PROCEEDINGS OF SCIENCE

Development of tools for the SALT/RSS spectropolarimetry reductions: application to the blazar 3C 279

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Blazars represent a subset of AGN with relativistic jets, where the direction of the jet lies very close to our line of sight. The highly Doppler boosted emission from the blazar's jet results in high apparent luminosities, and blazars display variability on periods from less than one day up to years. At optical wavelengths, the observed emission of the blazar is a superposition of the polarised non-thermal synchrotron emission, arising from the jet, and the unpolarised thermal emission, arising from the accretion disc, broad line region, torus and host galaxy. Polarimetry observations can serve as an important tool for diagnosing the emission from blazars. The RSS spectrograph, on SALT, can operate in spectropolarimetry mode and is currently being used to undertake spectropolarimetric observations of transient blazar sources. We present additional tools developed to work in conjunction with the current SALT spectropolarimetry reduction pipeline, POLSALT, that aims to streamline the reduction of the SALT polarisation data, including the testing of the wavelength calibration of the individual O and E beams. This was applied to observations of 3C 279 during 2017.

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1. Introduction

Active Galactic Nuclei (AGN) are the centres of galaxies powered by accretion onto a supermassive black hole. The accretion can power relativistic jets which produce non-thermal emission over multiple wavelengths [1]. Blazars are a subclass of AGN where the direction of the jet lies very close to our line of sight. The highly Doppler boosted emission from the jet results in high apparent luminosities.

At optical wavelengths the observed emission is a superposition of polarised non-thermal synchrotron emission, arising from the jet, and unpolarised thermal emission, arising from the disc, broad line region, torus, and host galaxy [2].

The Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT) [3] [4] is capable of long-slit spectropolarimetry and has been used to observe blazars in flaring and quiescent states. Data reduction of these observations is processed using the SALT spectropolarimetry reduction package POLSALT.[1] POLSALT allows for the full reduction, from pre-reduction to the extraction of the target spectra, and the measuring of the polarisation. However, it does not allow for much flexibility with the wavelength calibrations, nor does it provide tools to confirm that the wavelength calibrations lead to similar wavelength calibrated spectra for the O and E beams.

In order to streamline the data reduction we are developing additional tools to work in conjunction with POLSALT. We present the overview of this pipeline and demonstrate its application to an observation of 3C 279 taken in 2017.

2. Pipeline Overview

The tools being developed are designed to work in conjunction with POLSALT and provide a method to perform the wavelength calibrations using conventional IRAF methods [5]. They also allow easy comparisons to be made between the wavelength solutions of the O and E beam, to determine their quality and reliability.

The workflow for reductions is depicted in figure 1. It summarises the steps followed to reduce spectropolarimetric data. Steps that are performed using POLSALT are indicated in blue; steps performed by the new tools are shown in orange, while the IRAF calibration is shown in green.

If the wavelength solutions are found with IRAF, the tools split the multi-extension FITS files into the correct format for IRAF and the IRAF wavelength calibration is performed. The files are then written back into multi-extension FITS files in the correct format for POLSALT to complete the extraction and measurement of polarisation.

The cross-correlation between the O and E beam spectra, named correlation in figure 1, and relative flux calibrations are optional, though correlation is suggested. Relative flux calibrations may be performed assuming a standard and published standard spectra can be acquired. We performed the relative flux calibrations using the ASTROPY [6, 7] and SCIPY[2] packages.

[1]https://github.com/saltastro/polsalt
[2]http://www.scipy.org/

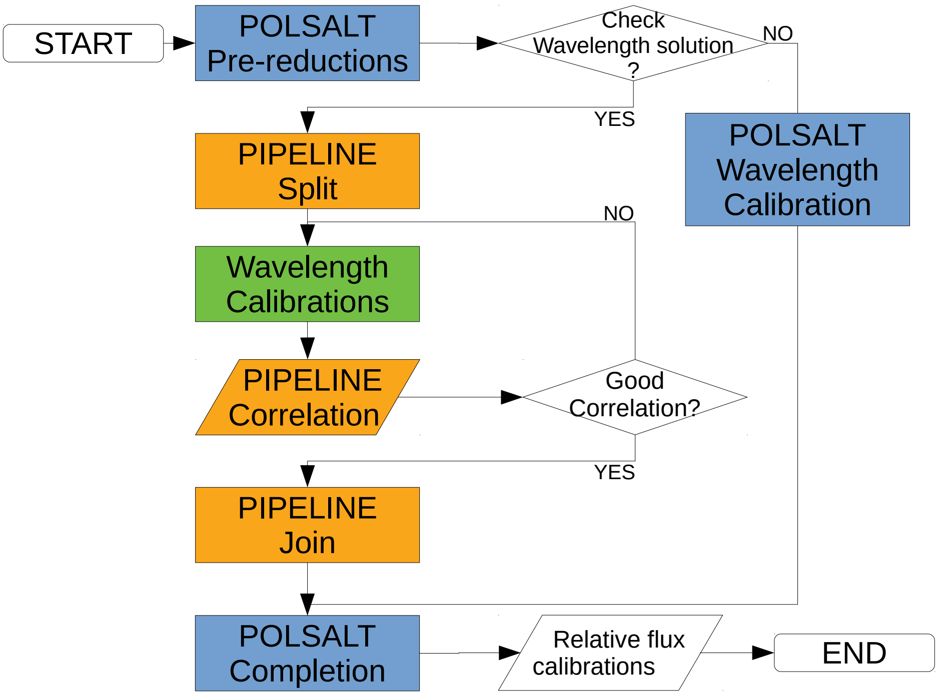

Figure 1: The flow diagram of the SALT RSS spectropolarimetry reductions steps.

2.1 Pre-reduction

The first step in the pipeline uses POLSALT and this performs the pre-reductions, the over-scan subtraction, gain and cross talk corrections, and mosaicing. After the pre-reduction is performed, the next step is to either undertake the wavelength calibration with POLSALT, or to split the files into the correct format for IRAF.

2.2 FITS split

Once all pre-reductions are complete, the tool SPLIT converts the multi-extension FITS files into multiple, single extension O or E beam FITS files. This is done as some IRAF tasks do not handle multi-extension FITS files well. The O and E beam frames are cropped to remove any non-exposed rows to accommodate the standard IRAF tasks and the FITS files saved with updated header information.

2.3 Wavelength calibration

If the POLSALT pipeline is used, the wavelength calibration is performed using the wavelength calibration tools which form part of PYSALT [8].

If the files have been formatted for IRAF, standard wavelength calibration methods are followed, using the NOAO package and the `identify`, `re-identify`, and `fitcoords` tasks. This allows greater control of the resultant wavelength solution.

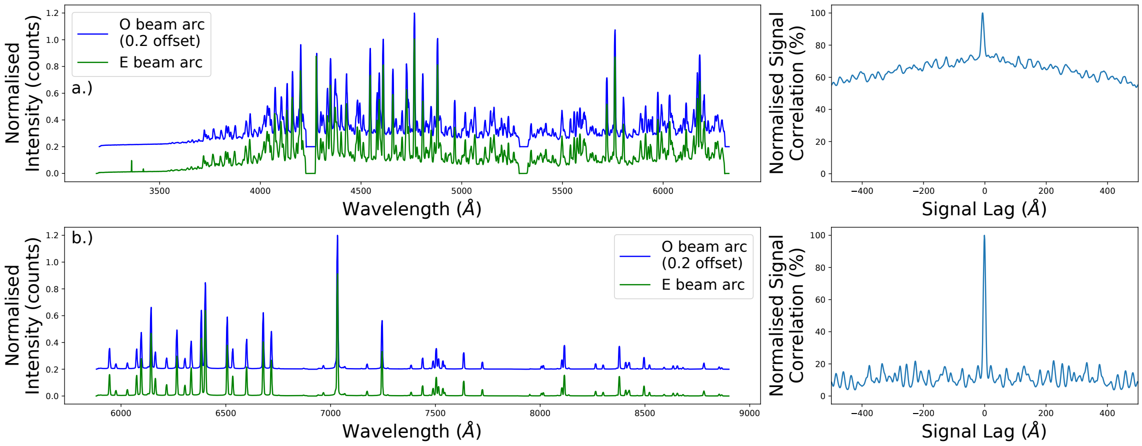

Figure 2: Comparison of the O and E beams for a.) ThAr and b.) Ne arc lamp spectra as well as the cross-correlation of their O and E beams.

2.4 Correlation

Our tool CORRELATE allows a comparison to be made between the O and E beam solutions, by performing a cross-correlation between the two arc or target observations, after the wavelength solution as been applied by IRAF. This is important as the polarisation is calculated from the difference between the O and E beam and, therefore, accurate wavelength solutions are required. The comparison between the O and E beams for a ThAr and Ne arc spectra and their cross-correlations, with a near zero lag, are shown in figure 2.a) and figure 2.b), respectively. Figure 2's Signal Lag plots show a clear peak at zero lag but also show an important distinction between noisy and quiet spectra in the non-peaking region.

2.5 FITS join

Once the IRAF wavelength calibrations are complete, the tool JOIN performs cosmic-ray cleaning using the LACOSMIC package [9], applies a wollaston correction which accounts for the physical shift of the spectra on the CCD, and then formats the single extension O and E beam FITS files into the multi-extension format required by POLSALT. This includes saving the wavelength solution found in IRAF as an additional extension. Currently only wavelength solutions fit with a Chebychev function are recognised but further development is planned to recognise Legendre functions.

2.6 Completion - extraction and polarisation measurement

After the wavelength solution is found, the final step is performed using POLSALT, which performs the curvature corrections, background subtraction, spectral extraction, and the raw and final stokes calculations. The binning and plotting also form part of the POLSALT completion.

3. Application to 3C 279

The blazar 3C 279 was observed in linear spectropolarimetry mode, on 2017 May 17, using the the PG0900 grating with two different grating angles (12.5° and 19.5°). The spectrophotometric

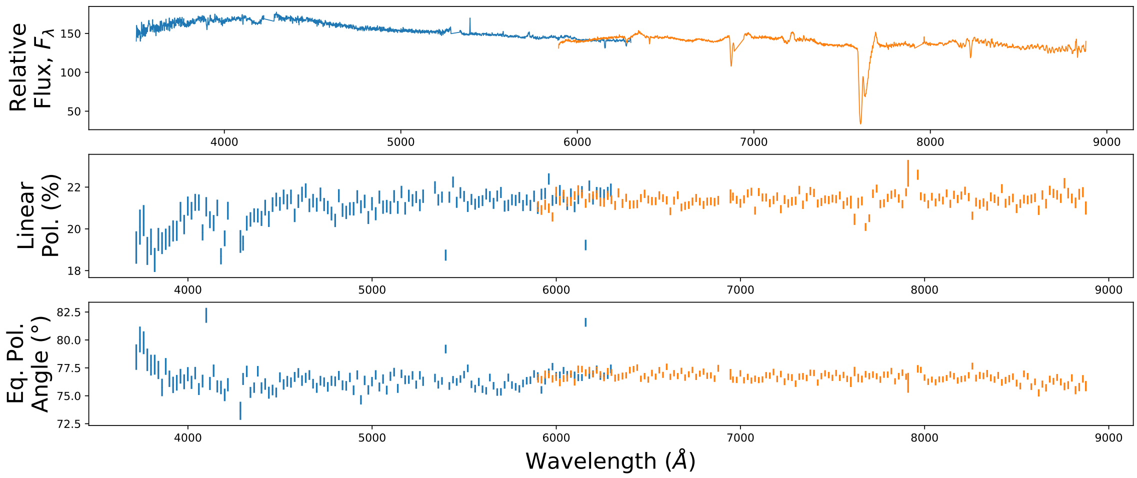

Figure 3: Reduced observations of 3C 279, taken with grating angle 12.5° (blue line) and 19.5° (orange line). Top: relative flux calibrated spectra. Middle: degree of linear polarisation. Bottom: Polarisation angle (relative to instrument).

standard star Hiltner 600 was observed on 2017 February 24, using the same configuration and was used for relative flux calibrations.

The target and standard were reduced following the steps discussed about. The flux correction was performed using ASTROPY and SCIPY python packages to correct the flux shape.

The results are shown in figure 3, indicating a good overlap between the observations taken at two different grating angles, with the polarisation measurements generally agree well where the observations overlap.

Figure 2 shows the comparison of the O and E beams for this observations. The cross-correlation is very close to zero lag, indicating the wavelength solution is similar for both the O and E beams.

4. Discussion and Conclusions

Creating an independent 2D wavelength solution for the O and E beams using IRAF allows for more flexibility in obtaining the wavelength solutions and provides a tool to directly compare the O and E beam solutions. This is useful for difficult cases, such as arc line identification for the PG0300 spectral grating, because there are fewer arc lines in some parts of the spectra and it is more complicated to create a consistent solution across the full wavelength range covered.

The cross-correlation plot cannot only be considered when deciding on whether to proceed onward with the reductions or to return to wavelength calibrations as depicted in figure 1. The comparison of the spectra is as important since the cross-correlation may show zero lag but lines in the spectra could still be mis-identified in both beams. The cross-correlation serves as a method to check the similarity of the wavelength solutions but not the accuracy of said solutions.

The tools developed create an alternative to the POLSALT wavelength calibration and add a method to check the consistency of the wavelength solutions, as can be seen with the application to 3C 279. These assist with the wavelength calibration, in particular for observations taken with the PG0300 and PG0900 RSS gratings, that have been used for numerous observations of blazar sources.

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References

[1] C.M. Urry and P. Padovani, *Unified Schemes for Radio-Loud Active Galactic Nuclei*, PASP **107** (1995) 803 [astro-ph/9506063].

[2] M. Böttcher, B. Van Soelen, R.J. Britto, D.A.H. Buckley, J.P. Marais and H. Schutte, *Salt spectropolarimetry and self-consistent sed and polarization modeling of blazars*, *Galaxies* **5** (2017) .

[3] E.B. Burgh, K.H. Nordsieck, H.A. Kobulnicky, T.B. Williams, D. O'Donoghue, M.P. Smith et al., *Prime focus imaging spectrograph for the southern african large telescope: optical design*, in *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, vol. 4841, pp. 1463–1471, International Society for Optics and Photonics, 2003.

[4] H.A. Kobulnicky, K.H. Nordsieck, E.B. Burgh, M.P. Smith, J.W. Percival, T.B. Williams et al., *Prime Focus Imaging Spectrograph for the Southern African Large Telescope: operational modes*, in *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, M. Iye and A.F.M. Moorwood, eds., vol. 4841, pp. 1634 – 1644, International Society for Optics and Photonics, SPIE, 2003, DOI.

[5] D. Tody, *The IRAF Data Reduction and Analysis System*, in *Instrumentation in astronomy VI*, D.L. Crawford, ed., vol. 627 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 733, Jan., 1986, DOI.

[6] Astropy Collaboration, T.P. Robitaille, E.J. Tollerud, P. Greenfield, M. Droettboom, E. Bray et al., *Astropy: A community Python package for astronomy*, A&A **558** (2013) A33 [1307.6212].

[7] Astropy Collaboration, A.M. Price-Whelan, B.M. Sipőcz, H.M. Günther, P.L. Lim, S.M. Crawford et al., *The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package*, AJ **156** (2018) 123 [1801.02634].

[8] S.M. Crawford, M. Still, P. Schellart, L. Balona, D.A.H. Buckley, G. Dugmore et al., *PySALT: the SALT science pipeline*, in *Observatory Operations: Strategies, Processes, and Systems III*, D.R. Silva, A.B. Peck and B.T. Soifer, eds., vol. 7737 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 773725, July, 2010, DOI.

[9] P.G. Van Dokkum, *Cosmic-ray rejection by laplacian edge detection*, *Publications of the Astronomical Society of the Pacific* **113** (2001) 1420.