# Circular Polarimetry Now Offered at EFOSC2

Ivo Saviane[1]
Vilppu Piirola[2,5]
Stefano Bagnulo[3]
Lorenzo Monaco[1]
Damien Hutsemekers[4]
Seppo Katajainen[2]
Harry Lehto[2]
Tommi Vornanen[2]
Andrei Berdyugin[2]
Pasi Hakala[2]

[1] ESO
[2] Tuorla Observatory, University of Turku Piikkiö, Finland
[3] Armagh Observatory, Armagh, Northern Ireland
[4] University of Liège, Belgium
[5] Vatican Observatory, Città del Vaticano, Rome, Italy

**Starting from period P79, circular polarimetry measurements can be carried out with EFOSC2 at the ESO 3.6-m telescope. Here we describe the motivations behind the upgrade of the instrument, and a few results from the commissioning runs are used to show the excellent performance of the new polarimetry unit.**

## Reasons for having the new EFOSC2 mode

Polarisation originates whenever any kind of anisotropy occurs in the radiative source, e.g., scattering by matter, presence of collimated beams of particles, presence of a magnetic field, and so forth. Thus it occurs in many different physical processes of emission of photons, and in many different kinds of astrophysical objects. Therefore, instruments offering imaging and/or spectro-polarimetry are of interest to a broad astronomical audience. Indeed there has been a recent increase in the pressure on the polarimetric modes of both FORS1 at the VLT and EFOSC2 at the ESO 3.6-m telescopes. Just in the two ESO periods P77 and P78, about 1/3 of the EFOSC2 proposals asked for the polarimetric mode, and the subjects ranged from Solar System objects (comets and Near-Earth Objects), to planets and dust in nearby stars, to stars in the Galaxy and the Magellanic Clouds (magnetic cataclysmic variables (CV), asymptotic giant branch (AGB) stars, magnetic white dwarf (WD) stars, Galactic super star clusters), to active galaxies (Seyfert, active galactic nuclei (AGN), BL-Lacs), and interacting galaxies. The proposals came from seven countries (Finland, Switzerland, UK, Germany, Italy, Chile, and France), and ten institutes altogether (just counting the PIs). For this reason, more than one year ago it appeared that expanding the polarimetric capabilities of EFOSC2 would meet a substantial demand of the European astronomical community.

In April 2006 a proposal for a new polarimetric unit was then submitted to the Director of the La Silla Paranal Observatory, and it was accepted shortly afterwards. The proposal was to offer the possibility to measure circular polarimetry with EFOSC2 in addition to the available linear polarimetry. EFOSC2 has a couple of advantages compared to FORS1. First, recently we have been able to offer fast imaging polarimetry of point sources, reaching a sample rate of 12 sec (plus exposure time), thanks to the possibility to read only a corner of the CCD, and to the faster retarder plate rotation. This is an essential requirement for example in the case of 'intermediate polar' cataclysmic variables, since circular polarisation originates close to the shock region near the surface of the fast spinning WD. In some cases significant variations can occur in a few minutes (e.g. GG Leo where circular polarisation rises from zero to + 20% in about 10 minutes). Furthermore, longer observing runs are easier to obtain at La Silla, allowing monitoring programmes to be carried out. Note also that preliminary measurements have shown that the instrumental linear polarisation is less than 0.1% at field centre, and about 0.4% at the edge, while FORS1 has an instrument linear polarisation reaching 1.5% at the edges.

A copy of the current polarimetry unit was then built, to house a new quarter wavelength ($\lambda/4$) retarder plate in a safe way. This allows to easily exchange the two units, making operations relatively easy (see Figure 1). Exchanging the two units only requires a few minutes, and in terms of both control software and observing templates, the operation is completely transparent. The super-achromatic quarter wave retarder plate (of 50 mm diameter × 12 mm thickness) was purchased from Astropribor Kiev at a special price, due to some minor defects of the glass, which do not compromise the quality of the measurements. Having two mutually exclusive units means that linear and circular polarisation will have to be measured in two consecutive nights, if required, but this is not a concern for most scientific cases. If absolutely needed linear and circular polarisation can be measured simultaneously with the $\lambda/4$ plate (rotated in 22.5° steps), but then with only 50% efficiency for linear, and 70% efficiency for circular polarisation. The old and new units are displayed in Figure 1.

## Commissioning and science verification

Due to the major problem with the dome of the 3.6-m telescope (see the article by Ihle et al. on page 18), which absorbed most of the resources of the mechanical

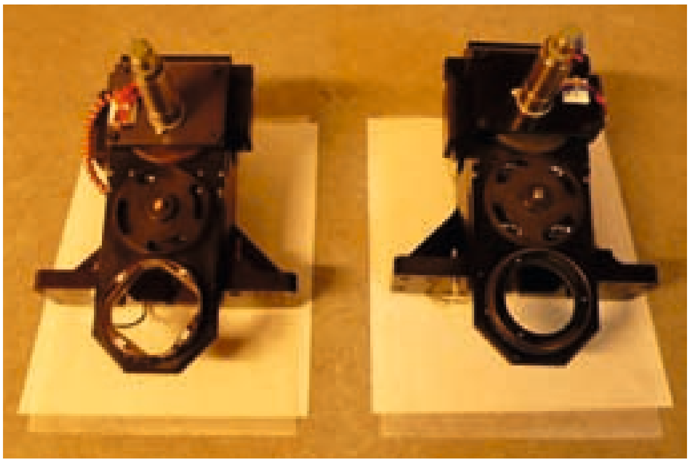

Figure 1: A photograph of the old (left) and new (right) polarimetry units.

workshop, the fabrication of the unit suffered a delay, and it was not ready at the very start of P79. So for the first commissioning, which was done in March, the observations were done with the λ/4 plate housed in the old unit. However the unit was ready for the second commissioning which happened in April, and just before the first visitor run. Several scientific and calibration targets were observed, and we illustrate here only a few cases. Results for another target observed in June are also included.

### Polarimetry standards

During the second commissioning night on 17 April, several standard stars and science targets were observed. In particular imaging polarimetry in broadband filters (*BVRi*) was obtained for the magnetic WD LP790-29, and the data were analysed with the following result: $V_B$ = 5.50 ± 0.07 %, $V_V$ = 7.10 ± 0.05 %, $V_R$ = 9.28 ± 0.04 %, $V_i$ = 7.12 ± 0.06 %. This is consistent with West (1989), who measured $V_B$ = 5 %, $V_V$ = 6.5 % and $V_R$ = 10 %. Another test was done by measuring Hiltner 652, a highly *linearly* polarised standard star. In this case we should measure null circular polarisation, and indeed $V_V$ = 0.03 ± 0.03 % was computed. Hence we can conclude that the cross talk between linear-polarisation and circular polarisation is comfortably small. Finally the measurement of WD1615-154, an unpolarised standard, gives $V_V$ = 0.03 ± 0.05 %, a result indeed consistent with zero polarisation.

As an additional test, LP790-29 was repeated with the retarder plate at slightly different angles with respect to the adopted reference, and it was found that a few degrees of difference do not have a significant impact on the measurements. During the first visitor night LP790-20 and WD1615-154 were observed again, obtaining consistent results: $V_V$ = 7.07 ± 0.09 % for LP790-29 and $V_V$ = 0.00 ± 0.04 % for WD1615-154. The linear-circular polarisation cross-talk was checked again with the highly linearly polarised standards Vela 1 95 and HD 155197, with results $V_V$ = +0.03 ± 0.05 % and $V_V$ = +0.03 ± 0.04 %. Again this is consistent with zero circular polarisation.

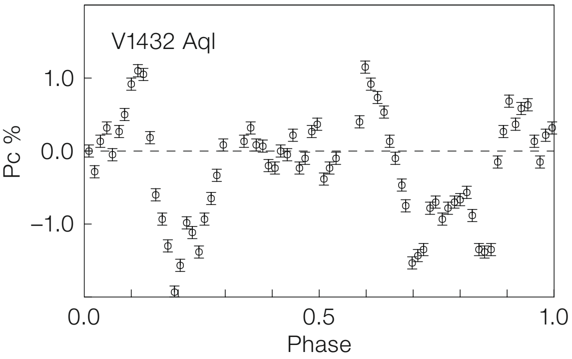

Figure 2: Circular polarisation curve over the WD spin period in the asynchronous polar V1432 Aql.

### Circular polarimetry of the asynchronous polar V1432 Aql

Polars (AM Her objects) are a subclass of magnetic cataclysmic variables (mCVs) and consist of a highly magnetic (B = 10–200 MG) WD accreting matter from a low-mass companion. The WD rotates synchronously (or nearly so) with the orbital motion. The strong field of the WD prevents the formation of an accretion disc. Instead, the matter is channelled along the field lines, and flows onto the WD surface through accretion columns (see e.g. Cropper 1990, for a review). The temperature of the accretion shock is $T_e$ ~ 10–40 keV, and the mildly relativistic electrons of the hot magnetised plasma emit strongly polarised cyclotron radiation in the optical and near-infrared.

*Asynchronous* polars are important to understand better the magnetic braking mechanism, which re-synchronises the WD with the orbital motion very rapidly ($T_s$ < 100–1000 yr) after nova eruptions (e.g. V1500 Cyg, BY Cam, V1432 Aql). An especially interesting system is V1432 Aql (see e.g. Staubert et al. 2003; Rana et al. 2005; Andronov et al. 2006). It is unique among asynchronous polars in the sense that the white dwarf spin period is about 0.3 % *longer* than the binary orbital cycle. This is against the earlier plausible explanation that synchronism in polars is broken by transfer of a small amount of orbital angular momentum during the common-envelope phase of a nova eruption, which should *speed up* the WD spin, as seen e.g. in V1500 Cyg = Nova Cygni 1975 (Schmidt, Liebert and Stockman 1995). Another possible mechanism is rotational braking of the white dwarf during the mass-loss phase by the strong magnetic field. The triple-hump profile seen in the *XMM-Newton* and the *ASCA* light curves requires *three* hot spots on the surface of the white dwarf (Rana et al. 2005). These peculiarities make V1432 Aql an important object for further study.

Circular spectro-polarimetry of V1432 was carried out with EFOSC2 on 28 June 2007. Figure 2 shows the variations of broadband optical circular polarisation over the 3.4 hr spin period of the WD. Fast excursions of positive (right handed) and negative circular polarisation are seen, as the visibility of the cyclotron emission regions on the spinning WD, and the angle between our line of sight and the magnetic field lines, change. The shape of the circular polarisation curves suggest that there are two negative poles dominating during these observations, and the field lines at the cyclotron emission region are significantly inclined with respect of the normal to the WD, i.e., accretion takes place onto the WD relatively far from the magnetic poles. The accretion geometry also changes during the 50-day beat period of the WD spin and orbital periods. These results demonstrate that circular polarimetry is an efficient tool for probing the magnetic field and accretion geometry in mCVs, and that EFOSC2 can detect variations of circular polarisation of the order of 0.1 % or less.

### Spectro-polarimetry of the magnetic WD G99-37

For the science verification, a number of targets were selected with known circular polarisation properties. One of the most interesting objects is the DGp WD G99-37. Circular polarisation in the optical continuum due to a strong magnetic field was discovered by Landstreet and Angel

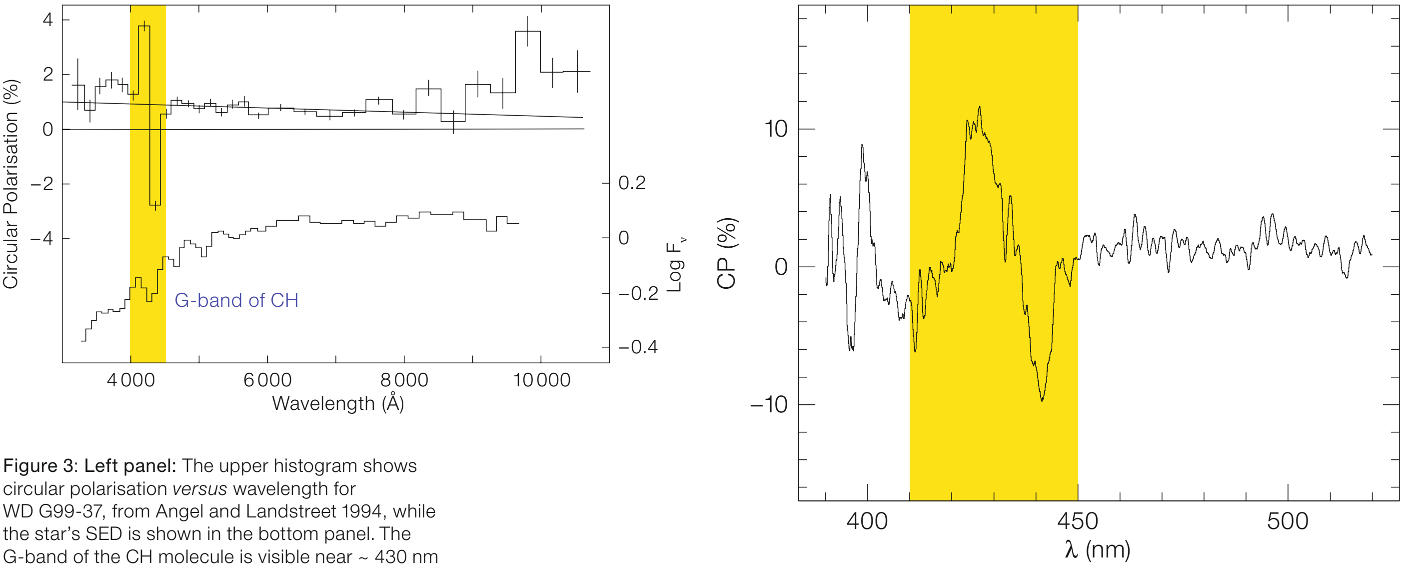

**Figure 3**: **Left panel:** The upper histogram shows circular polarisation *versus* wavelength for WD G99-37, from Angel and Landstreet 1994, while the star's SED is shown in the bottom panel. The G-band of the CH molecule is visible near ~ 430 nm in the SED, and its polarisation structure is evident in the upper histogram. **Right panel:** the polarisation spectrum of the same star as measured with the new EFOSC2 unit. In both panels the G-band is highlighted by the yellow shaded area.

(1971), and later Angel and Landstreet (1974) measured a field strength of $3.6 \times 10^6$ Gauss, using the Zeeman effect on the absorption G-band of CH at ~ 430 nm. The effect on the circular polarisation spectrum is shown in Figure 3 (left panel), and it can be qualitatively understoodby looking at Figure 1 in Landstreet (1980) and the inset in Bagnulo et al. (2001). A magnetic field parallel to the line of sight splits the band into two components symmetric with respect to the central wavelength, and the two components are circularly polarised in opposite directions. So if the magnetic field was purely longitudinal, the absorption band would appear bluer than the central wavelength in left-polarised light, and redder in right-polarised light. As polarimetry measures the ratio $(I_L - I_R)$ / I, where $I_L$ and $I_R$ are the intensities of the left- and right- polarised light, the spectrum of circular polarisation will show the rapid change across the G-band which is seen in Figure 3. This polarised absorption feature, at the wavelength range 0.42–0.44 nm, peaks from + 10 % to − 10 %, so it is relatively easy to measure.

The star was observed with EFOSC2 on the night of 16 March. Briefly, eight 15-min spectra were taken with the 20″ Wollaston prism and the quarter wave retarder plate scanning the angle sequence 135°– 45°– 45°–135°–135°– 45°– 45°–135°. The 1″ slit was used, together with grism #7, which allows to cover the range ~ 330 nm to ~ 520 nm at 0.2 nm px$^{-1}$ dispersion. The data reduction was carried out using standard IRAF reduction packages for extracting the two polarised spectra from each exposure, and our own routines to calculate the degree of circular polarisation from the exposures made at the two orientations of the quarter-wave plate.

The resulting spectrum of the circular polarisation (CP) is shown in Figure 3 (right panel), and the CP structure induced by the magnetic field across the CH band at 415–440 nm can be clearly seen. This demonstrates that useful measurements of this star were obtained, and that we recovered the ~ ± 10 % maximum values of the CP.

## Spectro-polarimetry of HD 94660

HD 94660 is a well-known chemically peculiar star that shows an almost constant longitudinal magnetic field of about −2 kG. This star has been repeatedly observed with FORS1 in polarimetric mode during various surveys of magnetic fields to check the instrument behaviour (see Bagnulo et al. 2001). We observed HD 94660 with EFOSC2, and measured the mean longitudinal field via formula (1) of Bagnulo et al. (2001). The result is $\langle B_z \rangle = -2105 \pm 80$ G (see Figure 4) which is fully consistent with the values measured during the last few years with FORS1 at the VLT (see Bagnulo et al. 2006).

## Acknowledgements

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Figure 4: The left panels show the Stokes I spectrum of HD 94660 (top left panel) and the Stokes *V* normalised to the intensity (bottom left panel), in the spectral region from *H*γ down to almost the Balmer jump. All Balmer lines show a well-detected signal of circular polarisation, and what appers as noise in between the various Balmer lines is in fact mostly a polarisation signal coming from hundreds of metal lines not fully resolved by the instrument. The right panel shows how the magnetic field is calculated. For a longitudinal field, the circular polarisation depends linearly on the expression given in the abscissa. The angular coefficient is the mean field, so a linear regression of the spectro-polarimetric data allows to compute $<B_z> \simeq -2000$ Gaus.

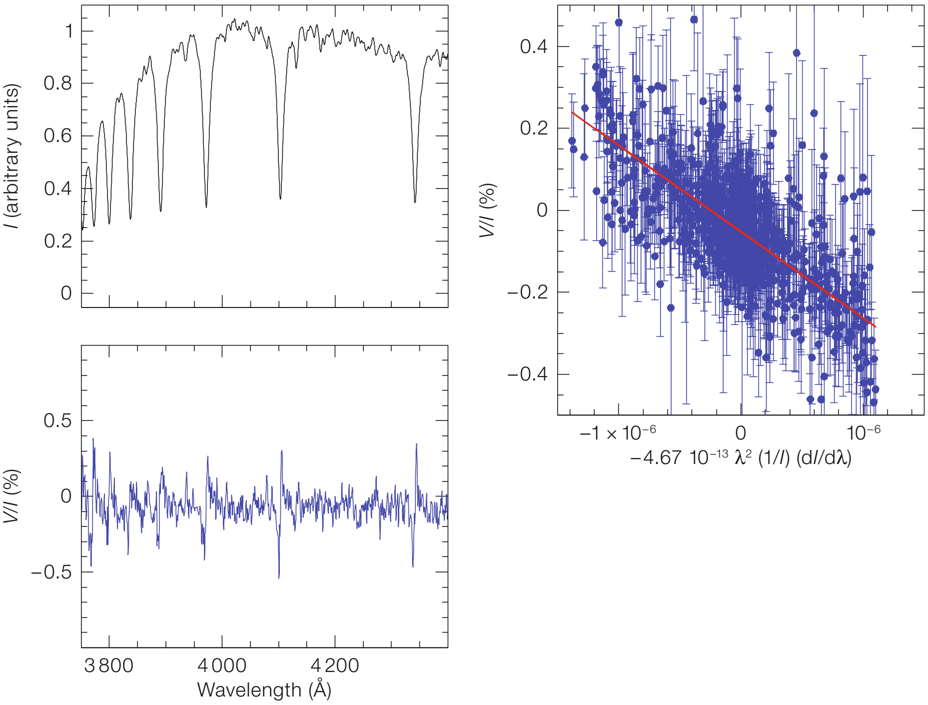

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Photo: H. H. Heyer, ESO

Maintenance work on the dome shutter of the ESO 3.6-m telescope. Below in the distance can be seen the SEST telescope, which is no longer in active use (photograph from 1996).