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X-shooter: a medium-resolution, wide-band spectrograph for the VLT

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X-shooter is the first second-generation instrument for the ESO *Very Large Telescope*, and will be installed in 2008. It is intended to become the most powerful optical & near-infrared medium-resolution spectrograph in the world, with a unique spectral coverage from 300 to 2500 nm in one shot. The X-shooter consortium members are from Denmark, France, Italy, The Netherlands and ESO.

1 X-shooter: a very efficient spectrograph

The concept of X-shooter has been defined with one single main goal in mind: The highest possible throughput for a point source at a resolution which is just sky limited in about an hour of exposure over the broadest possible wavelength range, without compromising throughput at the atmospheric UV cutoff (D'Odorico et al. 2006). The moderate size of X-shooter is, as opposed to most existing or planned VLT instruments, compatible with implementation at the Cassegrain focus.

The instrument design is based on multiple dichroics to split the light between the three spectrograph arms (Fig. 1). The central backbone supports

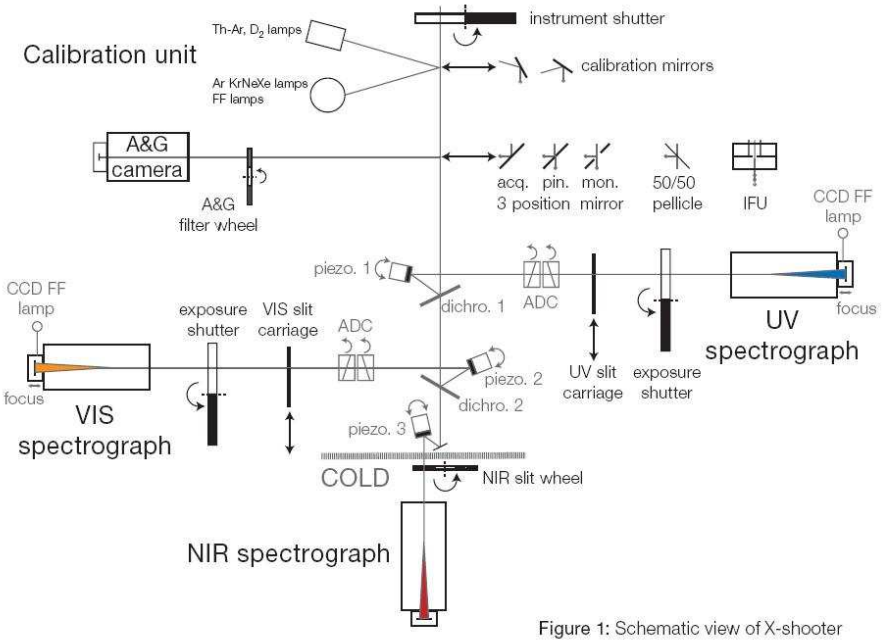

Fig. 1. Schematic view of X-shooter (Vernet et al. 2007).

three prism cross-dispersed echelle spectrographs (in double pass, optimized for the UV, visible and near-infrared wavelength range and based on the so-called 4C design Delabre et al. (1989)). The backbone contains the calibration and acquisition units, an IFU that can be inserted in the lightpath, the two dichroics that split the light into the three arms and relay optics to feed the entrance slits of the three spectrographs. The spectral performance and efficiency (better than 95 % reflectance, resp. transmission) of the two dichroics (cross-over wavelength 550 and 1000 nm) turn out to be exceptionally good, especially when considering the enormous wavelength range covered by X-shooter.

The standard slit measures $12'' \times 1''$; higher spectral resolution is obtained when using the $12'' \times 0.6''$ slit (Tab. 1). A wide slit ($12'' \times 5''$) is available for flux calibration. A dedicated program is being executed with VLT/SINFONI to extend the calibration of 16 optical spectro-photometric standards to the near-infrared in order to perform flux calibration of X-shooter spectra aiming at an accuracy of better than 5 %. The IFU has an entrance window of $4'' \times 1.8''$ and delivers three slices filling a $12'' \times 0.6''$ exit slit. The Acquisition and Guiding unit has a $1.5' \times 1.5'$ field and includes a comprehensive filter set; atmospheric dispersion compensation is performed in the UV and VIS arms (though not when using the IFU).

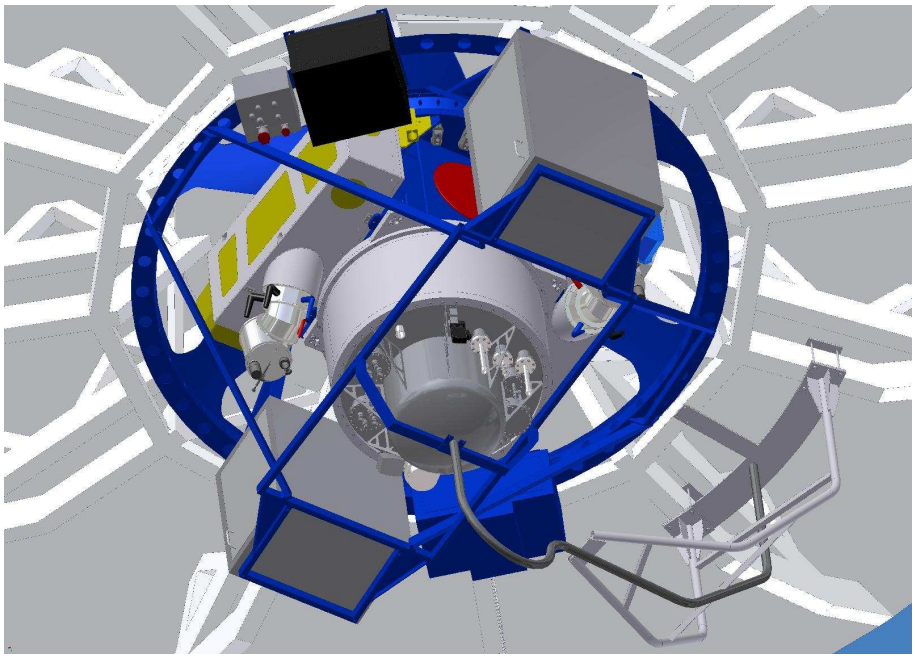

Fig. 2. The X-shooter spectrograph depicted in the Cassegrain focus below the M1 mirror cell of the VLT. To reduce flexure, the center of gravity is located as close as possible to the telescope, and the stiff elements are light-weighted. The UV and VIS spectrograph arms are mounted to the side; the NIR arm is at the bottom of the instrument.

Given its location in the Cassegrain focus, X-shooter has a tight weight (less than 2.5 tonnes) and flexure budget (Fig 2). Measures have been taken to reduce the effects of flexure, e.g. the optical bench of the NIR arm is extreme light-weighted (machined from a block of 850 kg aluminium to a weight of 25 kg, but similar strength). Also, three active flexure correcting mirrors are added to the system. During target acquisition, a calibration exposure is obtained from which the flexure is measured at the current instrument position. This information is fed to the piezo mirrors making sure that the object is centered on the three spectrograph slits during the observation.

The near-infrared arm is cooled by liquid nitrogen. Originally a closed-cycle cooler was planned to cool the instrument, but this could induce vibrations on the telescope platform prohibiting VLTI observations. The optical elements are cooled to 105 K, and the optimal operating temperature of the near-infrared $2k \times 2k$ Rockwell Hawaii 2RG MBE detector is 81 K, just above the liquid N_2 temperature (used area $1k \times 2k$). The UV detector is a $2k \times 4k$ E2V CCD; the VIS detector a $2k \times 4k$ MIT/LL CCD.

Given the large wavelength coverage in one shot, a compromise has to be found between the contribution of the read-out-noise in the UV (requiring a

Table 1. Predicted average efficiencies (at the blaze of the echelle orders and outside the dichroic cross-over range) per spectrograph arm. The technical specification requires an efficiency > 25 %. Also the predicted spectral resolving power ($R = \lambda/\triangle\lambda$) is listed and compared to the technical specification $R_{\rm spec}$ for a 0.6″ slit (excluding the detector LSF).

Spectrograph	**Spectral range** (nm)	**Average blaze efficiency**	$R_{\rm pred}$ (0.6″ slit)	$R_{\rm spec}$ (0.6″ slit)
UVB	307 – 529	41.6 %	8169	7600
VIS	558 – 966	35.6 %	12335	11500
NIR	1040 – 2370	27.8 %	7329	7000

long exposure time) and the sky background (variability) in the near-infrared (short exposure time). This compromise likely results in limiting the exposure time to about 20 minutes in "staring mode". We are currently investigating whether nodding in the near-infrared (using the telescope) can be compensated for in the other two arms using the piezo mirrors.

About 75 % of the costs of the X-shooter hardware, as well as labour, is funded by the external members of the consortium. ESO is responsible for the detector systems, project management, and commissioning. More than 60 people are involved in the project at nine different institutes distributed over four ESO member states and at ESO. A complete list of the contributors to the project can be found in Vernet et al. (2007). The overall cost of the project is 6.4 MEuro and the staff effort 69 FTEs. The consortium is compensated for the project investment with guaranteed time (156 nights over a period of three years). Even with the complex distribution of work over many different sites, the X-shooter project has advanced well on a relatively short timescale: $\sim$ 5 yr from the official kickoff to installation at the telescope.

First light of the visual spectrograph was achieved in July 2007 (Fig. 3); the NIR arm had first light in December 2007. In January 2008 integration of the full instrument has started in ESO Garching. The final delivery (the near-infrared arm) is planned for March 2008. The system test phase will conclude with the so-called Preliminary Acceptance Europe (PAE) review currently planned in June 2008. First light at the telescope is expected in September 2008. Normal operations should commence on April 1, 2009.

2 Science with X-shooter

X-shooter will have a broad and varied usage ranging from nearby intrinsically faint stars to bright sources at the edge of the Universe. The unique wavelength coverage and unprecedented efficiency opens a new observing capacity in observational astronomy. At the intermediate resolution of X-shooter 80-90 % of all spectral elements are unaffected by strong sky lines, so that one can obtain sky continuum limited observations in between the sky lines

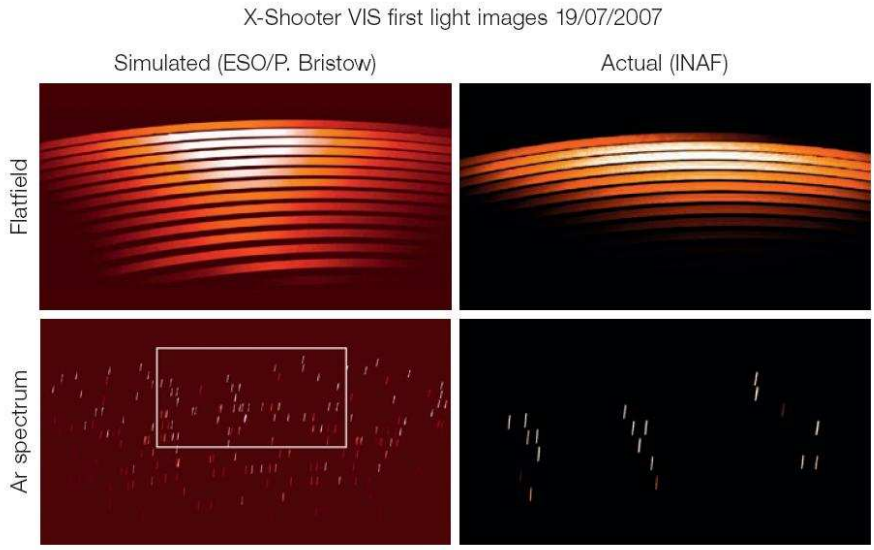

Fig. 3. Halogen flatfields and Ar line spectra in the VIS arm. The right panels show the first light images, the left panels display simulated images using the physical model. The first light Ar spectrum corresponds to the region enclosed by the white box in the simulated image.

within a typical exposure time. Key science cases to be addressed with X-shooter concern the study of brown dwarfs, the progenitors of supernovae Type Ia, gamma-ray bursts, quasar absorption lines, and lensed high-z galaxies. The advantage of the large wavelength coverage is that e.g. the redshift of the target does not need to be known in advance (such as in the case of GRBs); also, the study of Lymanα in high-redshift galaxies will be possible in the redshift range $1.5 < z < 15$.

X-shooter will complement and benefit from other major facilities in observational astrophysics operational in the same period: survey instruments like VST/OmegaCAM and VISTA working in the same wavelength range, and observatories like ALMA, JWST and GLAST operational in other observing windows.

3 Expected instrument performance

The performance of the instrument has been predicted on the basis of measured efficiencies of the telescope, optical elements, and detectors. Compared to the efficiencies predicted at the Final Design Review in June 2006, most delivered optical components (most importantly the dichroics and the gratings) are well above specification: an efficiency > 25 % in the centers of all

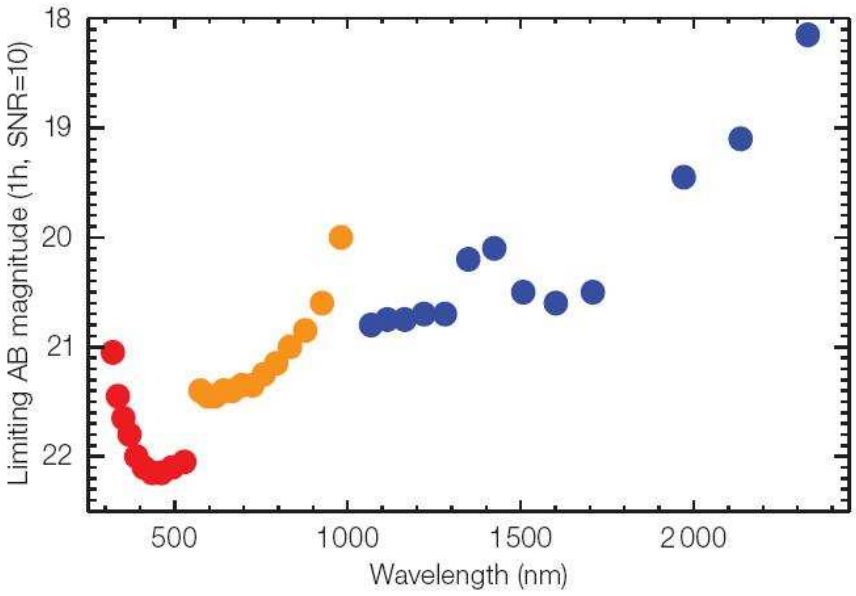

Fig. 4. Limiting AB magnitude of X-shooter per spectral bin at S/N=10 in a one-hour exposure. The other parameters used in this prediction are: airmass 1.2, 0.8″ seeing, 1″ slit, 2× binning in the spectral direction. The first version of the ESO ETC was used to compute these values (www.eso.org/observing/etc).

orders outside the dichroic cross-over range (from the top of the telescope to the detector). Table 1 lists the predicted efficiency at the blaze of the echelle orders averaged over each of the three arms of the instrument; the detection quantum efficiency is well over 40 % in most of the UVB range. Fig. 4 shows the predicted limiting AB magnitudes (S/N = 10 per resolution element for a 1h exposure, from the top of the atmosphere to the detector), calculated using a first version of the ETC, assuming that the sky background is due to the continuum in a region free of emission lines. In the near infrared the exposure is split in 3 exposures of 20 minutes and nodding is applied. The ETC uses the as-built values for optics and detector efficiency/noise, but still contains some assumptions that need to be verified during commissioning. The decrease in efficiency in the UV is due to atmospheric absorption; towards the red there is a decrease in CCD efficiency and the long-wavelength side of the near-infrared is limited to the rise of the thermal background. Also the predicted spectral resolution complies with the technical specifications.

4 Data reduction pipeline

The X-shooter data reduction software is being developed as a state-of-the-art ESO archival pipeline. About 15 % of the consortium's budget is spent on pipeline development, with the aim to deliver spectra ready for scientific analysis. The pipeline contains many novel features which are not commonly found in ESO pipelines, such as: (i) full optimal extraction of data which is distorted in both X and Y directions. The optimal extraction will be able to automatically cope with arbitrary spatial profiles; (ii) The pipeline will perform end-to-end error propagation. The pipeline includes a physical model of the instrument (provided by ESO) that allows for per-observation calibration of data, rather than relying on daytime calibration data. This should deliver an absolute calibration accuracy of 0.1 pixel for every frame taken by the instrument; (iii) A single frame sky subtraction technique is being implemented, so that the near-IR arm is useful for the long staring observations required by faint targets at the shortest wavelength ranges of X-shooter.

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