HARPSpol — The New Polarimetric Mode for HARPS

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The HARPS spectrograph can now perform a full polarisation analysis of spectra. It has been equipped with a polarimetric unit, HARPSpol, which was jointly designed and produced by Uppsala, Utrecht and Rice Universities and by the STScI. Here we present the new instrument, demonstrate its polarisation capabilities and show the first scientific results.

Introduction

Spectropolarimetry is one of a very few direct ways of detecting and studying magnetic fields. Magnetic fields are presumed to play crucial roles in all kinds of objects and environments in space, stirring turbulence, transporting angular momentum, converting kinetic energy to radiation, controlling plasma motion, etc. Magnetic fields create polarisation in spectral lines though the Zeeman effect, and thus polarisation measurements allow us to measure the strength and the orientation of the field vector, providing important clues for understanding star formation, the origin of structures in stellar atmospheres and stellar activity. In fact, the origin and the evolution of magnetic fields remains one of the most important topics in modern astrophysics.

Spectral lines formed in the presence of a magnetic field generally exhibit circular and linear polarisations across their profiles. For non-degenerate objects, the continuum is mostly unpolarised, which offers a reliable intrinsic calibration that is necessary for measuring very weak fields, but such measurements require a very stable spectropolarimetric instrument.

The HARPS spectrograph at ESO's 3.6-metre telescope at La Silla is one of the most successful spectroscopic astronomical instruments ever built (Mayor et al., 2003). The exceptional temporal and spatial stability of HARPS makes it an ideal instrument for spectropolarimetry. The new polarimeter takes full advantage of the two optical fibres to bring the collected light, split into two orthogonal polarisations, from the Cassegrain focus of the 3.6-metre telescope to the HARPS spectrograph. Analysing polarisations at the Cassegrain focus minimises the influence of instrumentation on the measurements. The new module, called HARPSpol, allows sensitive and accurate measurements of both circular and linear polarisations of stellar light as a function of wavelength, at high spectral resolution. In this article we give a short presentation of the polarimeter and show some results from the first year of operation.

HARPSpol — What's inside the box?

HARPSpol is installed inside the Cassegrain adapter, located directly below the primary mirror of the 3.6-metre telescope. This sets very stringent limits on the dimensions of the polarimeter, because it needs to fit in between various mechanisms (calibration light feeds, calibration mirror and fibre cover) filling the adapter. The polarimeter consists of the enclosure hosting a precision horizontal slider. The slider holds two identical optical tables installed perpendicular to the sliding direction. Each optical table contains a full set of polarisation optics (Figure 1), separating the incoming light into two beams. Since the polarising beam-splitter position is fixed relative to the fibres, the polarisation of the incoming light needs to be converted to the frame of the beam-splitter. This is achieved by rotating wave plates in front of the beam-splitters: a half-wave plate for the linear polarimeter and a quarter-wave plate for the circular one. The relative intensity of the two beams at each wavelength carries the information about the polarisation of the light.

The polarising beam-splitters consist of a Foster prism (a modified Glan–Thompson polariser). The primary beam suffers from crystal astigmatism, which is corrected by a cylindrical lens. The secondary beam is deviated by 45°. Beam-channelling prisms align the optical axis and the focus of the secondary beam with the second HARPS fibre. The selected optical scheme solves two

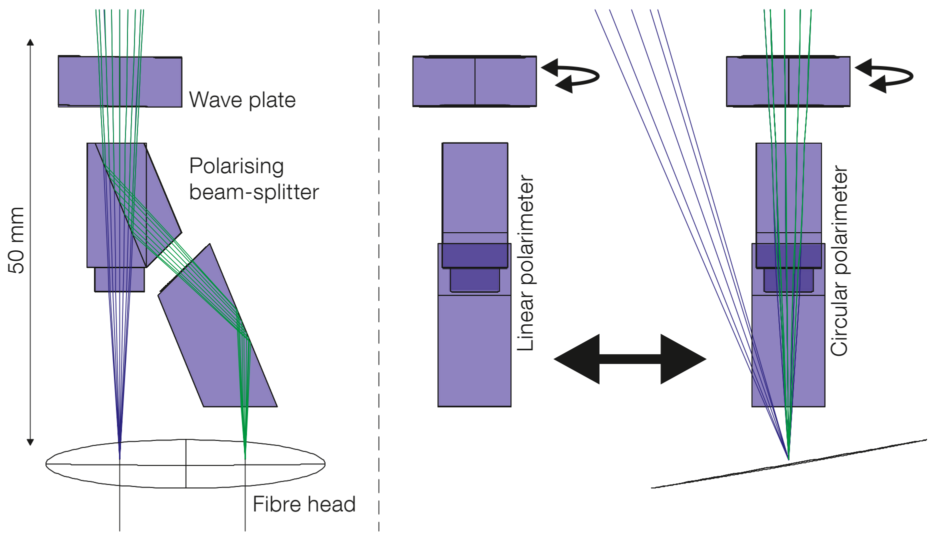

Figure 1. Schematic of the HARPSpol optical design. Left: the view in the sliding direction. Right: side view of the two polarimeters.

difficulties: (1) it is highly achromatic, that is, the image of a star after projection through HARPSpol is essentially the same in the red and in the blue parts of the spectrum; and (2) slight errors in positioning of the slider do not affect the optical/polarisation performance. More information about the optical design of HARPSpol can be found in Snik et al. (2008, 2010).

The selected wave plates are super-achromatic. They consist of five layers of birefringent polymer. This makes the polarimeters suitable for the entire HARPS wavelength range (380–690 nm) without introducing (polarised) fringes. The simultaneous measurements in two polarisation directions, together with the polarisation modulation by the wave plates, renders the polarimetry with HARPSpol to first order insensitive to seeing and fibre/spectrograph throughput (Semel et al., 1993; Bagnulo et al., 2009).

Integration

Once installed at the Cassegrain adapter, HARPSpol was integrated with the HARPS instrument control electronics and software. When inserted into the optical path, HARPSpol shifts the focus of the telescope by approximately 2 mm, which is compensated for by moving the secondary mirror. Figure 2 shows HARPSpol installed inside the Cassegrain adapter. Spectropolarimetry is performed by selecting the corresponding template(s) in the observing software. Calibration and science templates are available for circular and linear polarimetry. The science

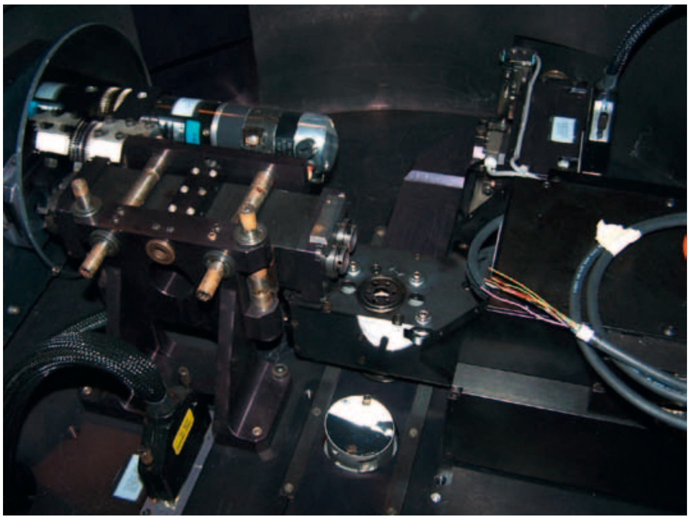

Figure 2. HARPSpol is shown during installation. The HARPSpol enclosure is on the right. The slider is in the linear polarisation position. The half-wave plate for the linear polarimeter is visible in the middle of the picture. The round mirror below the linear polarimeter is one of the HARPS fibre heads.

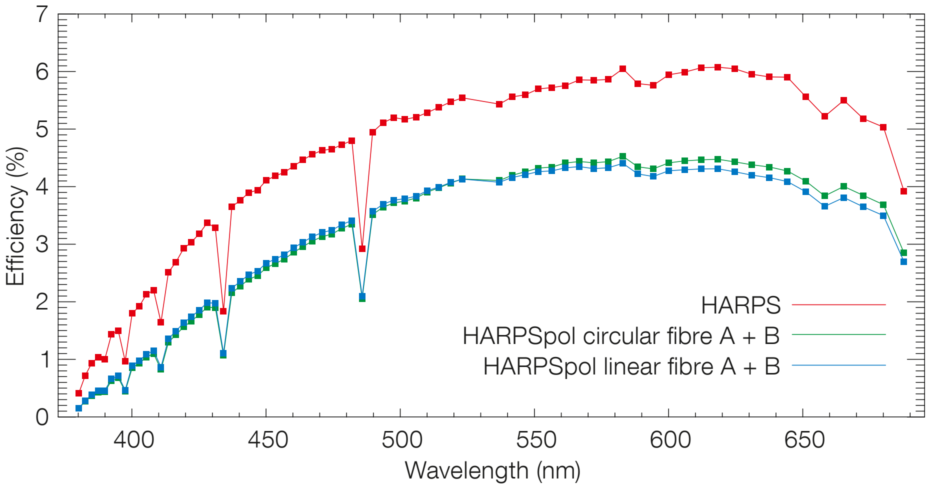

Figure 3. The total throughput from the telescope to the detector with and without HARPSpol is shown. The sharp drops are not real: they are due to hydrogen lines that are treated differently in spectrophotometry and spectropolarimetry.

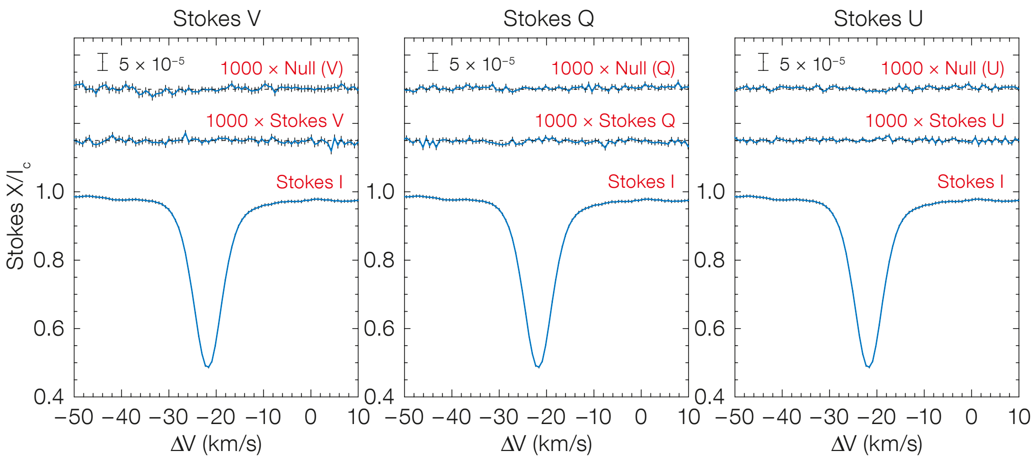

Figure 4. The combined average profile for intensity and polarisation (lower and middle plots) for α Cen A. Left panel shows circular polarisation measurements (Stokes parameter V). Middle and right panels are for linear polarisations. The null profile is shown uppermost.

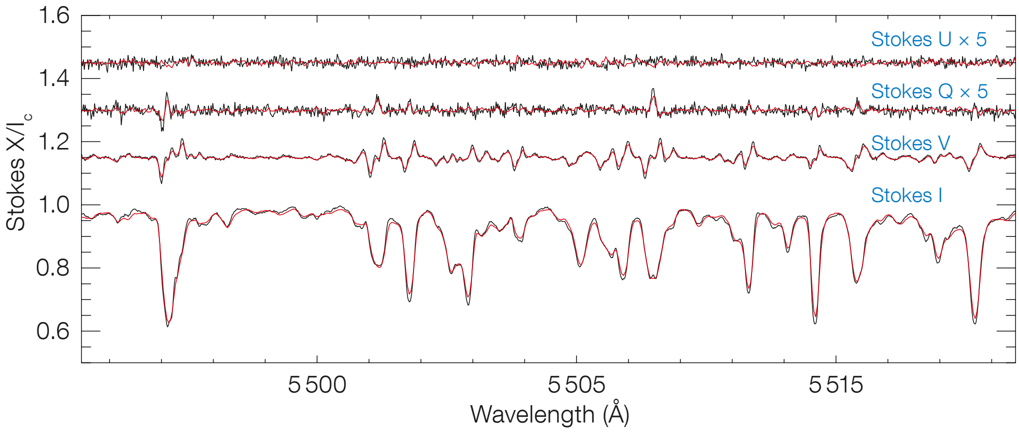

Figure 5. Comparison of the Stokes spectra of a standard magnetic star γ Equ taken at the CFHT with the ESPANDONS spectropolarimeter (red line) and with HARPSpol (black line) is shown. The ESPADONS spectra were taken as part of CFHT's calibration and engineering plan, and were retrieved from the Canadian Astronomy Data Centre. The visible differences are mostly due to the higher resolving power of HARPS.

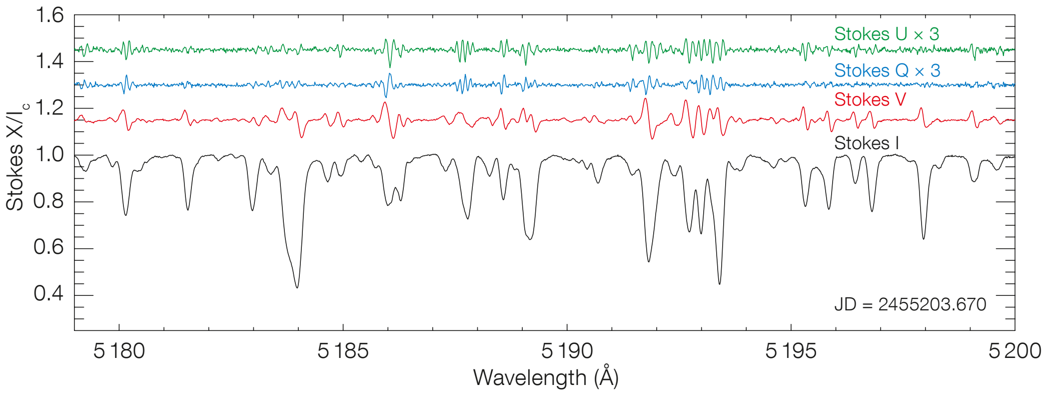

Figure 6. One of the HARPS polarisation spectra of a CP star, HD 24712, is shown. Both circular and linear polarisations are detected for practically every spectral line.

template allows multiple exposures to be taken in the selected mode (circular or linear) for a sequence of wave-plate angles. The full complement of polarisation characteristics can be registered in six or twelve exposures, with the latter offering intrinsic control over spurious polarisation signals. The HARPSpol pipeline then processes the data and the final products include the Stokes parameters as a function of wavelength.

HARPSpol: Performance

During commissioning we have measured several characteristics of HARPSpol. The most important ones for the observer are the total throughput of the system and the polarimetric sensitivity. The throughput (Figure 3) was measured by observing spectrophotometric standards, reducing the data, rebinning it to match the resolution of the spectrophotometry and deriving the sensitivity curves for each fibre. The total efficiency with HARPSpol is somewhat lower due to the lower throughput of the "sky fibre" (used to carry one of the polarised beams), but still sufficient to reach rather faint targets.

Systematic errors limit both the polarimetric sensitivity and the accuracy. The sensitivity is the weakest polarisation detectable with HARPSpol. After accumulating enough photons we expect to see spurious polarisation present in the light coming to the telescope. We test this by observing a bright source and collecting many photons in a series of many short exposures. Figure 4 shows the results of the test for an inactive solar-type star, α Cen A, where we reach the median signal-to-noise ratio of 2400 per CCD column. Besides combining multiple exposures we also derive the mean Stokes profiles using the least squares deconvolution (LSD) technique (Donati et al., 1997; Kochukhov et al., 2010), which takes advantage of the fact that most of the spectral lines are affected by magnetic fields in a similar way. This increases the signal-to-noise even further. The top plot in each panel of Figure 4 shows the so-called null spectrum, obtained by modifying the analysis in such a way as to destroy the polarisation signal in the incoming light (Bagnulo et al., 2009). What remains reflects the spurious polarisation induced inside the instrumentation or by the data reduction.

We do not expect any detectable polarisation signal from α Cen A and Figure 4 shows that our new instrument does not detect or induce any polarisation above the level of 10^{-5}, which is on a par with the best solar polarimeters like ZIMPOL (Ramelli et al., 2010). The accuracy (the level at which the HARPSpol measurements match the true polarisation signal) is assessed by observing objects with known polarisation spectra. Our observations of γ Equ demonstrate the high accuracy of HARPSpol. γ Equ is a well-studied magnetic star showing linear and circular polarisations. The lack of noticeable rotation makes γ Equ an excellent polarisation standard. Figure 5 shows the comparison of the HARPSpol polarisation

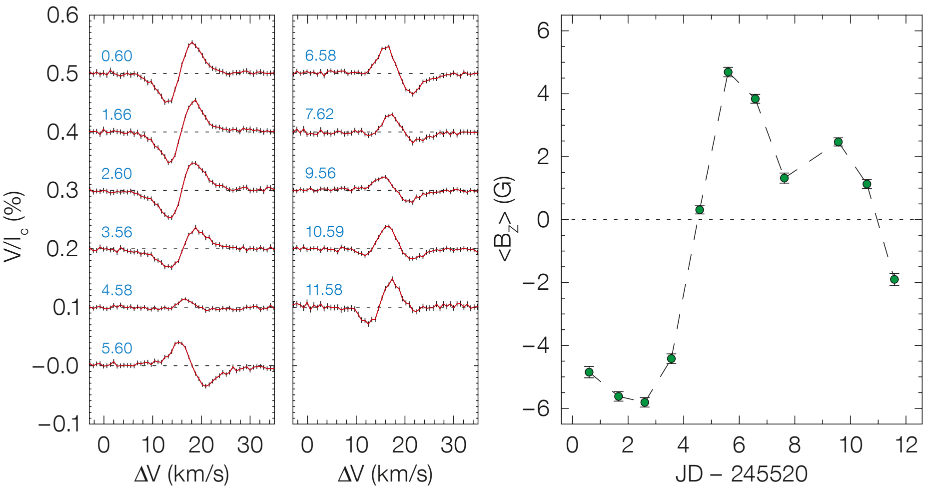

Figure 7. Spectropolarimetry of a K2 dwarf planet-hosting star ε Eri taken with HARPSpol. Circular polarisation profiles (left) are marked with observation times in days. Derived line-of-sight field strength and uncertainty in Gauss are shown against time (in Julian Day) on the right.

spectra of this star with those taken with the ESPADONS spectropolarimeter (Donati et al., 2006) at the Canada France Hawaii Telescope (CFHT) with a resolving power of 67 000.

HARPSpol: First results

One of the obvious applications of HARPSpol is in the study of the topology of magnetic fields on chemically peculiar (CP) stars. The goal is to understand the relationship between the field geometry and the surface/depth distribution of chemical elements. This task requires a series of observations well spread over the rotation period so as to see all visible parts of the stellar surface. Figure 6 shows an example of one measurement in such a series for a cool magnetic CP star HD 24712. Circular and linear polarisation were detected in all 13 phases covering the whole stellar rotation (bad weather prevented the collection of one set of circular polarisation data) and one can easily follow the evolution of polarisation spectra with stellar rotation. The low level of the noise makes the data quite adequate for reconstructing the field topology.

Another example is a chromospherically active cool dwarf ε Eri. This nearby star harbours at least two planets and a dust belt in orbit around it. Polarisation measurements of stars hosting planets may provide an important check for the presence of starspots that can mimic radial velocity variations. Detection of polarisation can reveal signatures of star–planet magnetic interactions. Our polarisation measurements for ε Eri are presented in Figure 7. Again, we applied the LSD technique to enhance the signal-to-noise ratio and we see an unambiguous signal in circular polarisation. A simplistic interpretation with a longitudinal field geometry shows field strength changing from −5.8 to +4.7 Gauss with median uncertainty of 0.1 Gauss! These values are comparable to the disc-averaged magnetic field of the Sun (Kotov et al., 1998).

Prospects

HARPSpol adds powerful polarimetric capabilities to the suite of ESO high-resolution spectroscopic instruments. It is fully integrated into the ESO operational environment and is equipped with a pipeline producing science-grade data products. The tests and applications to various types of objects have demonstrated high sensitivity and a low level of systematic effects, making HARPSpol an ideal tool for detecting and studying weak magnetic fields, reconstructing field topology and many other magnetic phenomena.

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