Good Vibrations: Report from the Commissioning of CRIRES

Hans Ulrich Käufl, Paola Amico, Pascal Ballester, Eduardo Bendek, Peter Biereichel, Paul Bristow, Mark Casali, Bernhard Delabre, Reinhold Dorn, Siegfried Eschbaumer, Raul Esteves, Enrico Fedrigo, Gert Finger, Gerhard Fischer, Gordon Gillet, Domingo Gojak, Gotthard Huster, Yves Jung, Florian Kerber, Jean-Paul Kirchbauer, Jean-Louis Lizon, Enrico Marchetti, Leander Mehrgan, Manfred Meyer, Alan Moorwood, Sylvain Oberti, Jean-François Pirard, Jérome Paufique, Eszter Pozna, Francesca Primas, Ricardo Schmutzer, Andreas Seifahrt, Ralf Siebenmorgen, Armin Silber, Alain Smette, Barbara Sokar, Jörg Stegmeier, Lowell Tacconi-Garman, Sebastien Tordo, Stefan Uttenthaler, Ueli Weilenmann (all ESO)

CRIRES is a cryogenic, pre-dispersed, infrared echelle spectrograph designed to provide a nominal resolving power $\lambda/\Delta\lambda$ of 10^5 between 1000 and 5000 nm for a nominal slit width of 0.2″. The CRIRES installation at the Nasmyth focus A of the 8-m VLT UT1 (Antu) marks the completion of the original instrumentation plan for the VLT. A curvature sensing adaptive optics system feed is used to minimise slit losses and to provide 0.2″ spatial resolution along the slit. A mosaic of four Aladdin InSb-arrays packaged on custom-fabricated ceramic boards has been developed. It provides for an effective 4096 × 512 pixel focal plane array to maximise the free spectral range covered in each exposure. Insertion of gas cells is possible in order to measure radial velocities with high precision. Measurement of circular and linear polarisation in Zeeman sensitive lines for magnetic Doppler imaging is foreseen but not yet fully implemented. A cryogenic Wollaston prism on a kinematic mount is already incorporated. The retarder devices are located close to the Unit Telescope focal plane. Here we briefly recall the major design features of CRIRES and describe the commissioning of the instrument including a report of extensive laboratory testing and a preview of astronomical results. Thanks to the strong efforts of the CRIRES commissioning team and all other ESO staff involved, it was possible to include the instrument in the general ESO call for proposals for Period 79.

The CRIRES spectrograph is the last instrument of the first-generation VLT instrumentation plan (D'Odorico et al. 1991). It was included in the very first call for VLT instruments in 1989. Then several options for this instrument were discussed during the Workshop on High Resolution Spectroscopy with the VLT held at ESO in 1992 (Ulrich 1992). By then, however, infrared astronomy had just left behind the era of single-pixel detectors. In fact in those days there was even a strong case to build a Fourier-transform spectrometer, rather than a grating spectrograph. The small detector formats of those days would have left a grating spectrograph with a rather limited spectral coverage. The trade-offs then were analysed in some detail at ESO. By 1997, however, detector formats and the respective performance had developed sufficiently to secure the formal inclusion of CRIRES in the VLT instrumentation plan. The CRIRES instrument is an entirely ESO internal project. The instrument team was advised, as for all other VLT instruments, by a specific science team[1]. As there was some competition for the limited resources within ESO, the project proceeded slowly but steadily. Finally the instrument had its real start in 1999. The preliminary design review (PDR) was held in April 2000 and the final design review (FDR) took place in October 2001. Assembly and integration progressed and in January 2005 the team celebrated 'first light' in the laboratory. For the rest of 2005 the team was busy bringing the spectrograph in line with specifications, understanding and fixing many problems. Finally, in December 2005 the two independent subsystems of CRIRES, the vacuum vessel with the cryogenic assembly and the adaptive optics part, were merged and integrated. This marked the start of end-to-end testing. Since then nearly all tests required to pass the Preliminary Acceptance Europe (PAE) review could be performed. CRIRES was then again split and the adaptive optics part sent to Paranal to be commissioned independently (c.f. Käufl et al. 2006). Meanwhile the cryostat underwent last modifications and tests to arrive at a state that also the basic spectrograph was itself ready for the review process. The PAE review meeting was held on 13 April 2006 and the green light for shipping – after completing the essentials from the action item list – was granted on 25 April. Thereafter, in a process which in retrospect resembles a miracle, CRIRES was literally ripped to pieces, packed, collected by the shipper in Garching on 28 April and shipped to Paranal to arrive in record time. Unpacking could commence on 7 May, only nine days later. The cryostat was pre-erected in the laboratory, while the (heavy) instrument support was mounted immediately directly to the Nasmyth platform of UT1. In spite of the extremely fast packing, shipping and unpacking not even minor transport damage was encountered. The instrument was then tested for two weeks in the integration lab of the VLT control building. Laboratory testing ended on 25 May and, after warm-up of CRIRES, a few minor last-minute changes were applied. CRIRES was then transferred to its final location for the foreseeable future, the Nasmyth platform A of UT1 (Figure 1).

Main characteristics

Figure 2 shows the general layout of CRIRES and Figure 3 gives an impression of the cryogenic instrument. The instrument main characteristics are summarised in Table 1. The instrument and its operations concept have been described in some detail by Käufl et al. 2004. For the latest state the reader is referred to the CRIRES User's manual: *http://www.eso.org/instruments/crires/*

For calibration a physical model approach has been taken. In spite of the crowded scheme, as shown in Figure 2, CRIRES is from the model point of view rather simple: once the telescope/slit-viewer scale in the slit-plane have been calibrated, the pre-slit optics has no real influence anymore on spectral and spatial calibration. It it thus not part of the model. The predisperser can be easily represented by a re-imager with a magnification close to unity and, according to the optical design calculations, negligible distortion. The

---

[1] The members of the CRIRES science team are: Catherine de Bergh, Meudon; Ewine van Dishoek, Leiden; Bengt Gustafsson (chair), Uppsala; Artie Hatzes, Tautenburg; and Ken Hinkle, Tucson.

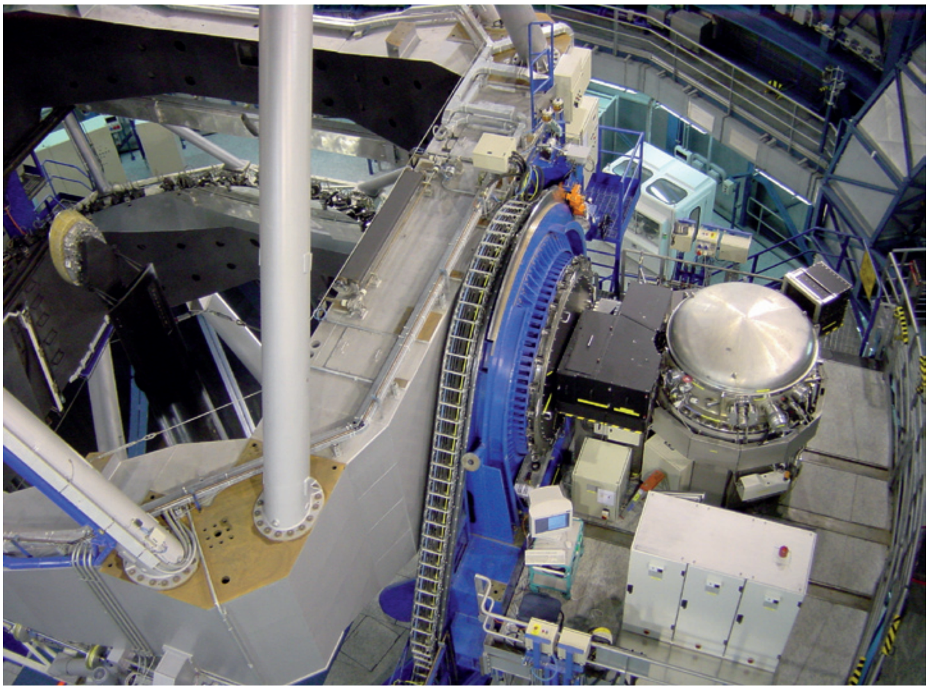


Figure 1: CRIRES at its final destination, the Nasmyth platform A of UT1 (Antu). It is still amazing that even a rather big instrument is literally dwarfed by the VLT. On the right side of the blue Nasmyth adaptor the 'black box' holding the de-rotator and the MACAO adaptive optics system can be seen. Below this box are calibration lamps and an integrating sphere. Inside the box is a motorised linear stage to position the gas cells, the retarder plates and other auxiliary optical elements. The gray cylindrical structure is the vacuum vessel containing the instrument cryogenic opto-mechanical assembly. CRIRES is cooled to ~ 65 K.

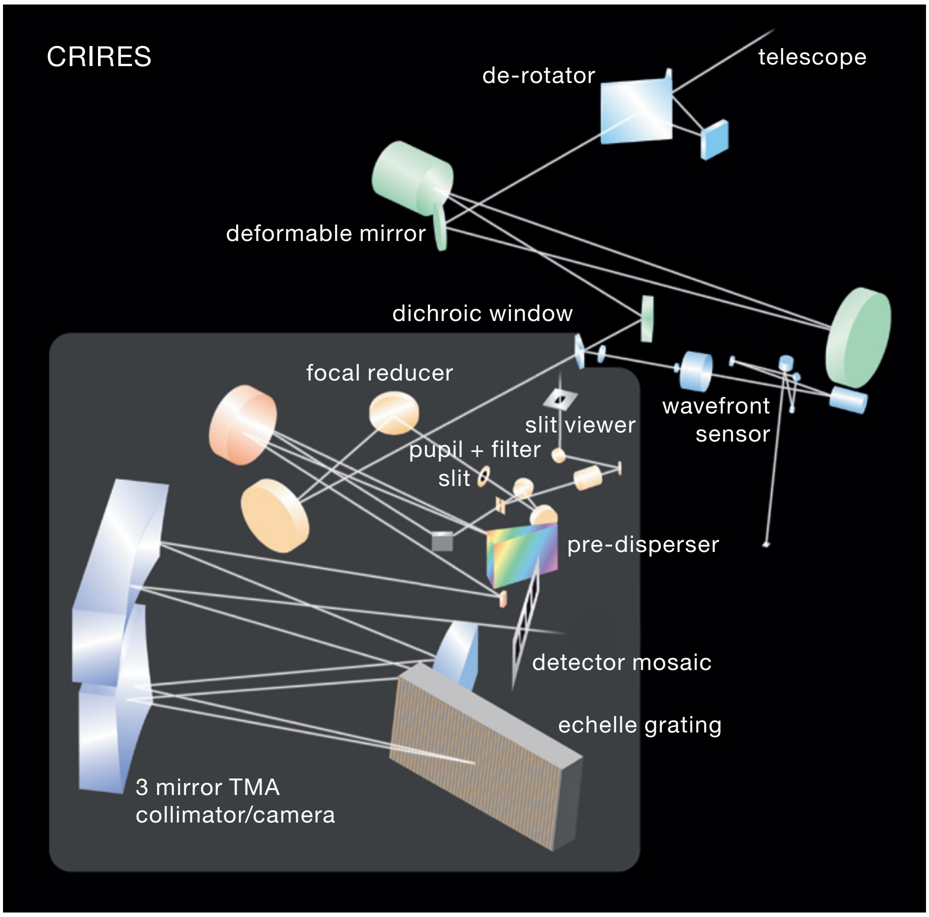


Figure 2: The CRIRES optical design. The VLT Nasmyth focus (f/15) is close to the first mirror of the de-rotator assembly. There is a calibration unit (neon arc-lamp, ThAr hollow cathode lamp, a halogen lamp and an infrared glower in combination with an integration sphere) for flat fielding and spectral calibration. In addition, a selection of gas cells can be moved into the beam for calibration and for search for very small radial velocity changes similar to the Iodine-cell technique applied in optical spectrographs. Instead of the gas cells retarders in a motorised mount can be placed to use CRIRES for spectro-polarimetry (see text). The de-rotator is followed by the curvature sensing adaptive optics system with the deformable mirror on a kinematic gimbal mount. The entrance window to the cryostat is a dichroic, separating the visible light with high efficiency for the AO wavefront control. The entire optical bench is cooled by three closed cycle coolers to ~ 65 K. The pre-slit optics of CRIRES consists of an all-reflective re-imager with a cold-pupil stop, reducing the f-ratio to an ~ f/7.5. Close to the cold pupil a Wollaston prism (MgF_2) can be inserted, eventually with a linear polariser compensating instrumental polarisation. The slit-viewer has a BaF_2/Schott N-SF56 doublet as an objective giving a pixel scale of ~ 0.05 arcsec/pixel and an unvignetted field of view of 25 × 50 $arcsec^2$. The main slit is continuously adjustable up to several arcsec with a closed-loop encoder controlling the slit separation. The pre-disperser has a collimated beam diameter of 100 mm and uses a ZnSe prism in retro-reflection. The collimator mirror can be slightly tilted with a piezo for vernier adjustment to compensate for stick-slip effects in the grating and the prism drives. Order selection in the pre-dispersed spectrum is provided by a second intermediate slit located close to the small folding mirror next to the pre-disperser. The main collimator, a three-mirror anastigmat, produces a 200-mm collimated beam which illuminates an R2 Echelle grating (31.6 gr/mm).

Photo: J.-L. Lizon, ESO

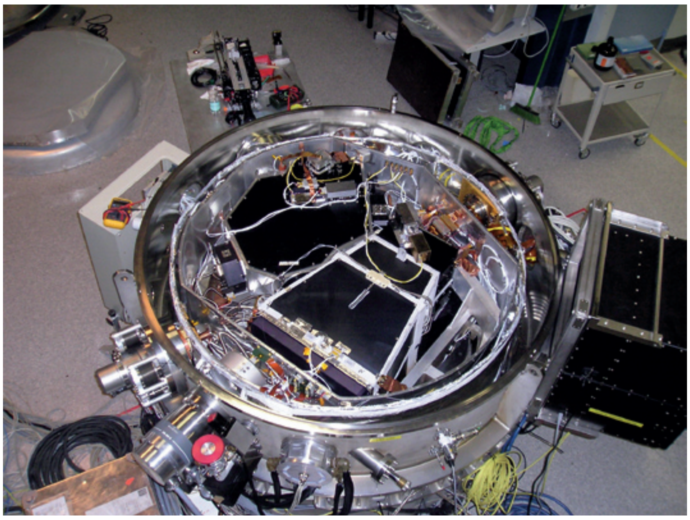


Figure 3: The CRIRES vessel open: a view to the interior of the cyrostat. On the circumference of the vacuum vessel two of the three cryo-coolers can be seen and next to the red safety valve there is the vacuum pump. To achieve the stability goal the instrument support and the radiation shield are thermally stabilised. Inside the radiation shield (round cylindrical shape, covered by 'super-insulation') there is the separate light shield (complex shiny structure). To avoid radiation leaks at the shield level, all cables are fed through with connectors, some of which can be seen on the photo. The optics itself is configured in two sub-assemblies. In the centre of the image there is the trapezoidally shaped 'Three-Mirror-Anastigmat' assembly (TMA), the main spectrograph. The grating is below the TMA structure and hence invisible. On the upper left side to the TMA there is the assembly holding pre-optics and prism predisperser. In the state the instrument is shown, all detectors, all sensors and motors are easily accessible. Thus CRIRES is relatively easy to maintain.

Table 1: Main characteristics of CRIRES.

Spectral coverage	λ ~ 950–5300 nm (ν ~ 56–315 Thz)
Spectral resolution	$\lambda/\Delta\lambda \approx 10^5$ or $\Delta v \approx$ 3km/s (2 pixel Nyquist sampling)
Array detector mosaic	4 × 1024 × 512 Aladdin III InSb mosaic, therefore instantaneous λ-coverage > 2.0 % pixel scale 0.1″ per pixel
Dark current	0.05–0.1 e^-/s per pixel
Infrared slit viewer	Aladdin III InSb with *J*, *H* and *K*-filters 0.05 arcsec/pixel
Precision	for calibration and stability (goal) ~ 75m/s i.e. 1/20th of a pixel or 5 mas tracking error
Intrinsic stability goal	spectrograph << 75m/s preference in design was given to stability therefore gas cells for high-precision radial velocity work
Adaptive optics	curvature sensing ESO-MACAO system 60 sub-apertures, *R*-band wavefront sensor
Spectro-polarimetry in lines	goal to measure all four Stokes parameter λ/4 Fresnel rhomb and λ/2 plate in rotary mounts on the gas-cell slide cold kinematic MgF_2 Wollaston prism in fore-optics
Cryogenic system	three closed-cycle coolers to reach 65 K liquid Nitrogen pre-cooling system

ZnSe-prism refractive index is parameterised with a Sellmeier formula. These parameters have been measured at operating temperature using the CHARMS facility at NASA-GSFC. Using (or one might even say abusing) CRIRES, the coefficients have been verified in the range ~ 60–80 K. To have a sufficient line density, the ThAr infrared spectrum has been explored and a corresponding hollow cathode lamp has been incorporated into the instrument (Figure 4). Using this facility as well as the N_2O gas cell the physical model is being calibrated. This model will soon be available within the instrument pipeline. These modelling efforts are based on established principles developed for Echelle spectrographs and have been applied previously to other ESO instruments (e.g. UVES).

Figure 5 shows the detector mosaic that is the 'eyes' of CRIRES.

Summary of status

At this point CRIRES is provisionally commissioned. While the activities in August 2006 and the first science verification observations were still plagued with alignment and focus problems, all these issues were solved in a final – at least for the moment – intervention to the instrument in September. The major specifications are met and the performance has been re-checked at the telescope. The details are condensed into the CRIRES exposure time calculator. However, already after the second commissioning run in August 2006, which was followed by four nights of early science verification observations, CRIRES and the associated software and documentation had reached a status which made it possible to include the instrument, basically unrestricted, in the regular call for proposals for Period 79. Many thanks go at this point to the colleagues who participated in the two calls for science verification and who have provided the team with valuable feed-back. The response from the community to the very first regular call was quite encouraging: more than 60 proposals asking for more than 160 nights!

In spite of all the efforts of the team, there is still a long list of action items to be completed. Fortunately, this list does not contain show-stoppers. Moreover, there is some room for improvements to the instrument. In the coming months the team will gradually work on the action item list, and CRIRES users can expect that the instrument performance will slightly improve its use.

Before the start of observations in Period 79 there will be one final commissioning run and a third call for science verification proposals. In parallel with the final commissioning and to the start of operations the polarimetric mode will be implemented, including a calibration module allowing to rigorously calibrate the instrument such that all four Stokes parameters can be measured. This will happen 'invisibly' for operations and first astronomical commissioning of spectropolarimetry is planned around August or September 2007. A detailed description of the polarimetric mode including its scienctific potential is given in Käufl et al. 2003.

Figures 6, 7 and 8 give some typical examples of data taken during commissioning and science verification observations.

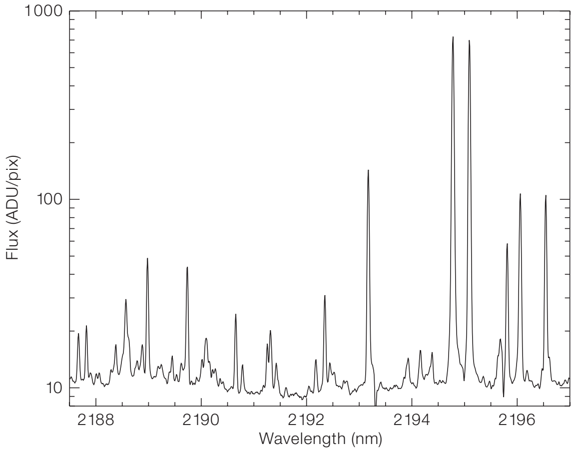
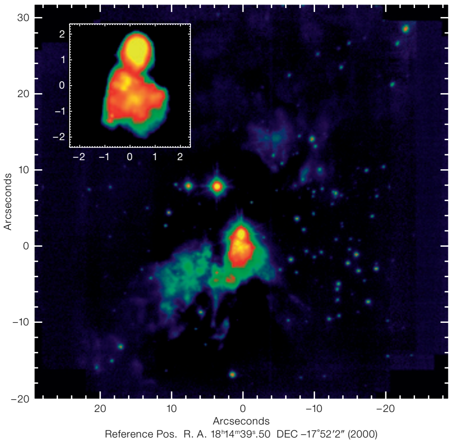


Figure 4: ThAr sample spectrum: The extracted spectrum corresponds to one of the four detectors and is a representative example of the line density. While the frequencies of the strongest lines have been measured with high precision in collaboration with NIST (F. Kerber, catalogue in preparation) the weaker lines will be catalogued with CRIRES and ways to measure their frequencies equally precisely have to be explored.



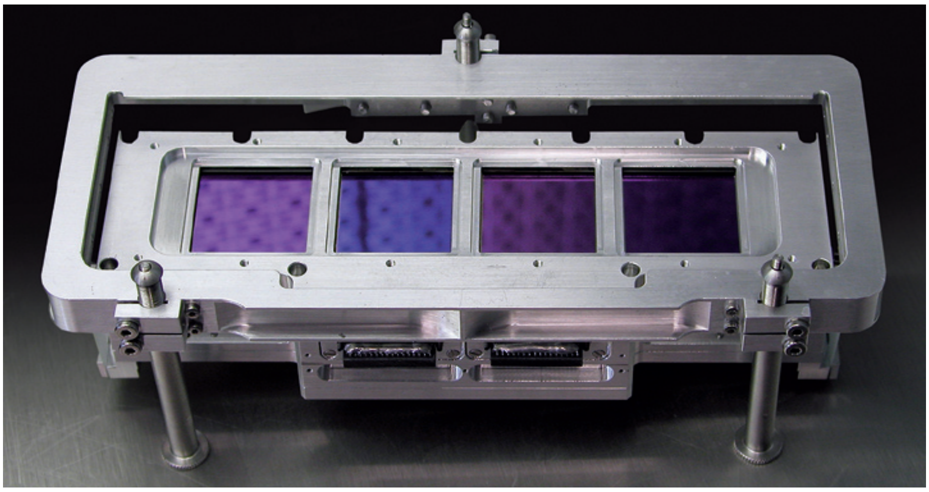


Photo: R. Dorn, ESO

Figure 5: CRIRES spectrograph detector assembly: The four Aladdin III detectors comprising the spectrograph focal plane in their mount. The detectors have been taken out of their original sockets and hybridised to custom-made ceramic boards. In this way the requirement of very high mechanical and thermal stability as well as a minimal gap between detectors (nominally 283 pixel) was achieved. While the complete assembly can be adjusted relative to the TMA-housing, the individual detectors – for reasons of stability – have not been mounted with means for relative adjustment. From each of the four 1k × 1k arrays the best two 512 × 512 quadrants are being used. Thus the two central detectors are being read perpendicularly to the dispersion direction while the devices left and right are read parallel to the dispersion direction. The effective useful area of the detector is ~ 5000 × 512 pixel which corresponds to an instantaneous coverage of a wavelength interval ~ 2.5 % of the central wavelength. As the detector focus can only be changed by manual intervention it is intrinsically quite stable, but it required an iterative process of thermal cycles for final alignment.

Figure 6: CRIRES as an adaptive optics pseudo imager: This *K*-band image was obtained using the MACAO adaptive optics system and the CRIRES slit-viewer camera. At the centre is the galactic H II region W33A (North is up, East to the right). To accommodate the very high dynamic range of this image a logarithmic intensity scale has been chosen. The insert shows the centre region with a different scale. It is remarkable to see in this image a dark lane South of the main source which is aligned with Maser spots reported in literature (data courtesy R. Siebenmorgen, K. Menten and the CRIRES science verification team). CRIRES is of course not meant to be a competitor to dedicated AO-imagers especially as the spatial sampling is only 0.05″ per pixel. However users can expect, if required, this kind of quality imaging to record the exact location of the spectrograph entrance slit.

Science with CRIRES

To have an optimum match between the scientific requirements and the Procrustes' bed of technical constraints, a second scientific workshop was organised in November 2003 at ESO on "High Resolution Infrared Spectroscopy in Astronomy" (Käufl et al. 2005). This workshop confirmed, that CRIRES is a long awaited unique observing facility, to which there will be a great demand in astronomy ranging from the inner Solar System to damped Lyman-α absorption systems. Correspondingly diverse were the many proposals received for science verification, and even new projects have emerged, which were not on the horizon at the time of the workshop in Garching.

While the frequency range accessible to CRIRES contains many atomic transitions, which match or complement optical observations very well, the really new features to be observed with CRIRES are molecular rotational-vibrational transitions. As many of these lines are seen in absorption while intrinsically quite narrow, the spectral resolution is an absolute must. CRIRES has a resolution nearly three times that of the next competing instrument and thus in many cases will be three times more sensitive. Thus many new discoveries can be expected. It should be noted, however, that any infrared observer *nolens volens* does high-resolution infrared spectroscopy as the infrared active trace-gases of our atmosphere provide for an extremely high-resolution quasi statistical narrow-band filter (Figure 8). A rigorous calibration of telluric effects is often only possible if the telluric lines are resolved, irrespective of the resolution required for the astrophysical object under study.

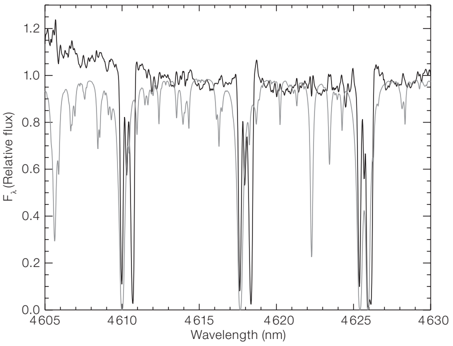


Figure 7: Sample spectrum from W33A: The sample spectrum is taken in the centre of the CO-fundamental band. It corresponds to a fraction of one of the four detectors. The solid line is the spectrum from the compact H II region and the gray line is a reference star to illustrate the telluric absorption. The W33A spectrum has been corrected as well as possible for the telluric absorption. The parabolic shape of the continuum from W33A is due to CO ice. As can be seen from the standard star, our local atmosphere also contains CO, however a bit Doppler-shifted. The local telluric CO is saturated, so that a correction in the centre of the lines is not possible. To be able to get good and useful data, i.e. data which can be calibrated, the CRIRES exposure time calculator has a tool to predict the telluric absorption taking into account the exact circumstances of the observations. For this sample spectrum, the Doppler shift is approximately 50 km/s. This needs to be compared with the orbital component of the Earth, i.e. the orbital velocity projected on the line of sight to the target which can be as much as +/-30 km/s. In that sense the exact timing of observations matters, and must be part of the planning process when preparing a proposal or observing blocks from P2PP. The CO spectrum will provide for new and extremely detailed constraints on the conditions of the molecular cloud surrounding this H II region (data courtesy R. Siebenmorgen, K. Menten and the CRIRES science verification team). CO, by the way, is the most abundant molecule in the Universe, which can be regularly observed (i.e. it emits dipole radiation).

Conclusion and outlook

With CRIRES the ESO VLT first-generation instrumentation plan has been completed. CRIRES fills a large gap in the parameter map. It complements space astronomy very well, because high-resolution observations from the ground complement satellite observatories such as HST, Spitzer or the planned JWST. While CRIRES was built at ESO, the detector technology has progressed, so that a speedy detector upgrade is being investigated. This, together with other measures, will ensure significant further improvements of performance.

CRIRES will also be very valuable to assess and prepare the science case for a similar instrument for the European Extremely Large Telescope project, which is presently taking its first steps.

Acknowledgements

Special thanks go to all colleagues on both sides of the Atlantic contributing to our project. Hans Ulrich Käufl feels particularly indebted to all colleagues and their families sometimes enduring a long string of quite extended missions to Paranal.

References

D'Odorico S., Moorwood A. F. M. and Beckers J. 1991, Journal of Optics 22, 85
Käufl H. U. et al. 2003, SPIE proc. 4843, 223
Käufl H. U. et al. 2004, SPIE proc. 5492, 1218
Käufl H. U. et al. 2006, The Messenger 124, 2
Käufl H. U., Siebenmorgen R. and Moorwood A. F. M. 2005, proceedings of the ESO Workshop on "High Resolution Infrared Spectroscopy in Astronomy", Springer-Verlag Berlin/Heidelberg
Ulrich M. H., proceedings of the ESO Workshop on "High Resolution Spectroscopy with the VLT", 1992

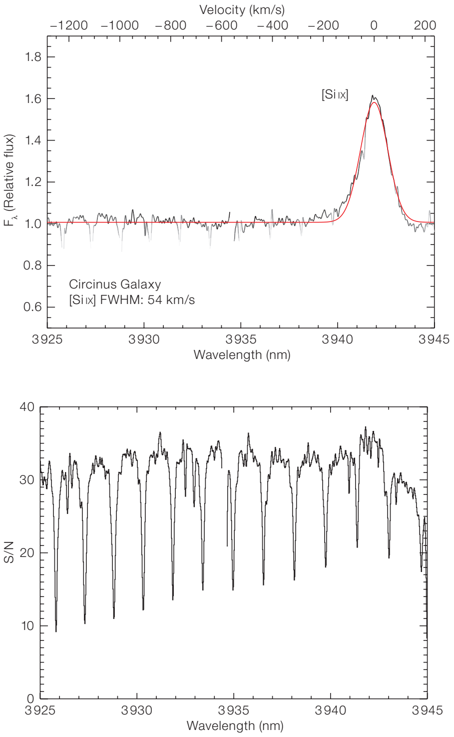


Figure 8: Sample spectrum of an active galaxy: The top spectrum shows a coronal line observed with CRIRES during commissioning originating from eight times ionised Silicon at 3 942 nm. This line has an intrinsic width of 54 km/s. One may wonder what could be the 'added value' of such an observation with a resolution of 1.5 km/s per pixel. The answer comes from looking at the raw data in the bottom figure, which shows the interfering telluric absorption spectrum. The Si IX line falls into a band of quite narrow telluric molecular absorption features. Only when resolving the telluric lines is it possible to correct for them. In other words, when observing this particular line with ten times lower resolution one would get both the equivalent width and the centre of gravity and thus the redshift wrong.

Figure 9: The happy commissioning team – at least most of them – shortly after first light in the VLT control room.