The polarimeters for HARPS and X-shooter

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Abstract. Spectropolarimetry enables observations of stellar magnetic fields and circumstellar asymmetries, e.g. in disks and supernova explosions. To furnish better diagnostics of such stellar physics, we designed and commissioned a polarimetric unit at the successful HARPS spectrograph at ESO’s 3.6-m telescope at La Silla. We present the design and performance of HARPSpol, and show some first science results. The most striking achievement of HARPSpol is its capability to measure stellar magnetic fields as small as 0.1 G. Finally, we give a sneak preview of the polarimeter we are currently designing for X-shooter at the VLT. It contains a novel type of polarimetric modulator that is able to efficiently measure all the Stokes parameters over the huge wavelength range of 300–2500 nm.

1. Stellar Spectropolarimetry

No star is perfectly spherically symmetric. Starlight is therefore never completely unpolarized, and measuring that polarization, however small, in spectral lines and/or the continuum therefore gives us crucial information on the physical environment within which the light we observe was created. The science cases for our polarimeters for HARPS and X-shooter are therefore widespread. A narrow selection is presented here, see Snik & Keller (2012) for a more comprehensive overview.

1.1. Stellar Magnetic Fields

400 years ago Galileo’s observations showed blemishes on the surface of the sun, now known as sunspots. Hale proved only some 100 years ago through polarimetric observations that sunspots and related activity are caused by magnetic fields. The very detailed observations of the sun to which many Utrecht astronomers have contributed

1The sun is currently only really blemished by Utrecht University still carrying its image in the logo...
significantly over the last century now also stand as a benchmark for the observation of the millions of other magnetic stars that are accessible to our night-time telescopes. Even though the overwhelming majority these stars remain a point source even when observed with the next generation of telescopes, polarimetric observations now allow us to infer (circum)stellar structure way beyond the spatial resolution limits. Indeed, by observing the (circular and linear) polarization signatures due to the Zeeman effect in spectral lines as a function of the stellar rotation, maps of magnetic fields can now be created for stars other than the sun (Semel et al. 1993). Often, these polarization signals are small ($<10^{-4}$) and buried in the noise for individual spectral lines. Clever line addition techniques (Donati et al. 1997) can improve the signal-to-noise ratio dramatically by using the information in all available lines simultaneously. Magnetic fields have thus been detected and mapped for stars throughout the HR diagram (see Donati & Landstreet 2009), including, surprisingly, massive stars.

1.2. Scattering Disks, Atmospheres and Supernova Ejecta

Like our blue sky, any volume of gas or dust can linearly polarize starlight upon scattering. Measuring stellar continuum polarization therefore yields information on the presence of asymmetric circumstellar structures as protoplanetary disks. Even the combined light of the star and scattered light off an exoplanetary atmosphere may be measurable. Scattering also takes place in the hazy atmospheres of brown dwarfs, and non-zero polarization hints at stellar oblateness or even patchy clouds. On larger scales, polarimetry also permits the detailed study of structure around Active Galactic Nuclei.

Supernova explosions are thought to be very asymmetric. These asymmetries can be probed through continuum and line polarization (see Wang & Wheeler 2008). The latter yields the detailed three-dimensional information on the location of the leftovers of the stellar shells. The same technique can also be applied to Gamma-Ray Bursts.

2. The HARPS polarimeter

2.1. Design and Performance

HARPS (Mayor et al. 2003) is arguably the greatest spectrograph in the world. To date, it has already detected or confirmed more than a hundred exoplanets, owing to its extreme sensitivity to radial velocity variations. The stabilized HARPS spectrograph is fed with light from two fibers that are connected to the Cassegrain focus of ESO’s 3.6-m telescope at La Silla, Chile. The first fiber usually carries the light of the star under investigation, while the second one is illuminated by light from a wavelength reference lamp. These two fibers, in combination with a previously unused volume in the Cassegrain adapter enable the HARPS polarimeter (Snik et al. 2008, 2011; Piskunov et al. 2011). The polarimetric unit can slide in a circular and a linear polarimeter in front of the fibers. Each polarimeter contains a custom-designed polarizing beam-splitter that injects perpendicularly polarized light in the two fibers. A rotatable superachromatic quarter- and half-wave plate converts respectively circular and linear polarization into the linear polarization analyzed by the separate beam-splitters. Thus, sensitive dual-beam polarimetry (Semel et al. 1993) can be performed for all polarized Stokes parameters $V$ (circular) and $Q, U$ (linear). The instrumental polarization is minimal thanks to the location of the polarization optics in the Cassegrain focus.
The HARPS polarimeter was assembled and tested in Utrecht in April 2009, and commissioned at La Silla in May-June 2009. The first observations showed exceptional performance of HARPSpol. Its polarimetric sensitivity after multiline addition reaches down to $\sim 10^{-5}$, which translates to a noise level on the magnetic field measurement for $\alpha$ Cen A of 0.1 G (Snik et al. 2011; Kochukhov et al. 2011). The polarimetric accuracy was established by comparing HARPSpol observations of the strongly magnetic roAp star $\gamma$ Equ with thoroughly calibrated measurements using ESPaDOnS. This comparison showed that without any calibration HARPSpol is accurate to within 1% (Snik et al. 2011). The residual errors are due to stress-birefringence in the ADC and due to the small chromaticity of the wave plates.

2.2. First Science Results

The polarimetric mode of HARPS was offered to the community in February 2010, and has been very popular. Several exciting science results have been achieved using HARPSpol. Due to the variability of the fiber transmissions during tracking, HARPSpol can only be used to measure line polarization, and is therefore particularly suited for magnetic field studies. With the GTO observations, Kochukhov et al. (2011) have shown that owing to the large spectral resolution of HARPS and the large sensitivity of the polarimeter, highly structured linear polarization signatures due to the Zeeman effect (which are much weaker but complementary to the signatures in circular polarization) can be measured for cool stars. Despite the large sensitivity of HARPSpol, no magnetic fields have been detected in a variety of mercury-manganese stars (e.g. 66 Eri; Makaganiuk et al. 2011). Their chemical spots therefore need to be attributed to other physical processes. Johns-Krull et al. (2012) investigated the polarization of the helium lines of the T Tau stars GQ Lup and TW Hya, and established a consistent picture of magnetically controlled accretion of disk material onto the star. Now HARPSpol opened up the southern skies for high resolution spectropolarimetric observations, many more detections of magnetic fields in massive stars are enabled. Indeed, Alecian et al. (2011) report on the first three HARPSpol detections of magnetic B stars.

3. The polarimeter for X-shooter

The X-shooter instrument (Vernet et al. 2011) at the 8.2-m VLT UT2 is a strong contender for runner-up position in the “greatest spectograph in the world” competition. It consists of three highly efficient slit spectrographs that have a combined spectral range of 300–2500 nm. X-shooter is a Cassegrain instrument, and therefore in principle very suitable for polarimetry. However, it is very challenging to design a polarization modulator that would span its enormous wavelength range, as even superachromatic wave plates can only cover about half this range. Tomczyk et al. (2010) introduce a novel principle for polarization modulators, which enables us to design a full-Stokes polarimeter for X-shooter. A so-called “polychromatic” modulator is not an achromatic wave plate, but instead its polarimetric efficiencies for all Stokes parameters are optimized at every wavelength within the required range. This means that at every wavelength the measurements for all four or more modulation states can be optimally demodulated. This modulation itself can therefore be very chromatic. The polarimetric efficiencies (del Toro Iniesta & Collados 2000) for $Q$, $U$ and $V$ are ideally $1/\sqrt{3}$, which means that the signal-to-noise ratio in $V/I$ is $\sim 58\%$ of that of a polarimeter with just a quarter-wave plate modulator, for the same total exposure time. However, the latter
polarimeter could just measure Stokes $V$ with large efficiency, whereas a polychromatic modulator measures all Stokes parameters simultaneously with optimal efficiency.

Van Harten et al. (2012) designed a number of polychromatic modulators for application within X-shooter, and traded off the designs in terms of its polarimetric efficiencies, its behavior in the F/13 beam at the Cassegrain focus, its temperature dependence and its polarized fringes. The current baseline design for the modulator consists of eight layers of quartz, and fulfills all requirements for the polarimetry (Snik et al. 2012). As X-shooter should exhibit minimal transmission variations during pointing (contrary to HARPS), particular care has been taken that continuum polarization can be measured down to the $10^{-4}$ level. A calcite Savart plate will be located after the modulator and splits up the beam along the slits according to perpendicular linear polarizations. As calcite loses its transparency at 2.2 $\mu m$ and no viable alternative material is available, the K-band has to be sacrificed for the polarimetric mode.

The X-shooter polarimeter will enable a wide range of science cases. Being attached to an 8-m telescope makes that it can target many more magnetic stars, although X-shooter’s spectral resolution is about ten times worse than HARPS’. Also the much larger wavelength range opens up many more possibilities. Furthermore, the capability of X-shooter-pol to measure continuum polarization will allow astronomers to address many more exciting astrophysical science cases. Thus, the heritage of Utrecht astronomy will be kept alive for many more years to come.

References


