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Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

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## ABSTRACT

The Robert Stobie Spectrograph is currently the main workhorse spectroscopic instrument on the Southern African Large Telescope (SALT), which has been undergoing regular scientific operations since 2011. The visible beam of the RSS was designed to perform polarimetry in all of its modes, imaging and grating spectroscopy (with Multi Object Spectroscopy capability) from 3200 to 9000 Å. The polarimetric field of view is 4×8 arcmin.

Initial early commissioning of the polarimetric modes was stalled in 2011 because a coupling fluid leak developed in the polarizing beamsplitter after less than a year of operation. As a result, it was decided to redesign the beamsplitter to use a different optical couplant. This was complicated by the unusual thermal expansion properties of the calcite optic, and by the necessity of aligning the individual elements in the beamsplitter mosaic (RSS is the first instrument to use a mosaic beamsplitter). Laboratory work selected a new couplant: a gel, Nye 451. Testing was completed with satisfactory results on a "sacrificial" calcite prism with the same geometry as an actual mosaic element. A successful assembly was performed and the beamsplitter was re-installed in SALT in mid-2015.

We describe results from the renewed commissioning efforts to characterize polarimetry from SALT and include some early performance verification science.

**Keywords:** SALT, SAAO, RSS, Robert Stobie Spectrograph, Polarimetry, Supernovae, quasar, white dwarf

## 1. INTRODUCTION

### The Robert Stobie Spectrograph on SALT

The observing station of the South African Astronomical Observatory (SAAO) is located 15kms from the small Karoo town of Sutherland in the Northern Cape; a 4 hour drive from Cape Town. SAAO operates several optical telescopes including the Southern African Large Telescope (SALT)[1,2]. The Robert Stobie Spectrograph (RSS)[3,4] is located at the prime focus of SALT and provides numerous capabilities, including: long-slit and multi-object spectroscopy (resolution powers between 800-10000 covering a wavelength range from 320nm to 1000nm are provided by 6 gratings), high speed spectroscopy (operating the CCD in "slot mode", a narrower field of view can be read out at 10Hz), imaging (through a suite of narrow-band filters), Fabry-Perot imaging spectroscopy (with one or two etalons enabling resolving power from 250-10000 over 430-900nm) and, finally, in combination with any of the above modes of operation, polarimetry[5]. All of the RSS modes potentially support linear, circular and all-Stokes polarimetry. RSS is permanently mounted at the prime focus and was designed so that all of its modes are available at all times.

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Ground-based and Airborne Instrumentation for Astronomy VI, edited by Christopher J. Evans, Luc Simard, Hideki Takami
Proc. of SPIE Vol. 9908, 99082K · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2232391

Quarter-wave and/or half-wave plates can be inserted into the collimator separately or together to provide linear, circular or all-Stokes polarimetry (see Figure 1). The splitting of the O and the E beams is achieved by the insertable beamsplitter in the camera. The beamsplitter consists of a 3x3 mosaic of calcite Wollaston prisms - RSS is the first instrument to use such a mosaic beamsplitter. Initial polarimetric commissioning began in April 2012 and successful polarimetric observations were made with the long-slit, imaging and Fabry-Perot modes[6].

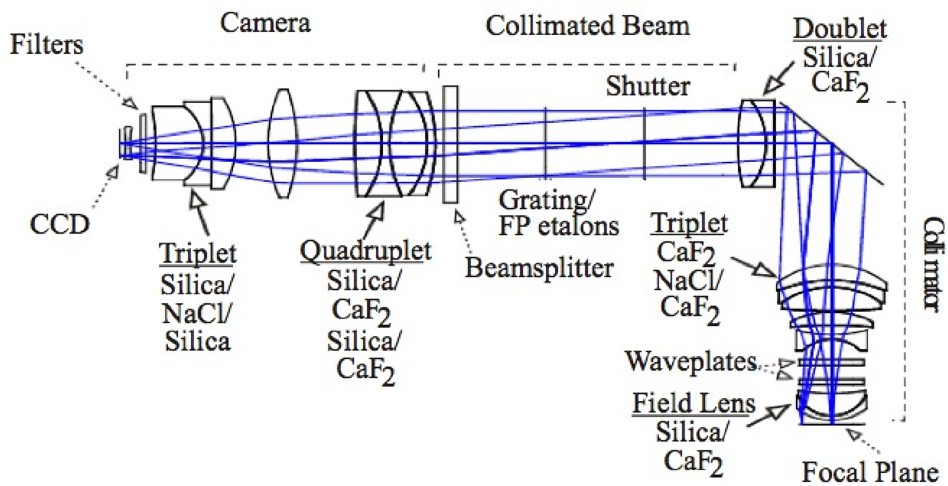


Figure 1. Optical schematic of RSS.

## 2. REPAIRS AND NEW CALIBRATIONS

**Repairing the Beamsplitter**

As mentioned above, the beamsplitter consists of a 3x3 mosaic of calcite Wollaston prisms. Each mosaic element consists of two prism wedges which were originally lens fluid coupled. After less than a year of polarimetric commissioning, the calcite beamsplitter developed a coupling fluid leak for a second time. Therefore, it was decided to redesign the beamsplitter to use a different optical couplant. Laboratory work was undertaken on a new couplant, a gel, Nye 451. Extensive tests were carried out on a "sacrificial" calcite prism with the same geometry as an actual mosaic element. After a successful assembly, bubbles removal and gel setting, thermal tests were performed. These were complicated by the unusual thermal expansion properties of the calcite optic, and by the necessity of aligning the individual elements in the beamsplitter mosaic. An extended thermal test, including a large temperature swing, was completed successfully in early 2015.

In the meantime, the actual mosaic had been disassembled, at which point it was found that the calcite surfaces that had been in contact with the couplant had developed a haze. This had to be polished off by the manufacturer (Karl Lambrecht Corp). One of the wedges was broken in the process and a replacement was fabricated, glued together from three smaller wedges of available UV calcite, and AR coated by OptoSigma Corp., the original coating vendor. The wedges were then repositioned on the mosaic. Optimal arrangement of the 9 elements in the mosaic was used to put any remaining defects in the corners, beneath the pupil mask. Next, the nine prisms were coupled with Nye 451, and the x-y tilt of each adjusted to align the images of each. The prisms were then assembled into the mosaic with thermal epoxy, adjusting the rotation so that the splitting of all the prisms lined up. Alignment was then found to be stable at the 3 micron level (.025 arcsec). The resulting RMS spot size is 7 microns (.06 arcsec) perpendicular to the splitting (parallel to the spectropolarimeter dispersion), and about 11 microns (.09 arcsec) along the dispersion.

**Calibration of linear spectropolarimetry**

Calibration and checking of linear spectropolarimetry with RSS involves three steps: calibration of the half-wave plate efficiency and position angle as a function of wavelength, establishment of the zero-point of linear polarization ("instrumental polarization") through observation of an unpolarized standard, and establishment of the position angle zero-point by comparison with a polarized standard. These have now been accomplished for stellar on-axis sources, although analysis continues. The half-wave plate calibration was done in the daytime by observing a standard continuum lamp through polaroids (HNP'B for UV-blue and HN7 for visible).

Figure 2 shows the RSS result for linear spectropolarimetry of the unpolarized standard HD94851. This observation takes advantage of the alt-azimuth SALT mount: by observing at two very different telescope azimuths, a separate estimate may be made of the standard star polarization (fixed in the sky) and the instrumental polarization (assumed fixed to the telescope primary and Spherical Aberration Corrector). The figure shows these two observations, taken on dates 2016-03-02 and 2016-04-02, each combined from two grating angles with the 900 l/mm VPH grating to cover 320 - 900 nm. The spectropolarimetry is reduced here, for visualization purposes, to filters U, B, and R. The instrumental polarization is shown by the dashed lines, and the standard star polarization by the filled circles. The latter may be compared to observations made in those filters by Tapia[7] , shown in diamonds. The formal RSS observation errors are smaller than the symbols, and differ from Tapia[7] by about 2σ of the Tapia[7] error bars (~.04%).

Figure 3 shows the RSS result for linear spectropolarimetry of the polarized standard star HD298383. These were obtained through the same grating configurations as the above observation, on two separate nights, and combined. The spectropolarimetry is presented unbinned, with 1 Angstrom pixels. Agreement with results from Tapia[7] in the N, U, B, G, R, and I filters is excellent for the position angle, and falls slightly below in polarization in the UV, where the wave-plate efficiency requires more analysis.

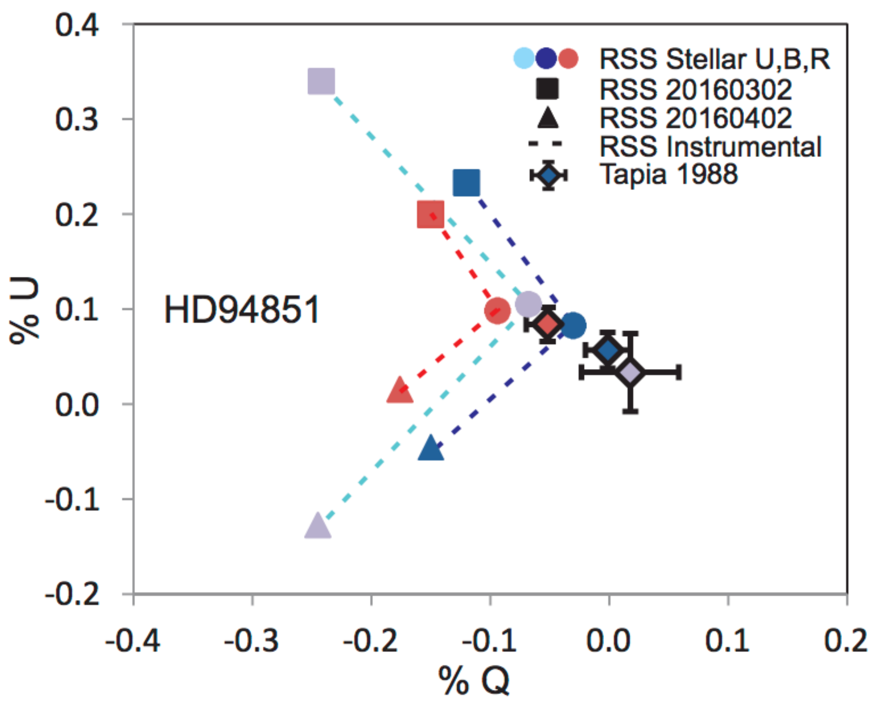


Figure 2. Linear spectropolarimetry of the unpolarized standard star HD94851 reduced to wavebands corresponding to the U, B and V filters compared to the results from Tapia[7].

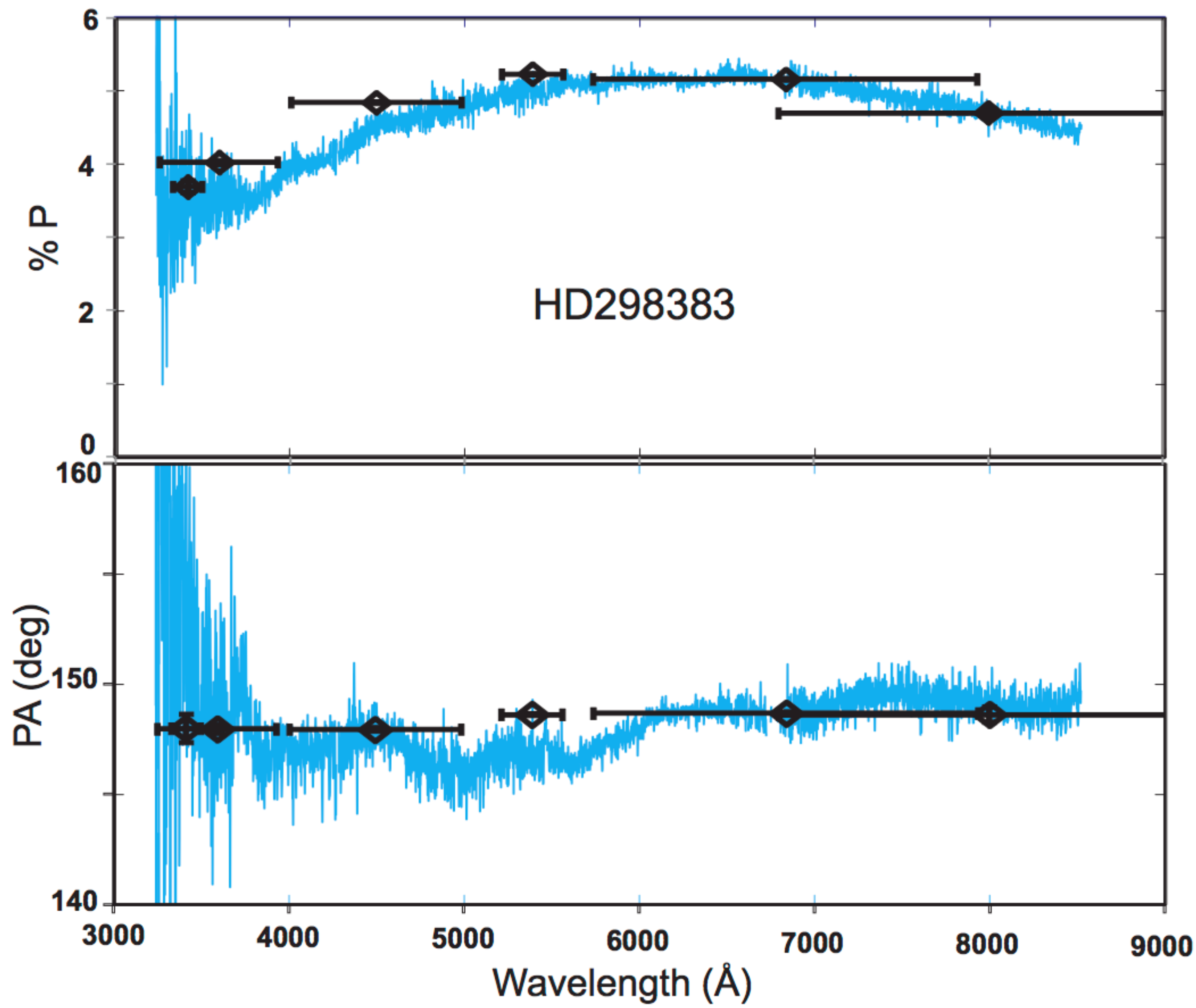


Figure 3. RSS linear spectropolarimetry of the polarized standard star HD298383. Comparison with N, U, B, G, R and I filters from Tapia[7] is also shown. Top and bottom show the degree of linear polarization *(p)* and position angle of linear polarization.

## 3. SCIENCE VERIFICATION

The second semester of 2015 saw the beginning of on-sky science verification. One of SALT's strengths is that it operates in a fully queue schedule mode and that all the modes of RSS are available at all times. This makes it ideal for Targets-of-Opportunity (ToOs). Three ToOs presented themselves during the period March-April 2016 that were ideal for science verification of on-axis, point source, linear spectropolarimetry.

**A highly variable and polarized white dwarf.**

In April 2016, a SALT ToO was triggered to observe a newly discovered, highly optically variable white dwarf in a binary system. The low resolution 300l/mm reflection grating (PG300) was used, at a grating angle of 5.375°, which covered the region ~350-900 nm. The high precision linear polarimetry mode ("linear-hi") was selected. This utilizes two repeat observations, each consisting of two independent rotation cycles of the ½ wave-plate, each at four different angles, namely at 0°, 22.5°, 45°, 67.5° and at 11.25°, 33.75°, 56.25°, 78.75°, to determine the Stokes $Q$ and $U$ parameters. This amounted to a total time of ~2800s for all 16 individual exposures, inclusive of acquisition time, CCD readout and calibration overheads. An order separating filter was used to exclude wavelengths < 340 nm, but because the second order spectrum is shifted in the spatial direction by the Wollaston polarizing beamsplitter, it does not overlap with the first order spectrum. A slit width of 1.5 arcsec was used with typical seeing-limited images ranging from 1.6 to 2.0 arcsec FWHM, which gave a spectral resolution of R ~ 350 at 620nm. The slit was aligned such that a nearby field star could be used as a comparison. The field star gave a constant polarization of 4-6% with a constant angle of ~211 degrees. Observations were obtained over four different nights. The white dwarf showed that the degree of linear polarization varied from 3-20% and in position angle from ~125 to 150 degrees (Figure 4). The results of an intensive multi-wavelength campaign on this source will be presented elsewhere.

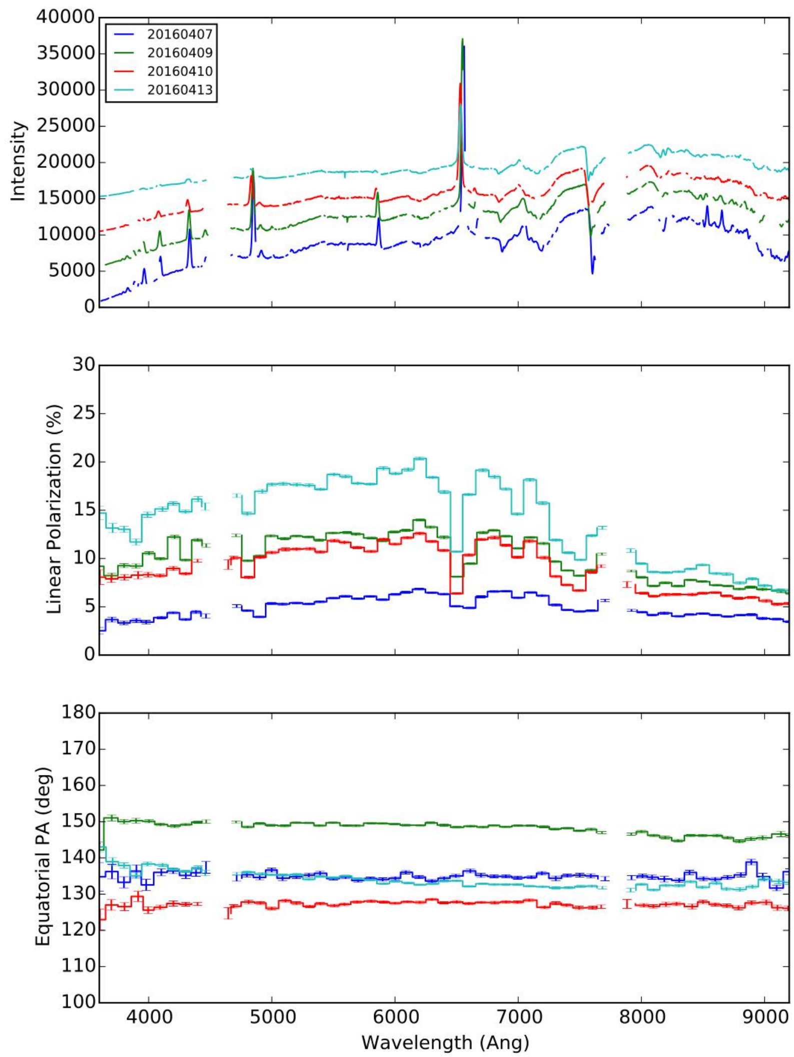


Figure 4. Linear spectropolarimetry of a highly polarized variable white dwarf. Observations made on 4 different nights show significant changes in polarization. Gaps in the spectra are due to excised cosmic rays, sky lines and gaps between the CCDs.

**Flaring quasar**

Also during April 2016, the Large Area Telescope on the Fermi Gamma-ray Space Telescope, detected increased gamma-ray flux from a source positionally coincident with a known flat spectrum radio quasar. Preliminary analysis indicated that the quasar was in a high state (flare) with a daily averaged gamma-ray flux about 16 times greater than its four-year average flux. This particular quasar has a relatively large redshift (z~1.4) and the flare was particularly extended, bright and had a very hard spectrum. Subsequently, a SALT ToO was triggered and a linear polarized spectrum was obtained (Figure 5). Again, the low resolution 300l/mm reflection grating (PG300) was used, at a grating angle of 5.375°, which covered the region ~350-900 nm. Figure 5 clearly shows high levels of linear polarization between ~20-28% and a relatively flat position angle ~160 degrees over the full spectral coverage.

**Supernova**

Atel #8651 (8 Feb 2016) reported a possible bright supernova (AT 2016adj) in the direction of Centaurus A (NGC 5228). Follow-up spectroscopy identified it as best resembling a Type I-b supernova (Atel #8657). ESO VLT spectropolarimetry taken on the 9 Feb 2016 (Atel #8668) shows strong polarization reaching 9.8% in the blue and decreasing to about 3.5% in the red. SALT ToO spectropolarimetric observations were triggered on the 2$^{nd}$ and 3$^{rd}$ of March 2016, almost 4 weeks after initial discovery. The PG0900, volume phase holographic (VPH) grating was used to cover the range ~320-900nm. The grating angle was changed in the second night in order to cover further into the red. Figure 6 shows the results. The percentage of linear polarization had decreased from the reported VLT observations of ~9.8% to ~3.5% in the blue. The redder part looks very structured with percentage of polarization between ~1-4%.

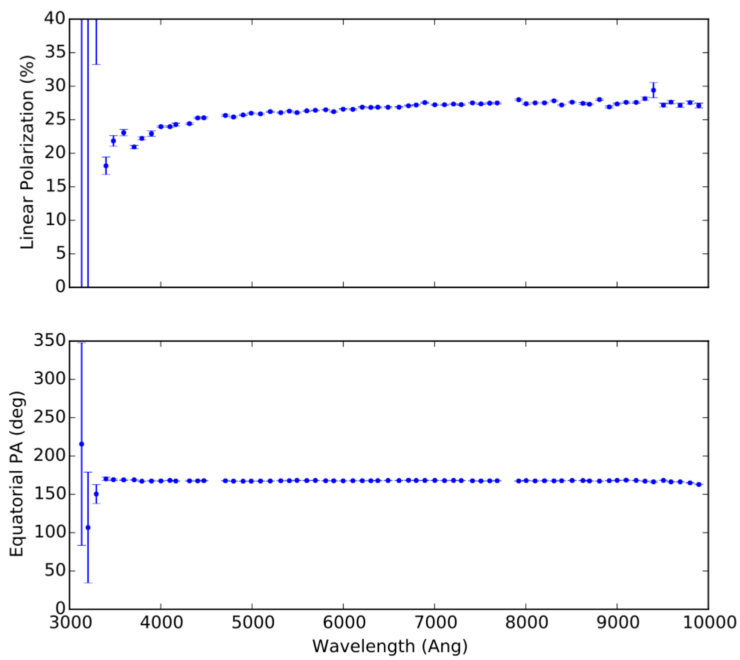


Figure 5. Linear spectropolarimetry of a BLAZAR during a period of increased gamma-ray activity. Top and bottom show the degree of linear polarization *(p)* and position angle of linear polarization.

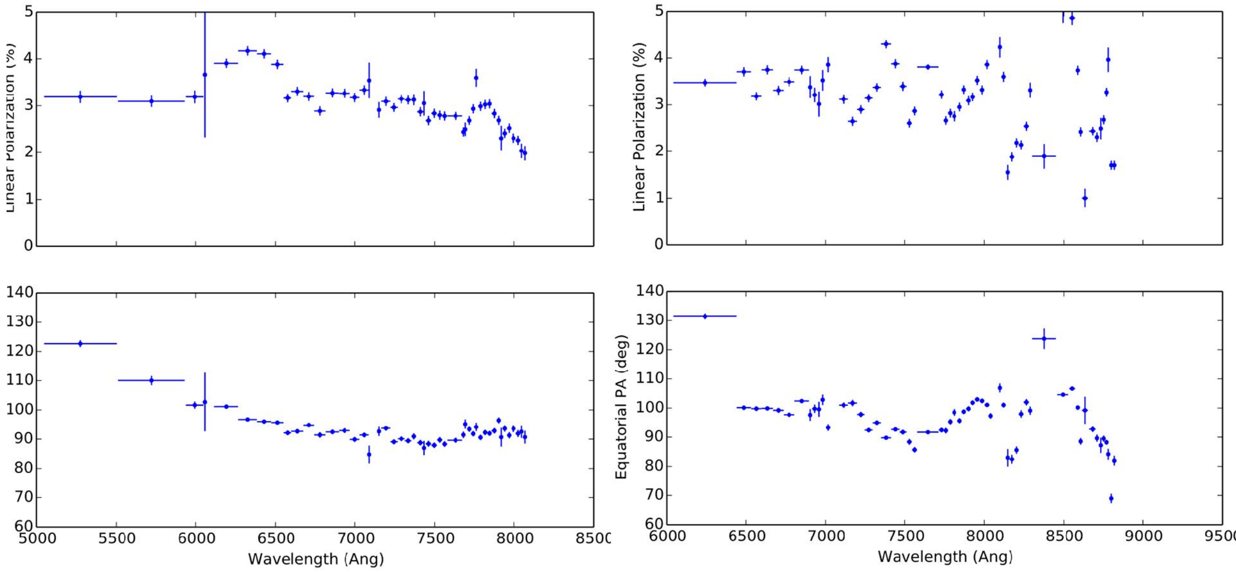


Figure 6. Linear spectropolarimetry of a super novae during the two nights of 2nd and 3rd March 2016.

## 4. ONGOING POLARIMETRY COMMISSIONING

At the time of writing, linear long-slit spectropolarimetry with the RSS on SALT is available for normal science operations. However, RSS offers several modes of polarimetry which are continuing to be commissioned. Each of the gratings will need to be characterized, as and when they are needed, and effects of the location of the target in the RSS field of view and of the position of the telescope tracker with respect to the primary mirror need to be fully understood.

RSS offers several polarimetric modes which can be broken down into three main groupings: Spectropolarimetry with gratings, which has been the topic of this paper, and imaging and Fabry-Perot polarimetry. Each of these can be operated with the half- and/or the quarter-waveplates, thus enabling linear, circular and all-Stokes polarimetry.

An additional prospect is the possibility of High-Speed spectropolarimetry. This requires that the beamsplitter be manually rotated through 90 degrees and thereby splitting the O and E beams horizontally rather than vertically on the detector. With the O and E spectra side by side, the CCD can be operated in a narrow window mode (slot-mode) thus enabling fast readout times. We anticipate using this mode on rapidly varying polarized sources such as magnetic Cataclysmic Variables.

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