate goal, should answer the question of whether it is the Galaxy's oldest region, perhaps together with the Halo. Alternatively, it could have been gradually formed, at least partially, from stars and gas in the disc that migrated inwards. These hypotheses can be discriminated by obtaining the ages of a considerable number of Bulge red giant stars using the ratios of heavy element abundances, in combination with their kinematics, as a chronometer. The main reason for observing in the IR (see Ryde et al. 2005) is the much smaller interstellar extinction so that the whole Bulge is observable and not just a few windows transparent at optical wavelengths. Only the near-IR offers all the indicators necessary for accurate determination of the important C-N-O molecular equilibrium in the atmospheres of cool stars, through the simultaneous observation of many clean CO, CN and OH lines. The goal with the SV run was to test the method. The result was successful, even though, only three Bulge stars could be observed. Figure 7 shows the CRIRES spectrum of one of them, Arp 4203. The wavelength range 1531–1570 nm was recorded and only a 1/4 of the spectrum is shown for clarity. From the derived abundances, the findings are that, e.g., the giant star Arp 4203 is depleted in C, enriched in N, with an excess of O relative to Fe but compatible with the alpha elements (Mg, Si and Ca). The C and N abundances are signs that matter exposed to the CN cycle (which conserves the sum of C and N nuclei) has been dredged up to the stellar surface. The sum of the abundances of C, N, and O is close to that expected from a non-processed old star, formed with an excess of oxygen and alpha elements relative to iron. The preliminary elemental abundances are presented in Ryde et al. (2007), while a full analysis will be presented in a forthcoming paper.

Outside the Galaxy

Two extragalactic SV projects were executed. Siebenmorgen [ID 24] tried to constrain variations in the fine structure constant, $\alpha = e^2/hc$ by observing the [O III] doublet redshifted to $z \sim 2$. The QSO 1148-001 was selected as it shows a bright doublet unresolved at low resolution. Unfortunately, the lines are too broad when observed at a resolution of

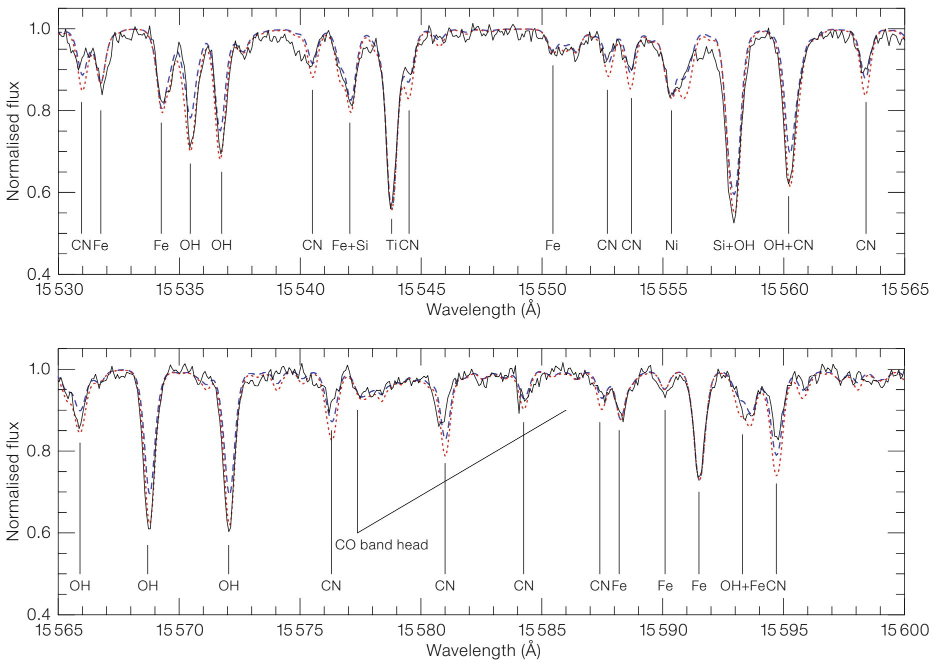

Figure 7: Two sections of the CRIRES spectrum of Arp 4203 are presented (full line, black) together with models with nitrogen increased by +0.4 dex (dashed, blue) relative to the best fit, and when oxygen is instead decreased by 0.2 dex (dotted, red). For clarity the best-fit model is not shown (Gustaffson et al.).

50000 and no useful constraint could be derived.

A second project focused on the ISM of proto-galaxies at $z > 2$ (Smette [ID 25]). The Na I and Ca II absorption lines are common features in the ISM of our Galaxy, but so far they have never been observed in the ISM of objects with redshifts larger than one. CRIRES offers the possibility to extend the study of the ISM by means of these important lines for damped Lyman-systems (DLA) at high *z*. These lines provide important information regarding the velocity structure of the gas. Na I can be compared with the low-ionisation lines seen in UVES spectra to better constrain the ionisation conditions. At low redshift, Ca II is often seen in turbulent material such as the one seen in the merging galaxies. Comparison between Na I and Ca II is also a very good indicator of the clumpiness of the gas. The QSO HE0251-5550, chosen from the H/ESO DLA survey (Smette et al. in prep.), has a hydrogen column density $\log(N_{HI}) = 20.7$ DLA in its spectrum and a redshift of $z = 2.3$, allowing the search for Na I and Ca II doublets with CRIRES. Although the object is bright enough in *R*-band to close the AO loop, though with little improvement in image quality, the faintness of the QSO (H = 14.6) made guiding somewhat difficult, as insufficient flux is reflected back from the slit jaws to the slit viewer detector. The spectra covering the Na I lines reached the expected S/N but did not reveal the lines, probably because of the low metal abundance of this system. Unfortunately, the seeing degraded during the promising, yet challenging, observations of the Ca II lines and the spectra have an unusably low S/N. Despite the non-detection, these observations were a good test of the feasibility to observe such 'faint' targets with CRIRES, in particular, when the high resolution allows one to avoid the effects of telluric lines.

Calibration of CRIRES data: CRIRES and the Earth's atmosphere

Observing with CRIRES as well as calibrating and reducing CRIRES data revealed multiple challenges that the science verification programmes helped to identify. A large number of the problems that the CRIRES team met during the execution of the programmes have been solved in time for science operations, while work is still going on for others.

For example, the high-resolution capabilities of the instrument are a challenging aspect when it came to the development of a precise ($\sigma(v) \sim 70$m/s), robust and automatic wavelength calibration procedure. The pipeline, now in use to assess the quality control of the data, uses as first guess the wavelength solution provided by a physical model of the instrument, which is accurate to about 1–2 pixels. It then cross-correlates data with other catalogues such as telluric features computed by HITRAN or OH line lists. In addition, CRIRES supports high-accuracy wavelength calibration by means of gas cells and a ThAr hollow cathode lamp (Kerber et al. 2007).

But an accurate and precise wavelength calibration relies on a large number of lines on each detector. Ideally, these lines should be observed simultaneously with the target. Such is the case for observations through gas cells. In several spectral bands, the sky lines are very numerous. However, little is known of their apparent wavelength stability which could limit their use for high-accuracy wavelength calibration. Such a study – the feasibility of using OH lines to calibrate CRIRES data – is at the base of the proposal of Lidman [ID 12], as this molecule shows a rich ro-vibration spectrum. Before CRIRES, OH sky line spectra had only been systematically obtained with spectral resolutions of 10000 or less. CRIRES spectra of the OH lines were taken during evening twilight, which is the time when they are at their brightest. In a single 300-s exposure it is possible to see up to a dozen lines on a single detector and up to four times that number over the entire mosaic. In order to assess their wavelength stability, data over several nights were obtained, immediately followed by a ThAr spectrum. A quick inspection of the R ~ 100000 spectra reveals that CRIRES resolves doublets which are seen as single lines at spectral resolution of 10000 (see Figure 9 in Siebenmorgen and Smette 2007). However, even at a resolution of 100000 CRIRES does not resolve individual lines. Also, a number of sky lines appear that are not listed in available catalogues and *vice versa*.

CRIRES is also helping ESO in preparation for the next generation of giant telescopes. Kerber [ID 9] tested a method to measure the atmospheric content of precipitable water vapour (PWV) using the equivalent widths of H_2O absorption lines in the near-IR which are imprinted onto the spectra of early-type stars. An accurate and efficient method to determine the PWV is highly valuable for any thermal IR instrument at an E-ELT. For quantitative measurements, unblended water lines are selected to have a minimum dependence of their absorption coefficient at a temperature of ~ 300 K. CRIRES spectra of bright stars were observed on several nights during SV. On some of these nights routine measurements with VISIR (see Smette et al. 2007) can be used to establish the PWV from mid-IR data allowing for comparison across wavelength and method. Very acceptable agreement between both methods and instruments is found.

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