A new 2 channel HHigh-speedPhoto-POLarimeter (HIPPO) for the SAAO

Stephen Potter\textsuperscript{a}, David Buckley\textsuperscript{a}, Darragh O'Donoghue\textsuperscript{a}, James O'Conner\textsuperscript{a}, Piet Fourie\textsuperscript{a}, Geoff Evans\textsuperscript{a}, Craig Sass\textsuperscript{a}, Lisa Crause\textsuperscript{a}, O. W. Butters\textsuperscript{b}, Andrew Norton\textsuperscript{b}, Koji Mukai\textsuperscript{b}, Martin Still\textsuperscript{a}
\textsuperscript{a}South African Astronomical Observatory, PO Box 9, Observatory 7935, Cape Town, South Africa;
\textsuperscript{b}Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK;
\textsuperscript{c}CRESST and X-ray Astrophysics Laboratory NASA/GSFC, Greenbelt, MD 20771, USA;
Department of Physics, University of Maryland, Baltimore county, 1000 Hilltop Circle, Baltimore, MD 21250, USA;
\textsuperscript{d}Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT;

ABSTRACT

We report on the completion of a new 2 channel, HHigh speed Photo-POLarimeter (HIPPO) for the 1.9m optical telescope of the South African Astronomical Observatory. The instrument makes use of rapidly counter-rotating (10Hz), super-achromatic half- and quarter-waveplates, a fixed Glan-Thompson beamsplitter and two photo-multiplier tubes that record the modulated O and E beams. Each modulated beam permits an independent measurement of the polarisation and therefore simultaneous 2 filter observations. All Stokes parameters are recorded every 0.1sec and photometry every 1 millisecond. Post-binning of data is possible in order to improve the signal. This is ideal for measuring e.g. the rapid variability of the optical polarisation from magnetic Cataclysmic Variable stars. First light was obtained in February 2008.

Keywords: Photometry, polarimetry, high-speed, magnetic Cataclysmic Variables

1. INTRODUCTION

SAAO's (South African Astronomical Observatory) HIPPO was designed and built in order to replace the highly successful but aging single channel equivalent, namely the UCT (University of Cape Town) photo-polarimeter\textsuperscript{1}. Its purpose is to obtain simultaneous all-Stokes parameters, multi-filtered observations of unresolved astronomical sources. In addition it is capable of high speed photo-polarimetry in order to permit investigations of rapidly varying polarised astronomical sources. Of particular interest are magnetic Cataclysmic Variables (mCVs).

MCVs are short period binaries that contain a white dwarf and a red dwarf companion star that overflows its Roche lobe. In some cases the magnetic field of the white dwarf is sufficiently strong to lock the system into synchronous rotation and to prevent an accretion disc from forming. Instead, the overflowing material from the secondary initially continues on a ballistic trajectory until, at some distance from the white dwarf, the magnetic pressure overwhelms the ram pressure of the ballistic stream. From this point onwards the accretion flow is confined to follow the magnetic field lines of the white dwarf\textsuperscript{12}.

The now supersonic accreting material suddenly becomes subsonic at a shock region, which forms at some height above the white dwarf surface. The shock-heated material reaches temperatures of 10-50keV and is ionised. The hot plasma cools by two different mechanisms as it settles onto the white dwarf, resulting in a density and temperature stratification in the post-shock region. The two cooling mechanisms are X-ray cooling, in the form of bremsstrahlung radiation and, with sufficient magnetic fields, cyclotron cooling in the form of polarised optical/IR cyclotron radiation, see Fig. 1.

The nature of the polarised optical emission depends on the viewing angle to the shock. Consequently the percentage of linear and circular polarisation varies as a function of orbital period of the mCV (see e.g. observations of the mCV V834 Cen\textsuperscript{11}). The cyclotron emission regions can then be reconstructed with appropriate modeling of the polarimetric observations. In addition, multi-filtered observations permit an estimate of the magnetic field strength.
In the following sections we describe the new instrument and our first science results of a candidate mCV.

![Diagram of the accretion shock on the surface of the white dwarf.]

**Fig. 1.** Diagram of the accretion shock on the surface of the white dwarf.

### 2. INSTRUMENT DESIGN

![Optical layout of the polarimeter. Channel 1 is a copy of channel 2.]

**Fig. 2.** Optical layout of the polarimeter. Channel 1 is a copy of channel 2.
Optical design

Fig. 2 gives a schematic diagram of the optical layout of the polarimeter. Light from the telescope first encounters a field lens that produces a collimated beam. Within the collimated beam is placed a polarising calibration filter wheel followed by superachromatic ¼ and ½ waveplates. The polarising calibration filter wheel consists of 2 linear polaroids, 1 circular polaroid (a linear followed by a ¼ wave plastic retarder to produce a circularly polarised beam), a Lyot depolariser and an open position. These filters are used for calibration and efficiency measurements of the instrument and/or the telescope. The ¼ and ½ waveplates are also placed in the collimated beam in order to minimise any lateral modulation of the pupil image as the waveplates are rotated. A Thompson beamsplitter then produces the ordinary and extraordinary beams. All the above polarising optics are placed before any filters or apertures, to avoid problems caused by metallic apertures or filters with residual stress birefringence.

Each beam then has its own neutral density, colour filter and aperture wheels. The beams are focused at the aperture wheels by lenses at the top of each channel. Fabry lenses re-image the pupil onto two photomultiplier tubes. There is also an eye-piece (used for initial alignment) and a dark slide on each channel.

The waveplates are contra-rotated at 10Hz and therefore modulate the ordinary and extraordinary beams. The modulation is sufficiently rapid that errors that arise as a result of variable atmospheric conditions or telescope guiding modulations, are much reduced. In addition, modulations that occur as a result of wedge shaped rotating elements, dirt on the rotating components or dichroism from refraction at the element surfaces appear mostly at harmonics not of interest. The remaining sources of error are photon statistics, which can be minimised by collecting a larger number of photons, and instrument/telescope polarisation, which can be calculated/measured by observing polarised and unpolarised standard stars and by using the calibration filters. This description for measuring polarimetry is based on the work of Serkowski

Instrument control and data flow

Fig. 3. Schematic of communication and data flow. The upper and lower shaded regions represent the main components of the instrument and the control PC respectively. PMT1/2, Aper1/2, Filter1/2, ND1/2, ½, ¼ and Cal are the photomultiplier tubes, aperture wheels, filter wheels, neutral density wheels, ½ ¼ waveplates and calibration wheels respectively. Arrows indicate direction of data flow. See text for more details.
A schematic of the communication and data flow is shown in Fig. 3. User commands to control the instrument are sent from an industrial PC via a PLC (programmable logic controller). The PLC is programmed to control the 2 sets of aperture, colour filter and neutral density wheels, as well as the 2 rotating waveplates and the polarising calibration wheel. The PLC also relays (upon request) the status of the instrument to the industrial PC via its serial port. Photometer counts (from the 2 photometers), minute and second time pulses (from the SAAO time service) and 1/2 and 1/4 waveplate pulses (from the waveplate sensors) are received by an in-house SAAO photometry card in an ISA slot of the PC. MT (mean time) and a KHz signal (from the SAAO time service) are received by an in-house SAAO time card in another ISA slot of the PC.

The control and data acquisition software is written in C and is hosted by the industrial PC. The photometer counts, minute and second time pulses and the 1/2+1/4 waveplate pulses are handled by real time C code in order to ensure correct and absolute timely recording of the data. The real time code is driven by a 1 milli-second time interval interrupt driven by the 1 KHz signal from the SAAO time card. At every interrupt, the status of the waveplate pulses, time pulses and the photometer buffers are recorded. These data are then sent to the user C code, where on-the-fly data reductions are performed. The 1 milli-second data stream is also saved to disk for later off-line data reduction. With a data rate of 1KHz, the 10Hz rotating waveplates are sampled 100 times per revolution. Therefore every 0.1 seconds a polarisation measurement is made. The GUI is also written in C and uses the xforms libraries.

**Data reduction**

Serkowski\(^{11}\) provides the formalism for calculating the Stokes parameters from O and E beams that are modulated as a result of passing through two retarders in series. In our case, for constantly contra-rotating 1/4 and 1/2 waveplates in series, the modulated intensities are given by

\[
I_O = \frac{1}{2} \left( I + \frac{1}{2} Q \left[ \cos 8\psi_8 + \cos 4\psi_4 \right] + \frac{1}{2} U \left[ \sin 8\psi_8 - \sin 4\psi_4 \right] - V \left[ \sin 6\psi_6 \right] \right)
\]

\[
I_E = \frac{1}{2} \left( I + \frac{1}{2} Q \left[ -\cos 8\psi_8 - \cos 4\psi_4 \right] + \frac{1}{2} U \left[ -\sin 8\psi_8 + \sin 4\psi_4 \right] + V \left[ \sin 6\psi_6 \right] \right)
\]

for the O and E beams respectively. Where

\[
\psi_8 = 8\psi - 4C^{(1/2)} + 4C^{(1/4)} \quad \psi_6 = 6\psi - 4C^{(1/2)} + 2C^{(1/4)} \quad \psi_4 = 4\psi - 4C^{(1/2)}
\]

where \(\psi\) is the angle between the waveplates and referenced to the 1/4 waveplate fast axis, \(C^{(1/2)}, C^{(1/4)}\) are the zero point constant offsets for the half- and quarter-waveplates respectively and I,O,U and V are the Stokes parameters. From these equations one can see that the linear component of the polarization is modulated equally at the 4\(^{th}\) and 8\(^{th}\) harmonics of the rotation frequency. The circular component is modulated at the 6\(^{th}\) harmonic. The linear polarisation is measured by adding the amplitudes of the 4\(^{th}\) and 8\(^{th}\) harmonics and similarly by measuring the 6\(^{th}\) harmonic for the circular polarisation. The constant zero point offsets are calculated by observing polarised standard stars of known position angle. A least squares algorithm is used to obtain the amplitudes and phases of the harmonics. Correction factors are applied to each harmonic in order to compensate for the fact that the modulated signal is made up of a finite number of bins (100). Efficiency factors, to compensate for the slight wavelength dependence in retardance of the waveplates and instrumental polarisation, are measured by observing polarised and unpolarised standards stars and then subtracted from the data.
3. FIRST SCIENCE OBSERVATIONS

Fig. 4. Upper and lower left panels: The photometry (1sec time resolution) and circular polarisation (30 sec bins) of IGR J14536-5522. Observations cover ~1.3 orbits. Upper and lower right panels: Same as left panels but zoomed in order to show the short period (~4-5 minutes) quasi periodic oscillations.

Introduction

IGRJ14536-5522 (=Swift J453.4-5524) was discovered as a hard X-ray source by INTEGRAL\(^1\) and by Swift/BAT\(^3\). A pointed Swift/XRT observation led to the identification with a ROSAT all-sky survey (RASS) source 1 RXS J145341.1-552146, and hence to optical identification\(^4\). Follow-up spectroscopy and photometry with SALT and with the SAAO 1.9m telescope showed that this object belongs to a rare subtype of magnetic CV: a hard X-ray bright polar or a soft intermediate polar\(^5\). Further observations were clearly needed.

Data reduction

In Fig. 4 we show our first science results with the new SAAO polarimeter. The observations span a period of 3.94 hours which corresponds to approximately 1.3 orbits. Background sky measurements were taken at regular intervals (every 30-40 minutes), the data are thus background subtracted. Polarized standard stars (HD111579 and HD111613) were observed during the night in order to calculate the waveplate zero points. The unpolarised standard star (HD100623) was observed in combination with the calibration filters in order to measure instrument and/or telescope polarisation and to calculate the efficiency factors. The data have also been atmospheric extinction corrected. As both channels were unfiltered the data have been co-added in order to improve the signal-to-noise.

Data analysis and interpretation

The upper left plot in Fig. 4 shows the photometry, binned to give 1 second time resolution. The overall single sinusoidal variation over one orbit is very typical of the orbital variations of low to intermediate inclination polars (e.g. UW Pic\(^b\)). There appears to be a dip once per orbit (mHJD=0.03 and 0.16), which we attribute to absorption of emission from the accretion shock by the accretion stream, although more observations are required in order to rule out completely a grazing eclipse. However, the fact that the photometry and polarimetry do not show a very distinct bright and faint phase over the orbital cycle, as in other high inclination polars (see e.g. VV Pup\(^c\)) tends to favour the stream absorption explanation. The photometry also shows short timescale (~2-5 minutes) quasi-periodic oscillations (QPOs) which are also
typically seen in some polars in X-rays and optical\cite{1}. The upper right plot of Fig. 4 shows the 2-5minute QPOs more clearly. Each data point corresponds to 1 second. A closer examination reveals that there are also even shorter oscillations on the order of 10-30 seconds. These have also been observed in other polars\cite{2}.

The lower left plot of Fig. 4 shows the percentage of circular polarisation. It displays the typical morphological features of polarised cyclotron emission from a magnetically confined accretion shock in polars, i.e. a double-humped variation ranging from 0 to almost 20\% (negative). The variation arises due to the angular dependence of the beaming of the cyclotron radiation. The variation in angle occurs as the binary system revolves from our point of view. Although linear polarisation was measured simultaneously, no significant signal was detected.

Coherent periods shorter than the orbital period were not detected in these observations, thus ruling out the possible intermediate polar identification. In addition, the high levels of circular polarisation are not typically seen in intermediate polars.

The upper and lower right plots of Fig. 4 show a closer view of part of the photometric and polarimetric data respectively. These figures show the photometric QPO variations more clearly and also that the 2-5minute QPOs are present in the circular polarisation. The data are of insufficient signal-to-noise to bin at a smaller time resolution and thus search for polarised variations on smaller timescales. This is the first time that QPOs have been observed to be polarised. It is not yet clear if this is unique to this polar or whether this is the first time that the polarimetry has been observed and/or binned on a sufficiently small time resolution to see the QPOs.

The shorter QPOs (seen in the photometry) are thought to arise as a result of oscillations in the shock which modulate the physical structure of the post-shock region and hence the X-ray and optical luminosities. The first numerical studies of time dependent flows in shocks were performed in the early 1980s\cite{3}. The actual details of the oscillations are theoretically thought to be related to parameters such as the mass and magnetic field strength of the white dwarf and the specific accretion rate\cite{4}.

The longer timescale QPOs (∼minutes) that we have observed in our photometry and polarimetry are thought to arise from oscillations near the inner Lagrangian point of the two stars. King\cite{5} showed that steady irradiation by the white dwarf would form an ionisation front near the inner Lagrangian point. He goes on to justify that the front would be unstable and would undergo oscillations with a period similar to what we observe. The oscillations at the ionisation front would then lead to a corresponding variation in the accretion rate, which leads to a similar period for the light emitted at the base of the accretion column.

4. SUMMARY

The new instrument

HIPPO's first light was obtained in February 2008. The instrument makes use of rapidly counter-rotating (10Hz), super-achromatic half- and quarter- waveplates, a fixed Glan-Thompson beamsplitter and two photo-multiplier tubes that record the modulated O and E beams. Each modulated beam permits an independent measurement of the polarisation and therefore simultaneous 2 filter observations. All Stokes parameters are recorded every 0.1sec and photometry every 1 millisecond. Post-binning of data is possible in order to improve the signal. This is ideal for measuring e.g. the rapid variability of the optical polarisation from magnetic Cataclysmic Variable stars.

First Science

Our polarimetric observations of IGRJ14536-5522 have shown it to be a magnetic Cataclysmic Variable and belonging to the sub-classification of a polar. Additionally, the polarimetry shows QPO-type behavior of the order of 2-5 minutes. This is the first time that polarised QPOs have been observed in polars and thus show that they originate from the accretion shock and that cyclotron cooling is a significant factor on these timescales.

The QPOs also appear to be correlated with the photometric QPOs. Photometric QPOs have been observed in other polars and have been attributed to either shock oscillations or variations in the accretion rate originating from near the inner Lagrangian point. The observed timescales indicate the latter explanation. However, the data are of insufficient signal/noise to rule out polarised QPOs at the shorter timescales expected from shock oscillations.
Further observations of polars with different system parameters (magnetic field strength, orbital period, accretion rate etc) are encouraged in order to investigate this further.

REFERENCES