X-shooter Starts Operation at the Paranal Observatory: A New Opportunity for Extragalactic Astronomy

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X-shooter, the new three-arm spectrograph at the VLT promises to be a powerful tool for high quality observations of targets of intermediate and faint magnitude at any redshift. The instrument capabilities are summarised and several examples of its use for the spectroscopy of intermediate and high redshift objects presented.

X-shooter at the start of operations

X-shooter is the first of the second generation Very Large Telescope (VLT) instruments and replaces the workhorse FOcal Reducer and low dispersion Spectrograph (FORS1), which has been successfully in use for more than a decade. It is located at the Cassegrain focus of the Kueyen Unit Telescope (UT2). The consortium that built X-shooter consists of ten institutes in Denmark, France, Italy and the Netherlands. ESO delivered the detector's systems and the cryogenic system controller and undertook the final integration, first in Garching and then at the telescope. The instrument was completed in five years at a cost of 6 million euros and ~ 70 person-years. Details on the consortium and the instrument have been included in previous *Messenger* articles (Vernet et al., 2007; D'Odorico, 2008) and can be found on the ESO website[1].

X-shooter consists of a central structure (backbone), which supports three prism-cross-dispersed échelle spectrographs optimised for the ultraviolet–blue (UVB), visible (VIS) and near-infrared (NIR) wavelength ranges. At the entrance of each spectrograph there is a slit unit, equipped with 11-arcsecond-long slits of different widths. The light beam of the telescope after the focus is directed to the UVB and VIS arms and transmitted to the NIR spectrograph cryostat by two dichroics in series. It is also possible to use an image slicer in the focal plane that reformats a 1.8 × 4 arcsecond field on the sky into a 0.6 × 12 arcsecond-long slit. X-shooter simultaneously collects the full spectrum of the target from 300 to 2500 nm with an efficiency of between 15 % and 35 %, including the telescope and the atmosphere (see Figure 1a, b and c for the UVB, VIS and NIR efficiencies respectively). The spectral resolution varies between 3000 and 17000 depending on the slit width and wavelength range, as shown in Table 1. The optical image quality is between 1 and 2 pixels on the detector over the full range.

In the first two commissioning runs, in November 2008 and January 2009, only the UVB and VIS arms could be tested. The instrument was operated in its full configuration with the NIR arm from March 2009. It has lived up to expectations in terms of image quality, spectral resolution and simple and robust opera-

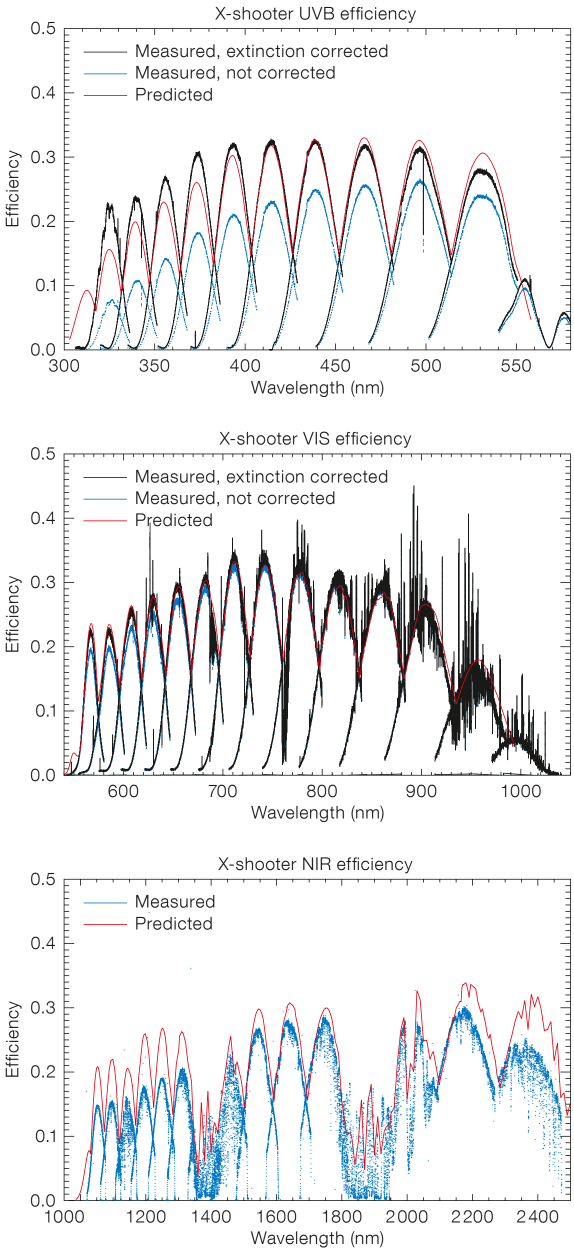

Figure 1a, b, c. The three plots show the predicted efficiency at airmass 1.0 (red lines) versus observed efficiencies (blue lines) of the instrument+telescope for all orders of the échelle spectra. For the UVB and VIS arms the correction of extinction to airmass 1.0 is also shown (black lines). For the NIR arm the prediction includes an estimate of telluric absorption at airmass 1.0. These measurements are based on observations of the flux standard GD71 obtained in June 2009.

UVB			VIS			NIR		
Slit width (arcseconds)	R λ/Δλ	Sampling (pixels/FWHM)	Slit width (arcseconds)	R λ/Δλ	Sampling (pixels/FWHM)	Slit width (arcseconds)	R λ/Δλ	Sampling (pixels/FWHM)
0.5	9100	3.5	0.4	17400	3.0	0.4	11300	2.0
0.8	6200	5.2	0.7	11000	4.8	0.6	8100	2.8
1.0	5100	6.3	0.9	8800	6.0	0.9	5600	4.0
1.3	4000	8.1	1.2	6700	7.9	1.2	4300	5.3
1.6	3300	9.9	1.5	5400	9.7	1.5	3500	6.6
IFU (1.8 × 4 arcseconds)	7900	4.1	IFU	12600	4.2	IFU	8100	2.8

Table 1. Offered resolution, *R*, and sampling as a function of slit width, and for the integral field unit (IFU).

tion. The overall efficiency is essentially as predicted, except for the *J*-band where it is ~ 30 % below the original goal, due to losses that can only be partly explained by scattering in the ZnSe cross-disperser prisms.

Following an open call there were two successful Science Verification (SV) runs in August and September 2009. A summary of the SV programmes is available[2]. Data from the commissioning and the SV runs have been made publicly available through the ESO archive and can be used to become familiar with the data format and to plan future observations.

The possibility of collecting the full spectrum from the atmospheric UV cut-off to the *K*-band at intermediate resolution in a single shot is an attractive option for a variety of scientific programmes, from the study of Solar System bodies to the search for emission galaxies at high redshift. In the first two proposal calls, where X-shooter was offered for general use (April and October 2009), it was the second most requested instrument at the VLT after FORS.

Examples of X-shooter observations

We present here examples of X-shooter observations from the commissioning runs which illustrate the capability of the instrument in extragalactic astronomy. The examples were also used as test cases for the data reduction software. All data shown here have been reduced, up to a 2D rectified, merged, wavelength-calibrated and sky-subtracted spectrum, with the data reduction pipeline, developed by the X-shooter consortium and integrated into the Data Flow System by ESO. The pipeline is used at the Paranal Observatory for online visualisation of the data and at ESO Headquarters in Garching for quality control and for reduction of the service observations. A preliminary version will be made available to the users of the instrument in Period 84.

An emission line galaxy at intermediate redshift

One of the key scientific drivers of X-shooter was the capability to collect a useful spectrum of a target of unknown redshift already in the discovery observation, thanks to its large spectral coverage. This capability — which is also the origin of the name of the instrument — was very much in mind for observations of gamma-ray bursts, where the rapidly-declining brightness calls for "shooting" an exposure of the target as soon as it is identified. This advantage however becomes equally useful in the observations of faint galaxies at unknown redshift. During commissioning, two lensed galaxy candidates from the Cassowary survey[3] (Belokurov et al., 2007) were observed. X-shooter spectra confirmed the nature of both candidates from several emission and absorption lines distributed over the three arms of the instrument. The first target, CASSOWARY 20, resembles an Einstein Cross and is a blue star-forming galaxy at $z = 1.433$ (Pettini et al., 2009).

Here we present, in Figure 2, data of another system, a star-forming galaxy at $z = 1.0688$ lensed by a pair of foreground galaxies at $z = 0.388$ (Christensen et al., in preparation). In the X-shooter spectrum we identify 20 different emission lines from [O II] 3727 Å to He I 10 830 Å. Even Hα, which is located in the region between the *J*- and *H*-bands, where the transmission is ~ 10 %, could be measured. Furthermore, in the 40-minute exposure it is still possible to identify UV absorption lines that are from the species Si II, Al III, Fe II, Mg II and Mg I. The resolution of X-shooter allows the strong emission lines to be decomposed into two components that are separated by ~ 50 km s^{-1}, a narrow one with a width of 50 km s^{-1} and a wider component of width 128 km s^{-1}. The interstellar medium absorptions are blueshifted by 43 km s^{-1} relative to the systemic redshift of the source, as determined by the emission lines.

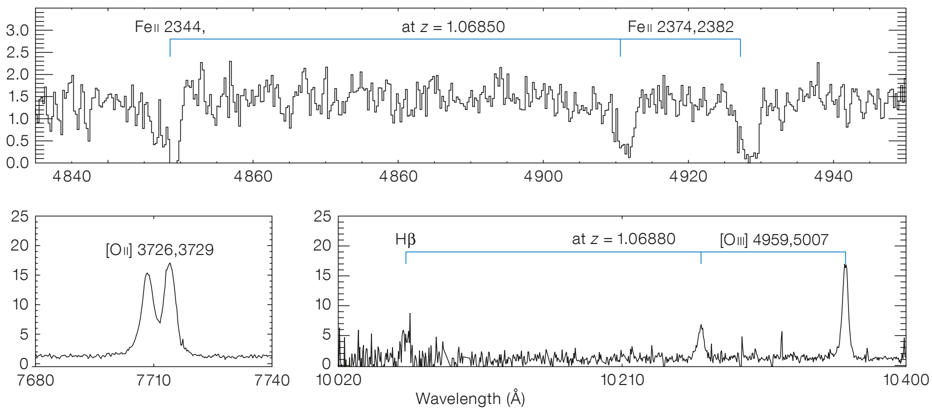

Figure 2. Sections of the UVB, VIS and NIR arm spectra of a lensed star-forming emission line galaxy. This spectrum was the confirmation observation of a candidate from the Cassowary survey (Belokurov et al., 2007). The target was observed with 2 × 1200 s on-target, aligning the slit between the two brightest images (*V* ~ 21 mag) of the lens.

High redshift quasars

B1422+231 (z = 3.62) is one of the brightest quasars in the sky (V ~ 16.5 mag), and is highly amplified by gravitational lensing. The X-shooter integration of total time 4800 s was split over 4 × 1200 s exposures and gives a final signal-to-noise ratio of between 50 and 100 over most of the spectral range. Two of the lensed quasar images, separated by 0.5 arcseconds, were aligned along the slit and the extracted spectrum refers to the sum of the two.

The resulting X-shooter spectrum (Figure 3) has resolutions of 6200, 11000 and 8100 in the UVB, VIS and NIR spectral regions respectively. At this resolution it is possible to study both narrow emission and absorption lines, from the gas in the quasar environment and from the intervening galaxies. The quasar continuum can be accurately traced even in the Lyman-α forest. The major advantage is the simultaneous coverage of a large wavelength interval. For this z = 3.62 quasar, the region from the Lyman continuum to redwards of the [O III] 5007 Å line can be investigated simultaneously. With a standard optical or infrared spectrograph only limited regions of the spectrum could be studied in a single exposure, with the potential risk of introducing errors in the final compilation of data taken at different times and under different weather conditions. With X-shooter it is now possible to circumvent these obstacles. The recovery of accurate profiles of several emission lines permits accurate determination of the redshift of the quasar, to be compared with the redshifts of the interstellar medium absorptions. Similarities and differences in the restframe UV and optical regions have allowed us to gain a better understanding of the accretion processes in the centre of the quasar.

A second example of a quasar observation is for the z = 5.99 SDSS QSO J130608.26+035626.3 (z = 19.5 mag, J = 18.8 mag). For objects from z = 3.5 up to z = 6.5, X-shooter permits Lyman-α to be obtained simultaneously in the visual arm up to a resolving power of 11000 (allowing a good tracing of the emission line profile) and absorption systems up to the Ks-band to be identified at a reso-

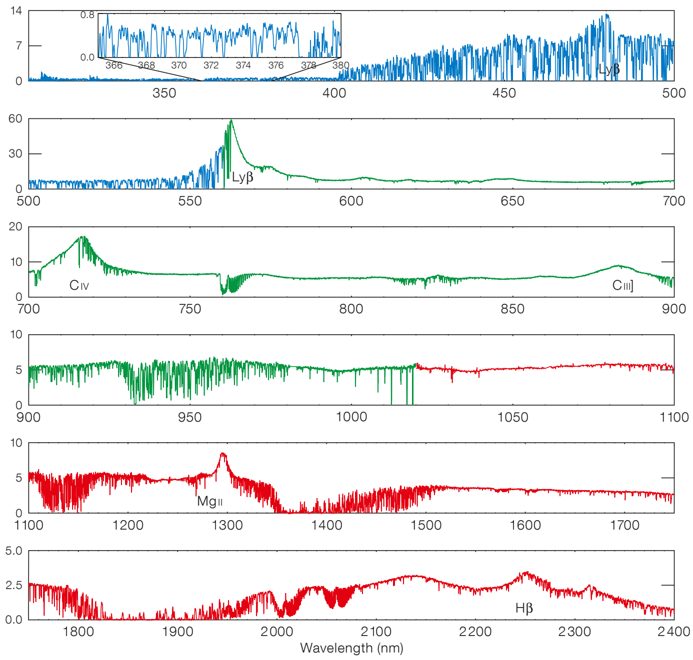

Figure 3. Spectrum of the lensed quasar B1422+231. The blue part of the spectrum shows the UVB, the green the VIS, and the red the NIR data in units of 10^{-16} erg s^{-1} cm^{-2}. No correction for telluric lines has been applied.

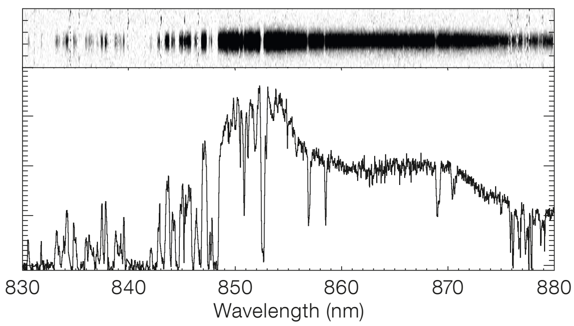

Figure 4a. Part of the extracted visual arm spectrum of the z = 5.99 SDSS QSO J130608.26+035626.3, encompassing the region of the Lyman-α emission. The upper panel shows the 2D, sky-subtracted, rectified and merged spectrum, the lower panel the corresponding 1D spectrum. The total integration time consisted of three 1800-s exposures nodded along the slit. The resolution is 8800.

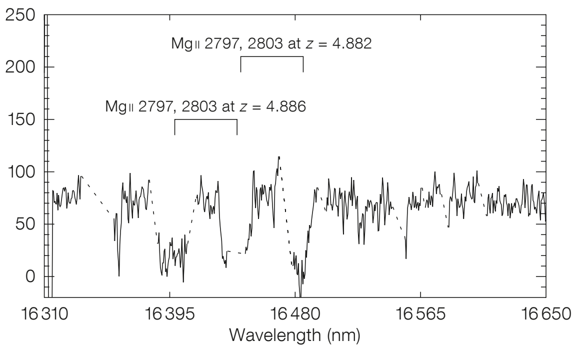

Figure 4b. A section of the H-band spectrum of the SDSS QSO J130608.26+035626.3, from the same integration detailed in Figure 4a. It shows a region with the highest redshift Mg II absorption systems as identified by Jiang et al. (2007). The resolution is 5600, or about eight times better than that of the discovery paper, permitting the measurement of column densities. The parts of the spectrum that have been interpolated at the position of strong OH sky lines are shown by a dotted line.

lution of up to 8000. This is illustrated in Figures 4a and b.

Acknowledgements

Without the X-shooter consortium, this new capability of the VLT would not have happened. We would like to acknowledge their expert and dedicated effort. We would also like to thank Jens Hjorth, Max Pettini and Vasily Belukurov for suggesting the test observations which are presented in this article.

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D'Odorico, S. 2008, The Messenger, 134, 12
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Pettini, M. 2009, arXiv0909.3301v1
Vernet, J. et al. 2007, The Messenger, 130, 5

Links

[1] http://www.eso.org/sci/facilities/paranal/instruments/xshooter
[2] http://www.eso.org/sci/activities/vltsv/xshootersv/
[3] http://www.ast.cam.ac.uk/research/cassowary/

ALMA First Fringes at 5000 m Altitude

The first two fully equipped ALMA antennas were transported to the ALMA Operations Site (AOS) at 5000 m altitude in September and October 2009 as planned. Figure 1 shows one of the antennas on its way to the AOS. After single dish functional tests, the two antennas were connected together (see Figure 2) as an interferometer using the ALMA production components previously installed inside the AOS Technical Building on Chajnantor at 5000 m. On 1, 2 and 5 November 2009, stable fringes were detected on the 160 m baseline at 3 mm, 1.3 mm and 0.85 mm. Figure 3 shows the amplitude and phase measured for the source 0538-440 at a frequency of 235.5 GHz and Figure 4 for the extragalactic radio source 3C454.3 at 345.8 GHz. The two-antenna array was remotely controlled from the Operations Support Facility (OSF) Technical Building at 2900 m altitude. In the near future further antennas will be added to the array in preparation for the start of early science operations in 2011.

More details at http://www.eso.org/public/events/announcements/aos_interferometer/.

Credit: ALMA (ESO/NAOJ/NRAO), A. Quintana/J. Olivares (ALMA)

Figure 2 (above). Fringes were obtained between these two antennas at the 5000 m ALMA Operations Site.

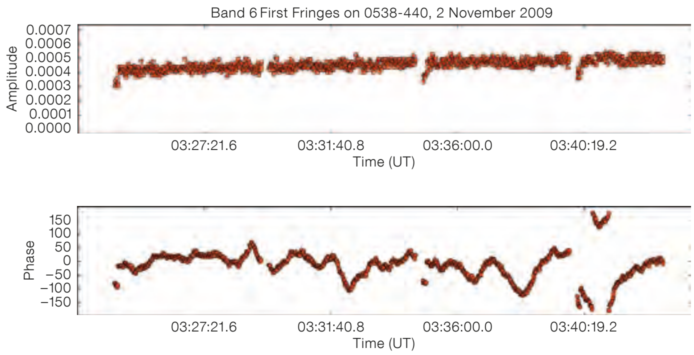

Figure 3 (left). Fringes at 235.5 GHz (ALMA Band 6) — amplitude and phase measured for the radio source 0538-440.

Credit: ALMA (ESO/NAOJ/NRAO)

Figure 1. The transporter Otto is shown carrying one of the antennas from the OSF to the AOS. See Kraus et al. 2007 (*The Messenger*, 132, 23) for more information on the ALMA transporters.

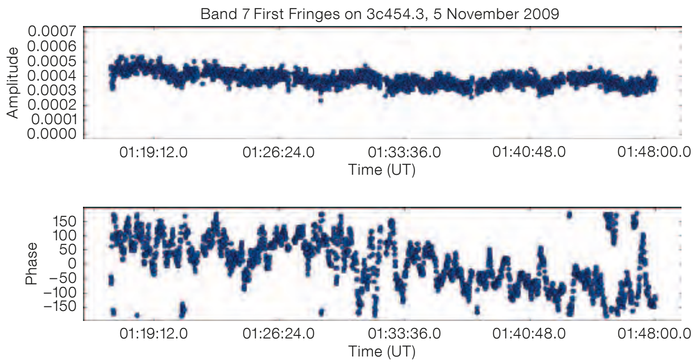

Figure 4. Fringes at 345.8 GHz (ALMA Band 7) — amplitude and phase measured for the radio galaxy 3C454.3.