CRIRES+: Exploring the Cold Universe at High Spectral Resolution

Reinhold J. Dorn[1]
Guillem Anglada-Escude[2]
Dietrich Baade[1]
Paul Bristow[1]
Roman Follert[3]
Domingo Gojak[1]
Jason Grunhut[1]
Artie Hatzes[3]
Ulrike Heiter[4]
Michael Hilker[1]
Derek J. Ives[1]
Yves Jung[1]
Hans-Ulrich Käufl[1]
Florian Kerber[1]
Barbara Klein[1]
Jean-Louis Lizon[1]
Matthew Lockhart[4]
Tom Löwinger[3]
Thomas Marquart[4]
Ernesto Oliva[5]
Livia Origlia[6]
Luca Pasquini[1]
Jérôme Paufique[1]
Nikolai Piskunov[4]
Eszter Pozna[1]
Ansgar Reiners[2]
Alain Smette[1]
Jonathan Smoker[1]
Ulf Seemann[2]
Eric Stempels[4]
Elena Valenti[1]

[1] ESO
[2] Institut für Astrophysik, Georg-August Universität Göttingen, Germany
[3] Thüringer Landessternwarte, Tautenburg, Germany
[4] Department for Physics and Astronomy, University of Uppsala, Sweden
[5] Osservatorio di Arcetri (INAF), Firenze, Italy
[6] Osservatorio di Bologna (INAF), Italy

The CRIRES upgrade project, CRIRES+, transforms this VLT instrument into a cross-dispersed spectrograph to increase the wavelength range that is covered simultaneously by a factor of ten. In addition, a new detector focal plane array of three Hawaii 2RG detectors with a 5.3 μm cut-off wavelength will replace the existing detectors. For advanced wavelength calibration, custom-made absorption gas cells will be added. A spectropolarimetric unit will allow circularly polarised spectra to be recorded. These upgraded capabilities will be all supported by dedicated data reduction software which will allow the community to take full advantage of the new capabilities offered by CRIRES+.

Introduction

High-resolution infrared spectroscopy plays an important role in astrophysics, from the search for exoplanets to cosmology. The majority of currently existing infrared spectrographs are limited by their small simultaneous wavelength coverage. The scientific community has recognised the need for large wavelength range, high-resolution infrared spectrographs, and several are currently either in the design or integration phase. Examples are: the Immersion Grating Echelle Spectrograph (ISHELL; Rayner et al., 2013) at the NASA Infrared Telescope Facility; SPIROU (Delfosse et al., 2013) for the Canada France Hawaii Telescope (CFHT); and the Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES; Quirrenbach et al., 2012) for the Calar Alto Observatory.

The adaptive optics (AO)-assisted CRIRES instrument, installed at the Very Large Telescope (VLT), is an infrared (0.92–5.2 μm) high-resolution spectrograph which has been in operation since 2006. CRIRES is a unique instrument, accessing a parameter space (wavelength range and spectral resolution) which up to now was largely uncharted, as described in Käufl et al. (2004). In its current setup, it consists of a single-order spectrograph providing long-slit (40-arcsecond) spectroscopy with a resolving power up to R = 100 000. However the setup is limited to a narrow, single-shot, spectral range of about 1/70 of the central wavelength, resulting in low observing efficiency for many modern scientific programmes requiring a broad spectral coverage.

By introducing cross-dispersing elements and larger detectors, the simultaneous wavelength range can be increased by at least a factor of ten with respect to the present configuration, while the total operational wavelength range can be preserved (see Figure 1).

Science drivers

A search for super-Earths in the habitable zone of low-mass stars

A large fraction of all exoplanets has been discovered primarily through radial velocity measurements. However, only 5% of the planets detected so far orbit stars with stellar masses less than about 0.5 $M_{\odot}$. Thus, we lack key knowledge about the process of planet formation around the most numerous stars in our galaxy — M dwarfs. Low-mass stars are especially interesting because these objects are cool and the habitable zones are quite close to the star. The reflex motion of an M star (0.15 $M_{\odot}$) with a 1 $M_{\oplus}$ planet in its habitable zone is about 1 m s^{-1}. Since M dwarfs and brown dwarfs have low effective temperatures, radiating most of their energy in the infrared (1.0–2.5 μm), a high-resolution infrared spectrograph is therefore ideal for searching for low-mass planets around these objects.

A new gas absorption cell to provide a stable wavelength reference as well as the increase in wavelength coverage by about a factor of ten should result in an attainable radial velocity precision for CRIRES+ of 2–3 m s^{-1}. This would enable the detection of superEarth-mass planets in the habitable zone of an M-dwarf star in the Solar Neighbourhood (see Figure 2).

Atmospheric characterisation of transiting planets

In-transit spectroscopy of exoplanets currently provides us with the only means of studying exoplanetary atmospheres. Transiting planets are almost always close-in planets that are hot and radiate most of their light in the infrared. Furthermore the infrared is a spectral region where lines of molecular gases like CO, NH_3, CH_4, etc. are expected from the exoplanetary atmosphere. This important wavelength region is covered by CRIRES+, which will also allow multiple absorption lines to be tracked simultaneously.

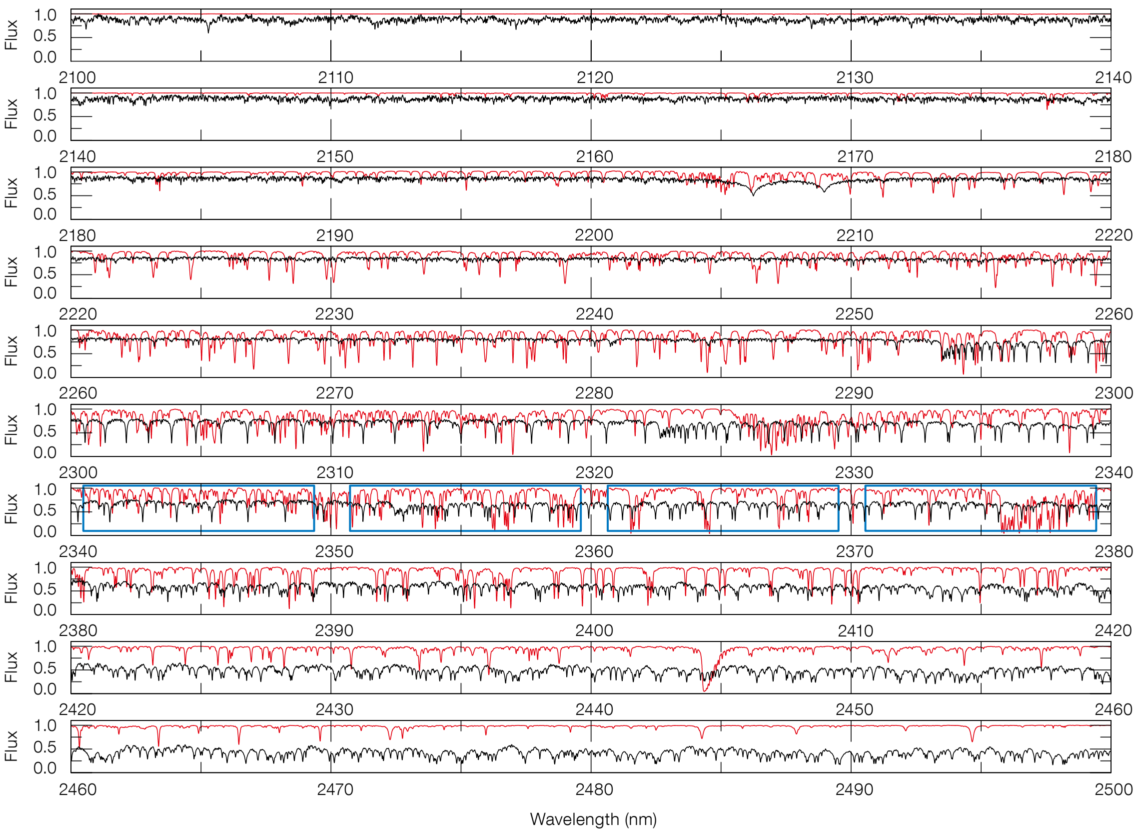

Figure 1. The wavelength coverage of the current CRIRES (blue boxes correspond to the four Aladdin detectors currently installed) in the *K*-band compared to the expected coverage of a single exposure from CRIRES+. The black line shows the spectrum of an M4 dwarf star (~ 0.15 $M_{\odot}$) and the light brown line is a laboratory spectrum of the first gas cell prototype being developed at the University of Göttingen.

Origin and evolution of stellar magnetic fields

Magnetic fields play a fundamental role in the life of all stars: they govern the emergence of stars from proto-stellar clouds, control the in-fall of gas onto the surfaces of young stars and aid the formation of planetary systems. Measurements of magnetic fields have mostly been confined to A- and B-type stars, so our knowledge of magnetic fields in Sun-like stars, and the low end of the main sequence, is still poor. CRIRES+ will make it possible to measure with greater accuracy magnetic fields in M dwarfs and brown dwarfs for several reasons:

1) The Zeeman splitting of a spectral line is proportional to λ^2, so there is a huge leverage in going to the infrared.
2) For cool objects most of the flux is in the infrared so there is also a gain due to the increased signal-to-noise ratio.
3) In order to disentangle Zeeman broadening from other broadening effects, one must compare the broadening of Zeeman sensitive lines to magnetically insensitive lines. The large wavelength coverage of CRIRES+ will include many more lines of different magnetic sensitivities needed for an accurate determination of the field strength.
4) The capability of CRIRES+ to take circularly polarised spectra will support these measurements.

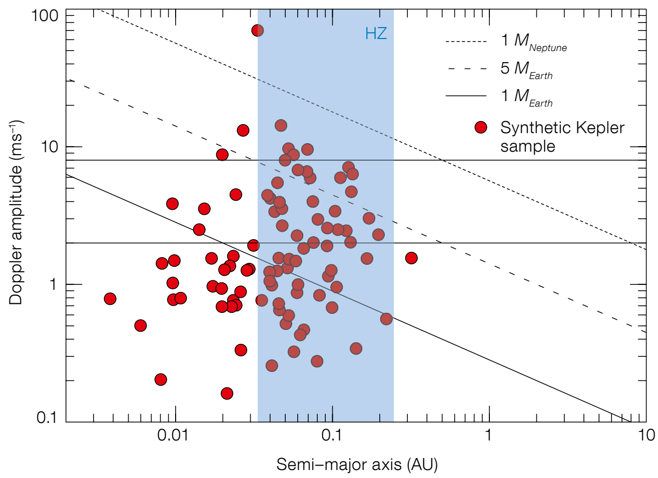

Figure 2. The expected Doppler amplitudes for different planet masses, depicted as diagonal lines, for a 0.1 $M_{\odot}$ star are shown. The top horizontal line is the current radial velocity precision of CRIRES; the lower is a conservative predicted value for CRIRES+. These horizontal lines also display the estimate of the detection thresholds after obtaining 25 epochs. The red dots correspond to the expected planets based on Kepler results (Dressing & Charbonneau, 2013). The blue shaded zone is the approximate extent of the habitable zone for low-mass stars.

The "+" for CRIRES

Many astrophysical applications will benefit significantly from the increase in wavelength coverage introduced by turning CRIRES into a cross-dispersed echelle spectrograph. The CRIRES upgrade project attempts to improve the

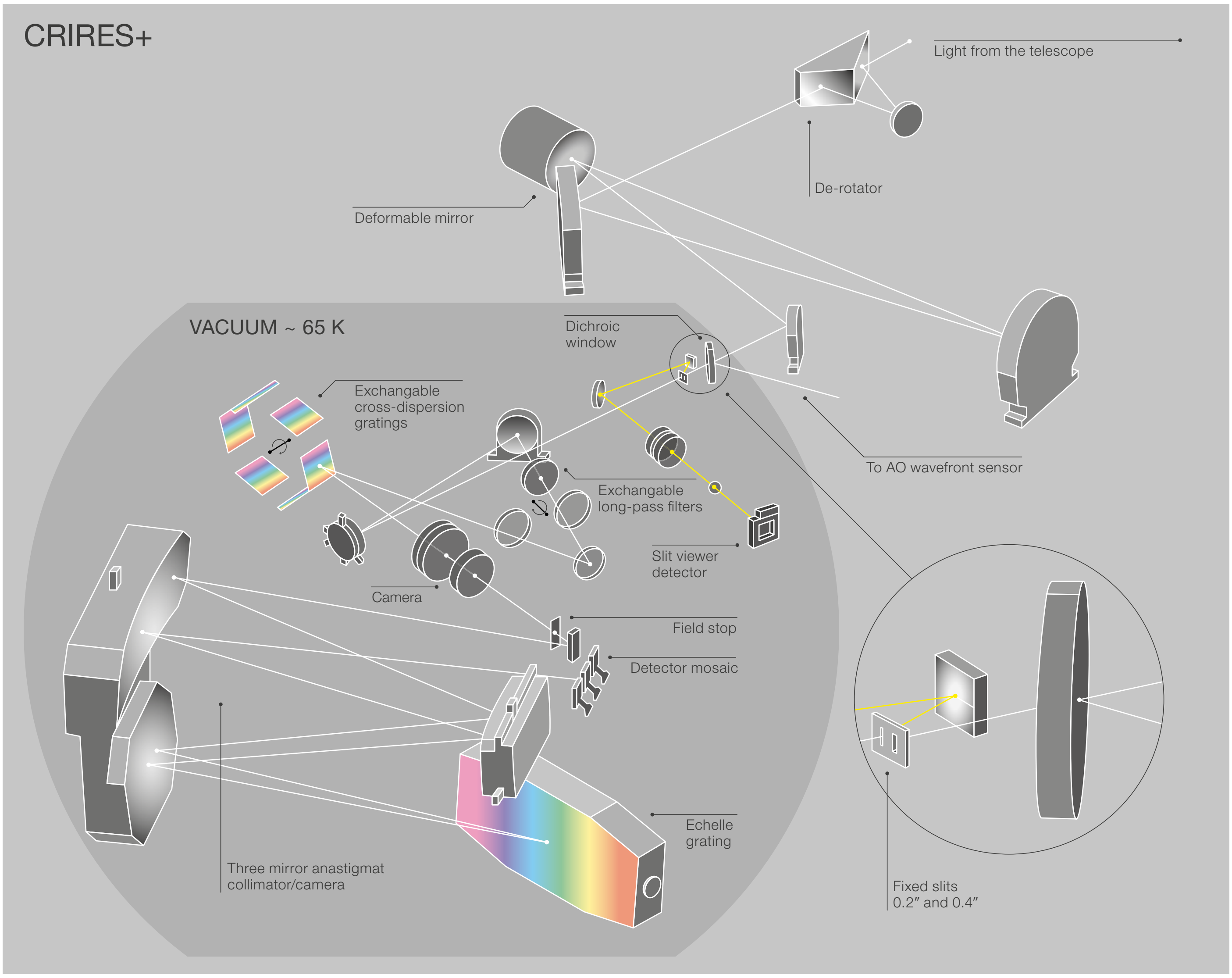

Figure 3. The optical design of the new cross-dispersion pre-optics for CRIRES+ is shown.

instrument by either refurbishing or replacing subsystems. Furthermore, there are plans to add subsystems that will provide additional observing modes. The project identified the following upgrades as significantly impacting the scientific capabilities of CRIRES.

Transform CRIRES into an echelle spectrograph

To assess how cross dispersion could be introduced into CRIRES, an analysis of the current and future scientific requirements and science cases was made. To cover the additional orders, the spatial extent of the main slit was reduced from 40 to 10 arcseconds, providing a balanced compromise between cross-dispersion implementation and catering for the current CRIRES long-slit usage. The cross dispersion of the spectrum will be carried out by reflection gratings. The optical layout of the new design is shown in Figure 3. Six gratings are foreseen, mounted on a cryogenic wheel. Each of them is optimised for operation in a single wavelength band (*Y, J, H, K, L* and *M*). Another wheel will carry the order sorting filters to eliminate contamination by second- and higher-order spectra of the gratings. The re-imaging of the slit is then performed by a fixed-lens camera, designed for the full wavelength coverage and used for all observing modes. In this configuration, the observing modes will require only one exposure to cover the full *Y*-band, two exposures, with different echelle angles, for the *J*- and *H*-bands, three exposures for the *K*-band, four for the *L*-band and five exposures are needed to cover the *M*-band. A new optical design for the slit viewer will complement the new pre-optics unit.

Overall the new design will maintain the current throughput of CRIRES (with

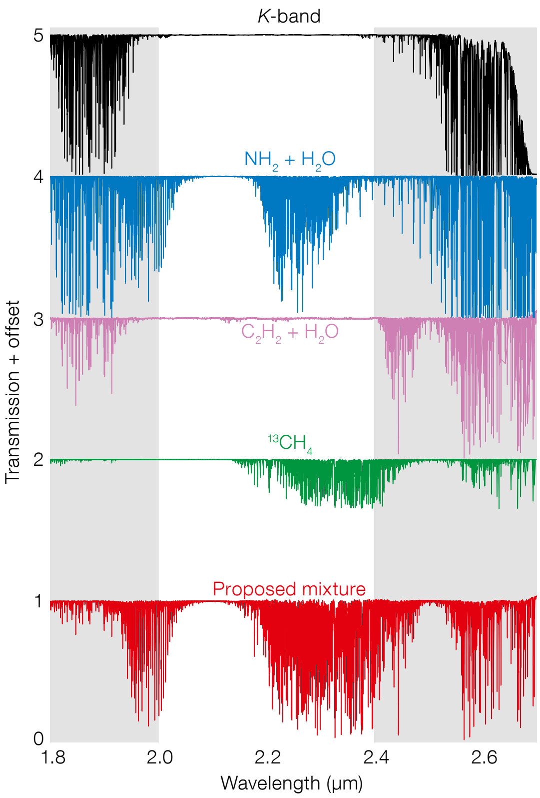

Figure 4. Transmission spectra of the gases for the CRIRES+ gas cell in the *K*-band are shown. The top panel plots the telluric (water) contribution, while the second to fourth panels show measurements of the individual species. The bottom spectrum presents the measured compound gas cell, which is a mixture of the above.

the goal of increasing it) and the spectral resolution of 50 000 and 100 000, as before. The slit length (10 arcseconds) will not limit observations of moderately extended sources and will allow nodding for precise background subtraction.

Gas cells for a new level of wavelength calibration

The CRIRES+ science cases also demand specialised, highly accurate wavelength calibration techniques. Therefore, another part of the proposed upgrade is concerned with the installation of novel infrared absorption gas cells with multi-species gas fillings (NH_3, $^{13}CH_4$, C_2H_2). These gases will provide a set of densely distributed absorption lines imprinted on the stellar spectra in the *H*- and *K*-bands (see Figure 4). In addition it is intended to replace the existing thorium argon hollow cathode lamps with similar uranium–neon lamps that produce a richer wavelength calibration spectrum.

New state-of-the-art detectors

The third major part of the upgrade project is to increase the coverage of the focal plane by introducing a set of new detectors. The current CRIRES scientific detector system uses four Raytheon 1024 × 1024 pixel InSb Aladdin arrays as described in Dorn et al. (2006). Another Aladdin detector is used for the slit-viewer camera. Owing to the planned cross dispersion, a larger field is required to cover the ten orders per band with a slit length of 10 arcseconds. Therefore a new and current state-of-the-art detector mosaic is foreseen. Figure 5 presents a comparison between the current CRIRES focal plane array area and the future array of CRIRES+. The future detector array, composed of three Hawaii 2RG detectors (a single H2RG detector is shown in Figure 6), will span 6144 × 2048 pixels (111 mm × 37 mm) at a pixel size of 18 µm. For comparison, the current mosaic spans only 4096 × 512 pixels (111 mm × 14 mm) with a pixel size of 27 µm.

The new detector mosaic will not only provide a larger area but also lower noise, higher quantum efficiency, better cosmetic quality and much lower dark current. Also the gaps between the detectors in the mosaic will be smaller. The detectors will be operated at 40 K with cryogenic preamplifiers located next to the focal plane. In addition all detector systems, including the slit-viewer camera, will be upgraded to the current ESO standard New General Detector Controller (NGC; Baade et al., 2009).

This detector upgrade will not only significantly increase the coverage of the focal plane, but the increased spatial homogeneity of the pixel response will result in improved data quality.

Spectropolarimetry with CRIRES+

The new polarimetry module planned for CRIRES+ uses two polarising gratings to split the incoming converging beam into left and right circularly polarised beams that continue along parallel optical axes. The choice of polarising gratings as polarising elements is motivated by their different behaviour at short and long wavelengths, their thinness, the possibility of producing large and homogeneous samples, and their modest price. The geometry of the periodic pattern that makes up the polarising gratings is chosen such that infrared light (with wavelength longer than 1 µm) is deviated, while optical light is transmitted essentially unaltered. Thus the polarising grating will act as a polarising beam splitter for circular polarisation without disturbing the operation of the AO system.

The polarisation module consists of a rotating stage with the two polarising gratings. The rotation axis is parallel to the axis of the incoming beam. It allows the positions of the two output beams to be switched to allow calibration of the difference in throughput for the two beams. Laboratory tests were already performed on a prototype system.
The measured polarisation extinction, throughput and scattering, as a function of wavelength, show that the proposed device fits the requirements for spec-

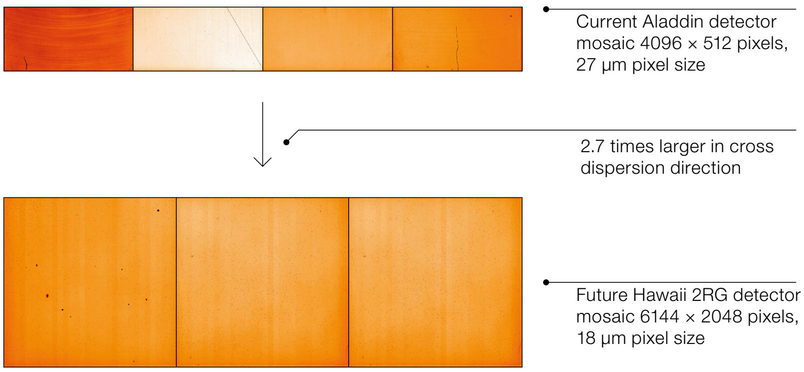

Figure 5. The present CRIRES detector mosaic focal plane array area compared to the new detectors with an increase of a factor of 2.7 in the cross dispersion direction.

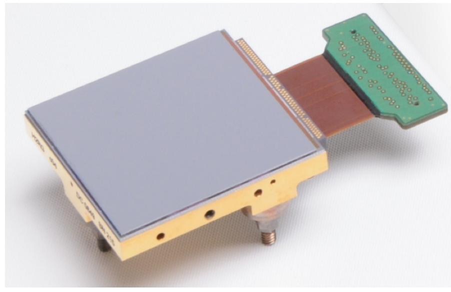

Figure 6. A ground-based astronomy HgCdTe H2RG is shown: Teledyne's H2RG package allows 32-output operation to be used for CRIRES+.

tropolarimetric measurements with CRIRES+ in the 1–2.7 μm wavelength range. The polarimetric unit will be compact and can be installed on the current CRIRES calibration slide.

MACAO refurbishment

The foreseen lifetime for the upgraded CRIRES+ is at least ten years. CRIRES is operated in conjunction with a 60-element curvature adaptive optics system, Multi-Application Curvature Adaptive Optics (MACAO), described by Paufique et al. (2004), and will require interventions to prevent its obsolescence. This is already planned for the MACAO Very Large Telescope Interferometer (VLTI) systems, installed in the coudé laboratory of the VLT Unit Telescopes (UTs). Accordingly, the CRIRES MACAO system will be refurbished in a similar manner to the VLTI systems by replacing and upgrading obsolete electronic boards. In addition there are plans to exchange the membrane mirror, re-coat additional mirrors, realign the optics and re-commission the full AO system.

The CRIRES+ metrology concept

In order to obtain deep enough datasets to explore exoplanetary atmospheres, CRIRES+ will need to be able to take stable exposures with high repeatability. The original CRIRES was limited by a spectral format reproducibility of about one pixel due to imperfect positioning of the pre-disperser and echelle grating mechanisms. However, a system of metrology was developed that facilitated the fine-tuning of the positioning of these mechanisms such that a 0.1 pixel reproducibility was achieved. Since CRIRES+ retains the original echelle grating mechanism, an adapted version of the metrology system will be required. This will comprise a fibre feed with an arc lamp spectrum that illuminates the echelle grating, automated detection and identification of reference lines, computation of correctional adjustment, and feedback to the grating mechanism and to a piezo actuator for fine tuning.

New data reduction software

The CRIRES+ project will also provide the community with a new data reduction software (DRS) package. The CRIRES+ DRS will support all of the offered observing modes and it is planned to provide the user with both science and publication-ready data products.

Project organisation and schedule

The project is being developed by ESO in collaboration with a consortium led by the Principal Investigator (PI) Artie Hatzes from the Thüringer Landessternwarte. Co-PIs are Ansgar Reiners (Göttingen) and Nikolai Piskunov (Uppsala). The partner institutes are:

- Thüringer Landessternwarte, Tautenburg (Germany)
- Georg-August-Universität Göttingen, Institut für Astrophysik (Germany)
- Istituto Nazionale di Astrofisica, Osservatorio di Arcetri and di Bologna (Italy)
- Uppsala University, Department of Physics & Astronomy (Sweden).

The reinstallation of NACO at the CRIRES focus of UT1 requires the removal of CRIRES in mid-2014, one year earlier than the original CRIRES+ schedule. For the upgrade, the instrument will be shipped back to ESO in Garching. Currently the project is in its preliminary design phase and the commissioning of the upgraded instrument is foreseen in 2017.

References

Baade, D. et al. 2009, The Messenger, 136, 20
Delfosse, X. et al. 2013, SF2A-2013: Proc. Annual meeting of the French Society of Astronomy and Astrophysics, ed. Cambresy, L., Martins, F., Nuss, E., Palacios, A., 497
Dorn, R. J. et al. 2006, SPIE, 5499, 510
Dressing, C. D. & Charbonneau, D. 2013, ApJ, 767, 95
Käufl, H. U. et al. 2004, SPIE, 5492, 1218
Paufique, J. et al. 2004, SPIE, 5490, 216
Quirrenbach, A. et al. 2012, SPIE, 8446, 84460R
Rayner, J. et al. 2012, SPIE, 8446, 84462C-12