Studying the Magnetic Properties of Upper Main-sequence Stars with FORS1

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We summarise the results of our recent magnetic field studies in upper main-sequence stars, which have exploited the spectropolarimetric capability of FORS1 at the VLT extensively.

Introduction

Currently, most stellar magnetic field observations are carried out using three spectropolarimeters. In the northern hemisphere, the high resolution spectropolarimeter ESPaDOnS is installed at the 3.6-metre Canada France Hawaii Telescope (CFHT) on Mauna Kea and its twin NARVAL at the 2-metre Telescope Bernard Lyot on Pic du Midi. ESPaDOnS and NARVAL can obtain linear and circular polarisation spectra at a resolution of about 65000. In the southern hemisphere, the visual and near UV FOcal Reducer and low dispersion Spectrograph, FORS1, at UT2/Kueyen of the VLT offers a spectropolarimetric mode with a resolution of up to 4000. The two smaller telescopes, in particular the Telescope Bernard Lyot, dedicate significant amounts of observing time to magnetic studies by the French and Canadian communities, making long-term magnetic monitoring and magnetic surveys of certain types of stars possible. However only a few programmes have been devoted to the study of stellar magnetic fields with FORS1 in recent years, on account of the high demand for observing time with all instruments installed on Kueyen.

One of the biggest advantages of using FORS1 at an 8-metre telescope is the large collecting area, giving high S/N polarimetric spectra of relatively faint stars, down to magnitudes 12–13. Further, due to the use of Balmer series lines for the measurements of stellar magnetic fields in the blue spectral region, observed with grisms 600B or 1200B, fast rotators with $v \sin i$ up to 300 km/s can be studied. The technique for measuring stellar magnetic fields with FORS1 in polarimetric mode was discussed by Bagnulo et al. (2001) eight years ago, when the first measurement of the well known strongly magnetic chemically peculiar A-type star HD 94660 was discussed in detail.

The measurement of magnetic fields makes use of the presence of circular polarisation in spectral lines, allowing longitudinal magnetic field, which is the component of the magnetic field along the line of sight, averaged over the stellar disc, to be determined. Since no ESO pipeline for the FORS1 spectropolarimetric mode exists, the spectrum extraction is performed using a pipeline written by Thomas Szeifert. The software for measuring the magnetic field strength was developed by us. In the following we describe our magnetic field discoveries achieved with FORS1 in recent years.

New magnetic chemically peculiar stars

The magnetic chemically peculiar stars with spectral classes A and B (Ap and Bp stars) are presently the best-studied stars in terms of magnetic field strength and magnetic field geometry. Contrary to the case of solar-like stars, their magnetic fields are dominated by large spatial scales and remain unchanged on yearly timescales. Braithwaite & Spruit (2004) confirmed, through simulations using 3D numerical hydrodynamics, the existence of stable magneto-hydrodynamic configurations that might account for long-lived, ordered magnetic fields in these types of stars.

During 2002–2004, our first survey of a sample of more than 150 Ap and Bp stars, including rapidly oscillating Ap stars (Hubrig et al., 2006a) confirmed that low resolution spectropolarimetry of hydrogen Balmer lines obtained with FORS1 represents a powerful diagnostic tool for the detection of stellar magnetic fields. We first discovered magnetic fields in 63 Ap and Bp stars in this survey. Some of these stars were used for a re-discussion of the evolutionary state of upper main-sequence magnetic stars with accurate Hipparcos parallaxes. These new observations confirmed our previous finding that magnetic stars of mass $M < 3\,M_{\odot}$ are concentrated towards the centre of the main-sequence band, whereas stars with masses $M > 3\,M_{\odot}$ seem to be concentrated closer to the zero-age main-sequence (Hubrig et al., 2000; 2007a).

In the course of this study we discovered an extreme magnetic Ap star, HD 154708 (= CD −57°6753), which has the strongest longitudinal magnetic field ever detected in a rapidly oscillating Ap (roAp) star, with a mean magnetic field modulus $\langle B \rangle = 24.5 \pm 1.0$ kG (Hubrig et al., 2005). This magnetic field is about a factor of three stronger than that of HD 166473, $\langle B \rangle \approx 5.5$–$9.0$ kG, the roAp star with the second strongest magnetic field. In Figure 1 we present recent FORS1 measurements of the former star over three months in 2008 used to determine the rotation period of $P_{rot} = 5.367 \pm 0.020$ days. HD 154708 is the first star observed with FORS1 with a sufficiently uniform phase coverage to establish its magnetic

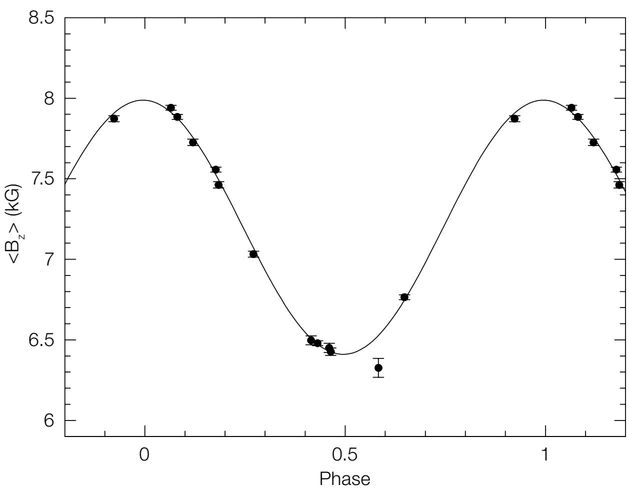

Figure 1. Phase diagram for the magnetic field measurements of the strongly magnetic star HD 154708; using hydrogen and metal lines the best frequency is 0.1863 d^{-1}, P_{rot} = 5.367 days.

period (Hubrig et al., 2009, submitted). Note that the size of the error bars is comparable to the size of the dots representing the individual measurements. The measurement with the largest sigma ($<B_z>$ = 6.326 ± 0.059 kG) was obtained in weather conditions classified as "thick clouds", where the guide star was frequently lost and thus was repeated by the service observer a couple of nights later.

O stars, pulsating B-type stars and early-type emission line stars

Massive stars usually end their evolution with a final supernova explosion, producing neutron stars or black holes. The initial masses of these stars range from 9–100 $M_\odot$ or more, which correspond to spectral types earlier than about B2. The presence of magnetic fields in massive stars has been suspected for a long time. The discovery of these magnetic fields would explain a wide range of well-documented enigmatic phenomena, in particular cyclical wind variability, Hα emission variations, chemical peculiarity, narrow X-ray emission lines and non-thermal radio/X-ray emission. Direct measurements of the magnetic field strength in massive stars using spectropolarimetry to determine the Zeeman splitting of the spectral lines are difficult, since only a few spectral lines are available for these measurements and these are usually strongly broadened by rapid rotation.

For a couple of years, the O6Vpe star θ^1 Ori C remained the only massive O-type star with a detected magnetic field (Donati et al., 2002). To examine the potential of FORS1 for the measurements of magnetic fields in massive stars, in 2007 we obtained 12 observations of θ^1 Ori C distributed over the rotational period of 15.4 days and compared them with previous measurements obtained with high resolution spectropolarimeters. The FORS1 measurements were sufficiently accurate to show a smooth sinusoidal curve in spite of a phase gap between 0.60 and 0.88, but with somewhat different values of the magnetic field strength compared to previous measurements obtained with Musicos, ESPaDOnS and NARVAL (Hubrig et al., 2008). Unlike FORS1 measurements, the high resolution spectropolarimeters usually do not employ measurements on hydrogen lines and thus different values of the magnetic field strength may be expected.

Recently we acquired 38 new spectropolarimetric observations of 13 O-type stars with FORS1, which led to magnetic field detections in an additional four massive O-type stars. As the lower number hydrogen lines in massive stars generally show variable emission, the measurements of magnetic fields are usually performed in two ways: using only the absorption hydrogen Balmer lines or using the entire spectrum including all available absorption lines of hydrogen, He I, He II, C III, C IV, N II, N III and O III. As an important step, before the assessment of the longitudinal magnetic field, we exclude all spectral features not belonging to the stellar photospheres of the studied stars: telluric and interstellar features, CCD defects, emission lines and lines with strong P Cygni profiles. This was the first time that magnetic field strengths were determined for such a large sample of O-type stars, with an accuracy of a few tens of Gauss, comparable to the errors obtained with high resolution spectropolarimeters. No magnetic fields stronger than 300 G were detected in the studied sample, suggesting that large-

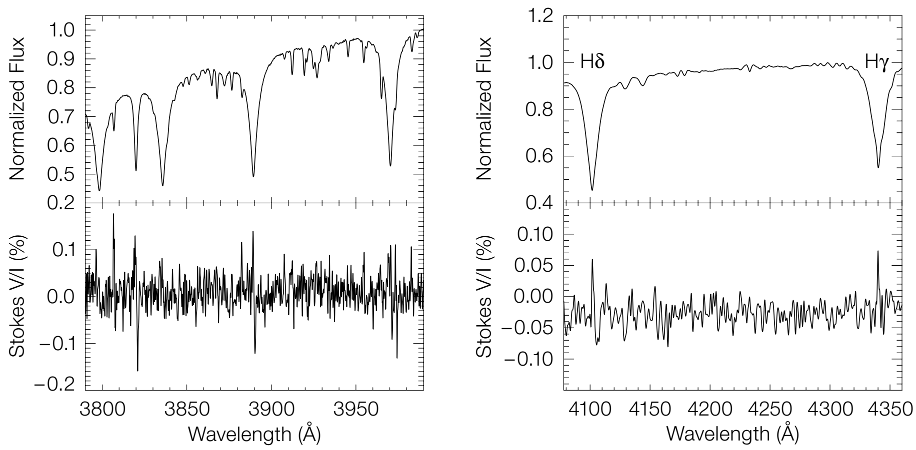

Figure 2. **Left:** Stokes *I* and *V* spectra of the β Cephei star ξ^1 CMa in the blue spectral region around high number Balmer lines. **Right:** Stokes *I* and *V* spectra of the Be star ο Aqr in the region including Hδ and Hγ lines.

scale, dipole-like magnetic fields with polar magnetic field strengths higher than 1 kG are not widespread among O-type stars.

Two other groups of massive stars, early B-type pulsating stars, such as β Cephei and slowly pulsating B (SPB) stars, and Be stars, that are defined as rapidly rotating main-sequence stars showing normal B-type spectra with superposed Balmer emission, had been a puzzle for a long time with respect to the presence of magnetic fields in their atmospheres. Only a very few stars of this type with very weak magnetic fields had been detected before we started our surveys of magnetic fields in B-type stars in 2004. Out of the 13 β Cephei stars studied to date with FORS1, four stars, δ Cet, ξ^1 CMa, 15 CMa and V1449 Aql, possess weak magnetic fields of the order of a few hundred Gauss. The star ξ^1 CMa is the record holder with the largest mean longitudinal magnetic field of the order of 300–400 G (Hubrig et al., 2006b; 2009). In Figure 2 (left) we present Stokes *I* and *V* spectra of ξ^1 CMa in the blue spectral region around the high Balmer series lines. Distinct Zeeman features, which are indicators of the presence of a magnetic field in this star, are easily detected at the wavelengths corresponding to the positions of strong spectral lines in the Stokes *I* spectrum. Figure 2 demonstrates the great advantage of using the blue-optimised EEV2 CCD of FORS1 for magnetic field measurements in the blue spectral region to cover all H Balmer lines from Hβ to the Balmer jump. Roughly half of the 34 SPB stars studied have been found to be weakly magnetic with field strengths of the order of 100–200 G.

In classical Be stars, a number of physical processes (e.g., angular momentum transfer to a circumstellar disc, channeling stellar wind matter, accumulation of material in an equatorial disc, etc.) are more easily explained if magnetic fields are invoked (e.g., Brown et al., 2004). The magnetic fields of Be stars appear to be very weak, generally of the order of 100 G and less. Furthermore, our time-resolved magnetic field measurements of a few classical Be stars indicate that some of them may display a magnetic cyclic variability on timescales of tens of minutes. In Figure 2 (right) we present Stokes *I* and *V* spectra of the typical Be star ο Aqr in the region including Hδ and Hγ lines with a measured longitudinal magnetic field $\langle B_z \rangle = +104 \pm 33$ G.

Another emission line star, υ Sgr, is a magnetic variable star, probably on a few months timescale with a maximum longitudinal magnetic field $\langle B_z \rangle = +38 \pm 10$ G (see Figure 3). The evolutionary status for this star is not obvious as it is a single-line spectroscopic binary system currently observed in the initial rapid phase of mass exchange between the two components (Koubský et al., 2006). The star is hydrogen-poor and the observed spectrum is extremely line-rich (see Figure 3). Future monitoring of its magnetic field over a few months with a high resolution spectropolarimeter would be of extreme interest to understand the role of the magnetic field in the evolutionary process of mass exchange in a binary system.

Our studies of massive stars revealed that the presence of a magnetic field can be expected in stars of different classification categories and at different evolutionary stages. Since magnetic fields can potentially have a strong impact on the physics and evolution of these stars, it is critical to answer the principal question of the possible origin of such magnetic fields. One important step towards answering this question would be to conduct observations of members of open clusters and associations of different ages. To date, we have studied the presence of magnetic fields only in members of the young open cluster NGC 3766 in the Carina spiral arm, known for its high content of early-B type stars, with very surprising results. Along with a strong magnetic field detected in a He-peculiar star, weak magnetic fields have been detected in a few normal B-type stars and in a few Be stars (Hubrig et al., in preparation). In Figure 4 we present the observed Stokes *I* and *V* profiles of the He-peculiar member of this cluster and of another cluster member that was classified as a potential Be star by Shobbrook (1985) with longitudinal magnetic fields of $\langle B_z \rangle = +1559 \pm 38$ G and $\langle B_z \rangle = -194 \pm 62$ G, respectively.

Obviously, to understand the role of magnetic fields in massive stars, future observations are urgently needed to determine the fraction of magnetic massive stars and the distribution of their typical field

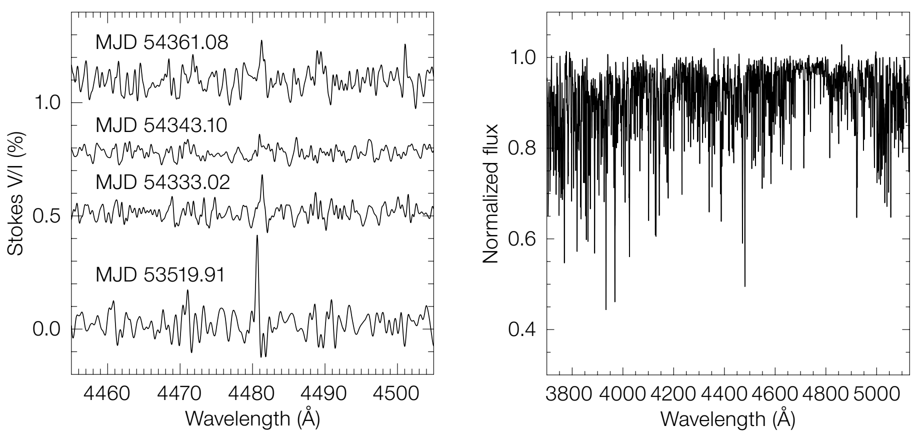

Figure 3. **Left:** Observed Stokes *V* spectra of the emission line star υ Sgr over two years in the vicinity of Mg II 4481. **Right:** Normalised FORS1 Stokes *I* spectrum of υ Sgr.

strengths. Further, we note that no physical properties are known that define these particular classes of stars as non-magnetic. It seems to be appropriate to admit that the inability to detect magnetic fields in massive stars in previous studies could be related to the weakness of these fields, which can, in some stars, be as little as only a few tens of Gauss (e.g., Bouret et al., 2008).

Herbig Ae/Be stars — resolving an enigma

In our recent studies of Herbig Ae/Be stars we sought to expand the sample of stars with measured magnetic fields to determine whether magnetic field properties in these stars are correlated with other observed properties such as mass-accretion rate, disc inclination, companions, silicates, PAHs, or show a correlation with age and X-ray emission as expected from the decay of a remnant dynamo (Hubrig et al., 2009, A&A submitted). During our two-night observing run in May 2008 we were able to obtain circular polarisation data for 23 Herbig Ae/Be stars and six debris disc stars. No definite detection was achieved for stars with debris discs, whereas for Herbig Ae/Be stars 12 magnetic field detections were achieved. One of the Herbig Ae stars, HD 101412, showed the largest magnetic field strength ever measured in intermediate mass pre-main-sequence stars with $<B_z> = -454 \pm 42$ G, confirming the previous FORS1 detection by Wade et al. (2007). The Stokes *I* and *V* spectra of this star are shown in Figure 5.

Strong distinct Zeeman features at the position of the Ca II H and K lines detected in four other Herbig Ae/Be stars are presented in Figure 6. As we already reported in our earlier studies (Hubrig et al., 2004, 2007b) these lines are very likely formed at the base of the stellar wind, as well as in the accretion gaseous flow and frequently display multi-component complex structures in both the Stokes *V* and the Stokes *I* spectra.

Observations of the disc properties of intermediate mass Herbig Ae stars suggest a close parallel to T Tauri stars, revealing the same size range of the discs, similar optical surface brightness and structure. It is quite possible that magnetic fields play a crucial role in controlling accretion onto, and winds from, Herbig Ae stars, similar to the magnetospheric accretion observed in T Tauri stars. Using our sample of Herbig Ae stars with masses of 3 $M_\odot$ or less, we searched for a link with other stellar parameters to put preliminary constraints on the mechanism responsible for

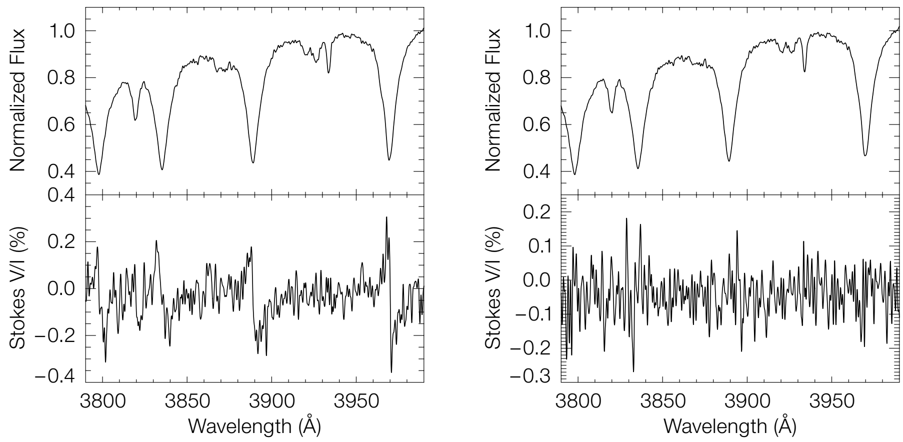

Figure 4. **Left:** Stokes *I* and *V* spectra in the blue spectral region around high number Balmer lines for an He-peculiar member of the young open cluster NGC 3766. **Right:** Stokes *I* and *V* spectra around high number Balmer lines for a candidate Be star belonging to the young open cluster NGC 3766.

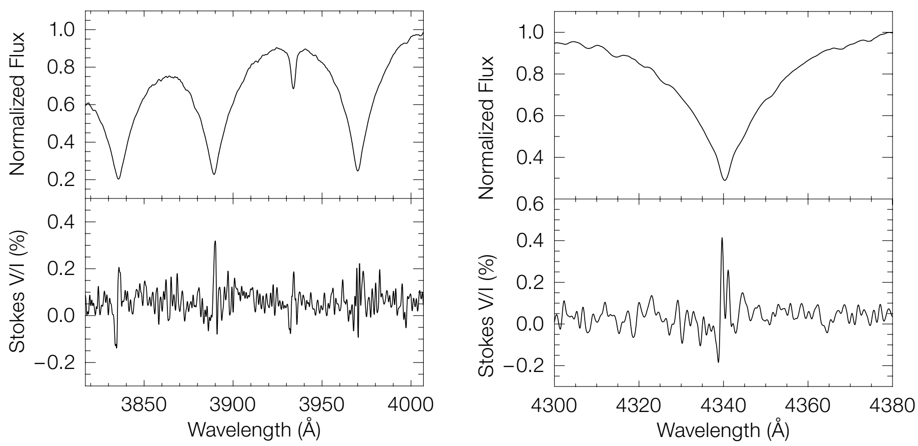

Figure 5. Stokes *I* and *V* spectra of the Herbig Ae/Be star HD 101412 with the largest detected magnetic field. **Left:** Zeeman features in H9, H8, Ca II H and K and Hε profiles. **Right:** Stokes *I* and *V* spectra in the vicinity of the Hγ line.

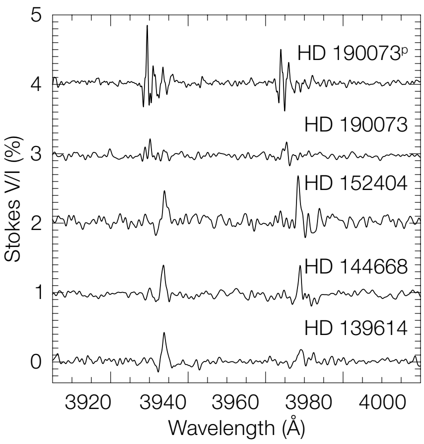

Figure 6. Stokes *V* spectra in the vicinity of the Ca II H and K lines of the Herbig Ae/Be stars HD 139614, HD 144668, HD 152404 and HD 190073. At the top is the previous observation of HD 190073, obtained in May 2005. The amplitude of the Zeeman features in the Ca II H and K lines observed in our recent measurement for this star has decreased by ~0.5% compared to the previous observations.

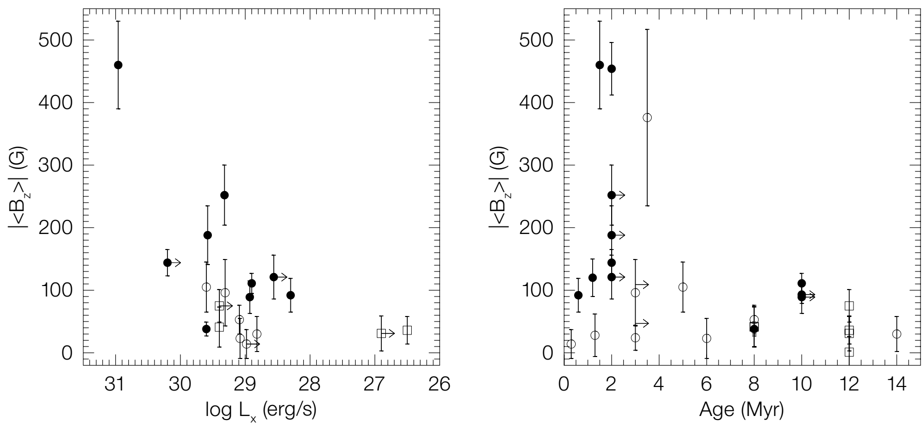

Figure 7. **Left:** The strength of the longitudinal magnetic field plotted against the X-ray luminosity. **Right:** The strength of the longitudinal magnetic field as a function of age. Filled circles denote Herbig Ae stars with a 3-σ magnetic field detection, while open circles denote Herbig Ae stars with a lower σ. Squares denote stars with debris discs, of which none has a 3-σ magnetic field detection.

magnetospheric activity. For the first time we established preliminary trends between magnetic field strength, mass-accretion rate, X-ray emission and age. We find that the range of observed magnetic field values is in agreement with the expectations from magnetospheric accretion models giving support for dipole-like field geometries. Both the magnetic field strength and the X-ray emission show hints of a decline with age in the range of 2–14 Myrs probed by our sample, supporting a dynamo mechanism that decays with age. In Figure 7 (left), we present the strength of the magnetic field plotted versus log L_X. It is noteworthy that we find a hint of an increase in the magnetic field strength with the level of the X-ray emission, which suggests that a dynamo mechanism may be responsible for the coronal activity in Herbig Ae stars.

There is obviously a trend showing that stronger magnetic fields tend to be found in younger Herbig Ae stars and that magnetic fields become very weak at the end of their pre-main-sequence life (see the right of Figure 7). These results are in line with the conclusions of Hubrig et al. (2000, 2007a) that magnetic fields in stars with masses less than 3 $M_{\odot}$ are rarely found close to the zero-age main-sequence.

Closing remarks

In summary, using FORS1 spectropolarimetric observations, considerable progress has been made over the last eight years in studies of the presence of magnetic fields in upper main-sequence stars. These results are providing several new clues, but are also posing a number of new open questions requiring future spectropolarimetric studies. Currently FORS1 in spectropolarimetric mode is the only facility regularly used for observations of circular and linear polarisation by the ESO community. Since FORS1 was decommisioned in P83, the polarimetric capability has been moved to FORS2 with the blue optimised EEV2 CCD available exclusively in visitor mode. We hope that the spectroscopic capabilities of FORS2 will be used in the future as intensively and successfully as they were used on FORS1 in the past.

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