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Observing cataclysmic variables with the Southern African Large Telescope (SALT): new capabilities and new insights

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Abstract. The Southern African Large Telescope (SALT) - a 10-m segmented mirror telescope - has recently (as of Sept 2011) begun science operations following a period of recommissioning during which two major problems (image quality and spectrograph throughput) were succesfully addressed. SALT and its First Generation science instruments provide a variety of capabilities which can be fully exploited in observing CVs and related objects. These include good UV performance (to the atmospheric cutoff at ∼310−320nm), high time resolution (0.1 sec) observations in many modes, full polarimetric capabilities (imaging & spectroscopy) and a 100% queue scheduling mode which is well suited to target of opportunity and synoptic observations of CVs. In this paper I present some initial results from commissioning science programs which highlight these capabilities. Examples include exquisite high time resloution eclipse light curves of Polars, which fully resolve the accretion hots spots. SALT observations of the recent outburst of the recurrent nova T Pyx have provided new insights by virtue of two capabilities: UV spectroscopy, revealing the Bowen flourescence lines, and spectropolarimetry showing line depolarization and little interstellar polarization.

Key words. Stars: Cataclysmic Variables – Telescopes – Instruments

1. Introduction

SALT (Buckley et al. 2006) is one of five 10-m class segmented mirror telescopes and the only one situated in the southern hemisphere. The two Keck telescopes (in Hawaii), the Hobby Eberly Telescope (HET, in Texas) and GRANTECAN (in La Palma, Canary Islands) are the other 4 members of the group.SALT is closely based on the innovative HET design, which began science operations in October 1999 (Ramsey et al. 1998). HET and SALT represent a completely new design paradigm for optical/IR telescopes, being optical analogues of the Arecibo radio telescope. The primary mirror consists of a 10-m × 11-m hexagonal array of 91 identical 1.2-m × 1.0-m hexagonal mirror segments (see Figure 1) with spherical surfaces, tilted 37° to the zenith. This array directs light to a 4-mirror spherical aberration corrector (SAC), mounted on a moving tracker at the prime focus. Thus the telescope can only access an annular region of the sky, 12° wide, which represents 12.5% of the instantaneously visible sky. This design implies

Send offprint requests to: D.A.H. Buckley that the entrance pupil of the telescope (11-m in diameter) is not fixed on the primary mirror array, but rather moves over it during an observation. This means that the effective aperture varies during an observation. Futhermore, because objects can only be observed when they move into the viewing annulus, this places specific observing constraints, namely that only objects in the Declination range +10° to -75° are observable, and total continuous observation time ranges from 1 − 3 hours, extendable to 4 − 5 hours at the extreme Declinations (if the telescope is re-pointed).

Significant design changes and enhancements were made to SALT following upon the experiences and lessons learned with HET and subsequent telescope technology innovations (Meiring & Buckley 2004; Buckley et al. 2006). SALT is designed to be seeing-limited and is most competitive spectroscopically, although its imaging capability has been greatly enhanced compared to the HET due to its redesigned SAC (O'Donoghue & Swat 2001). The science field diameter is 8 arcmin, twice HET's, and the image quality is specified to have a PSF FWHM < 0.7 arcsec, so with a median zenithal seeing FWHM of 0.92 arcsec, SALT does to not significantly degrade the PSF delivered by the atmosphere.Other innovations introduced in the SALT design included 1.) mirror edge sensors, 2.) a Shack-Hartmann mirror alignment system, 3.) an actively aligned prime focus payload, utiliizing a Mach-Zender distance measuring interferometer and a tip/tilt autocollimator, 4.) a thermally isolated and well ventilated telescope chamber (to minimize dome seeing), 5.) a greater capacity prime focus payload (in terms of volume and mass) allowing for more ambitous instrumentation. The latter includes a versatile prime focus imaging spectrograph − the Robert Stobie Spectrograph (RSS) − and a UV-Visible imaging camera − SALTICAM −, (seeBuckley et al. 2008 for details of SALT instruments). RSS also had some innovations, including all refractive UV transmissive optics, fully tuneable Volume Phase Holgraphic diffraction gratings, polarimetric and Fabry-Perot modes. In addtion, the detector consists of frame transfer CCDs, allowing for fast readout which supports high time resolution (to ~0.1 sec) observations. SALTICAM also makes use of UV transmitting optics and FT CCDs, both ideal for studying rapidly varying accretion phenomena, as in CVs, LMXBs and related objects.

2. Commissioning experience

The construction phase of SALT and its two "first-light" instruments was completed in November 2005, when it was officially inaugurated. Following this, SALT entered an intensive period of commissioning and performance verification, which included the intial science observations. "First Science" was announced in 2006, following the beginning of commissioning in mid-2005 of the UV-Visible imaging camera, SALTICAM (O'Donoghue et al. 2003), which culminated in the first SALT science paper (O'Donoghue et al. 2006). In parallel the commissioning of the Robert Stobie Spectrograph (RSS) began following its installation on the telescope in October 2005 and continued through to Nov 2006 (Buckley et al. 2008). It was during this commissioning period that problems with the telescope's image quality and the throughput of RSS were uncovered, which led to the eventual removal (in Nov 2006) of RSS for repair.

Despite the problems with image quality, SALT was scheduled regularly (~ 50% of nights) for science observations from 2006−2009, which has resulted in 40 publications in refereed journals since 2006 which feature SALT observations. We have essentially been in a completion and commissioning phase since 2006, which culminated in a 15 month engineering downtime from April 2009 in order to effect modifications to the SAC in order to improve the telescope's image quality. This was completed by mid-2010 when the telescope became operational again. RSS and SALTICAM were re-installed on the telescope in early 2011 and science commissioning programs initiated to characterise the performance of the telescope and instruments. This phase is due to be completed by later in 2011 and the first science semester began in September 2011.

2.1. Telescope image quality

SALT's initial problem with image quality was manifested as field-dependent aberrations, which became more noticeable for field angles in excess of ~2 arcmin. An extensive campaign to diagnose the cause of the image quality problem, lasting the better part of a year, indicated that the root problem lay in imperfect SAC-telescope optomechanical interface. Thermally and mechanically generated stresses were transfered through to the SAC optics, causing de-centre and tip/tilting of the mirrors leading to the field dependent aberrations. The design, fabrication, testing and installation of a new interface then followed from April 2009 to July 2010 O'Donoghue et al. (2010). Thereafter the telescope's optical performance was thoroughly tested, and results show that SALT is now delivering acceptable image qulaity.

2.2. Spectrograph throughput

Not long after the installation of the Robert Stobie Spectrograph and the commencement of commissioning observations in 2006, it was discovered that the overall throughput performance was significantly less than expected and much worse at shorter wavelengths. In-situ testing of the RSS optics indicated that the throughput losses occurred in both the collimator and camera optics, which necessitated their removal for further diagnosis and repair. The throughput losses were found to be due to two reasons: (1) a poor multi-layer anti-reflection coating on the camera's field-flattening lens, and (2) absorption losses in all of the lens multiplets. The first issue was dealt with be recoating the lens, while the problems with the multiplets were traced to lens coupling fluid material incompatibilities, which was eventually solved by replacing o-rings and changing the type of fluid used. The repaired and reassembled optics were then returned to SALT in July 2009 and reinstalled into RSS.

3. SALTICAM: SALT Imaging Camera

SALTICAM employs frame transfer (FT) CCDs, which allows for fast acquisition and imaging. Unlike normal FT CCDs, where a mask is permanently in place over half of the chip, SALTICAM employs a moving occulting mask. This allows for 3 imaging modes: full field imaging (non-FT operation), FT mode (half of the FoV is imaged) and a specialized high-speed mode, where a narrow slot is imaged. For frame transfer mode, with 2×2 binning, the shortest exposures are ~2.5 sec. The special high-speed photometry mode, known as slot mode, allows for just a small region of the CCD (144 rows) to be illuminated by moving a narrow slot (~11 arcsec wide), to just above the frame transfer boundary (i.e. between the image and store arrays).

In high-speed slot mode, the object of interest, plus ideally a nearby (< a few arcmin) constant source (i.e. a comparison star), are placed in the centre of the slot. This can be achieved by rotating the instrument on the sky to the desired position angle. The illuminated region of the CCD is then exposed (typically with exposure times ranging from 80-1000 ms) and then quickly (typically a few ms) row-shifted (by 144 rows) into the storage array, while another exposure begins. Thus exposed slot regions are sequentially moved through the storage array to the serial readout register. During the next exposure, the latest exposed region to reach the bottom of the chip is readout (in a time ¡ the exposure time, which is dependent on the on-chip binning factor). As there are two amplifiers per CCD chip, a total of 4 different slot images are created. To avoid any latencies when operating at such high frequencies (up to 12.5 Hz), the data a recorded in binary format with a predetermined number of exposures per file.

4. The Robert Stobie Spectrograph (RSS)

RSS resides at SALT's prime focus, where it takes advantage of direct access to the focal plane, and was designed to have a range of capabilities and observing modes, each one remotely and rapidly reconfigurable Buckley et al. (2008). In keeping with the overall philosophy of exploiting those areas where SALT has a competitive edge, the instrument has a range of capabilities, many well sutied to CV studies, including:

- Wavelength coverage from 320 to 900 nm for the initial UV−VIS configuration (a second near IR arm, extending to 1.7μm, is under construction). Low to medium resolution spectroscopy (up to R ~ 6000 with 1 arcsec slits; R ~ 9000 with 0.6 arcsec slits) using efficient and tuneable VPH gratings.
- Narrow band, tuneable filter and Fabry-Perot imaging.
- High time resolution (0.1 sec) spectrscopic modes.
- Imaging and spectropolarimetry (linear, circular and all Stokes modes), including high time resolution mode plus low resolution (R ~ 50) wide-field imaging spectropolarimetry.

5. High time resolution astronomy

One of SALTs science drivers is conducting time resolved studies of astronomical objects. A fully queue-scheduled telescope like SALT has the ability to regularly undertake synoptic or monitoring observations of variable objects, over wide timescales (from days to years), important for both stellar and extragalactic studies (e.g. AGN, Supernovae, GRBs). The duty cycle of the variability can be used to define the scheduling of the required observations.

In addition, for shorter timescale observations, typical of compact accreting stellar systems (e.g. white dwarfs, neutron stars and black holes), the instrument detectors (e.g. CCDs, photon counting detectors) limit the potential time resolution of observations. In most conventional telescopes utilizing standard CCDs, typical time resolutions are measured in seconds. While this is often sufficient for many purposes (e.g. non-radial pulsation studies of stars), it is often a limiting factor for probing astrophysical phenomena operating at higher timescales, typically less than a second (e.g. pulsar variability, occultations, eclipses, quasi-periodic oscillations).

Many of the SALT partners, like South Africa, have a well established tradition and reputation in time series studies of astronomical objects. In the era of modest sized (i.e. 1− 2 m class telescopes), this work concentrated on brighter stellar objects, particularly asterosiesmology, variability studies of cataclysmic variables and, to a lesser extent, X-ray binaries (Low Mass X-ray Binaries, X-ray transients, etc.). The limitation of such studies comes from simply too few photons: something that is now rectified with the access to the larger aperture (equivalent to a ~7 to 9m diameter telescope, depending on the entrance pupil geometry) of the SALT, coupled with its instruments capable of sub-second time resolved studies. This is now often referred to as High Time Resolution Astronomy (HTRA). The increase in telescope aperture has an obvious benefit in increasing the amount of flux detected from any given source by a factor determined by the telescope collecting area. This is a factor of ~20 times compared to the previously largest South African telescope, a 1.9-m reflector. What is sometimes not appreciated is the fact the detection of periodic variability in an object scales with the telescope diameter to the power of 4. Thus the detectability of a periodic signal in a power spectrum is greatly increased by having a larger aperture, more so than simply the increased flux.

6. SALT observations of catalcysmic variable

Initial high speed commissioning observations with SALT were mostly of eclipsing cataclysmic variable stars (CVs), specifically polars, which emit the bulk of their luminosity (from X-rays to the optical/IR) from small accretion regions near the magnetic pole(s) of a strongly magnetized (~10^1 to 10^2 MG) white dwarf. The dominant emission components in such systems included hard (>10-20 keV) thermal bremsstrahlung X-rays from an accretion shock just above the white dwarf surface. A fraction of this radiation is reprocessed in the white dwarfs photosphere into softer X-rays, UV and optical radiation. In some systems, ballistic "blobs" of accreting material bury into the white dwarfs photosphere, thermalize and add to the soft X-ray/extreme UV component. One of the dominant shock cooling mechanisms is cyclotron emission, spanning UV-optical-IR wavelengths, resulting from spiraling electrons in the strong (typically 20−100

MG) magnetic field. This emission is therefore strongly linearly and circularly polarized, at levels that can reach many 10s of %. In eclipsing polars, the size, structure and location of these regions can be determined from sufficiently high time resolution (sub-second) photometry. Structures the size of Greenland at distances of 100s of parsecs can be resolved, i.e. angular resolutions better than 0.1μarcsec.

6.1. FL Cet

One of the first observations testing SALTICAM's high time resolution capabilitiy was of the eclipsing polar FL Cet (SDSS J015543.40+002807.20) , taken in slot mode on 6 & 7 Sep 2005 with 112 ms sampling (O'Donoghue et al. 2006). These observations revealed two intensity steps in eclipse ingress and egress, lasting $\sim$1.5 sec, which are due to the progressive disappearance (ingress) and reappearance (egress) of two accretion hot-spots near the respective magnetic poles of a magnetic white dwarf. The eclipse data were fitted with a model based on the likely masses of the component stars as derived from the eclipse parameters and orbital period (1.45 h), plus the orbital inclination of the system and co-latitudes of the accretion spots. An excellent fit was achieved for an inclination = 83.5°, a secondary star mass = $0.07M_{sol}$, a white dwarf mass = 0.6 M_{sol} and magnetic co-latitudes of the accretion spots of β_1 = 25° and β_2 = 125°, respectively (O'Donoghue et al. 2006).

Similar observations have now been obtained on other eclipsing polar in a program to systematically determine accretion spot geoemetries. This work is now also being extended to time resolved spectroscopic observations in order to map the line emitting regions also.

6.2. T Pyx

Fortuitously, at the time SALT began to be recommissioned (April 2011), the recurrent nova T Pyx underwent a rare outburst (the last one being in 1966). A SALT Target of Opportunity program was immedaitelt instigated (demonstrating SALT's ability to react quickly to such events) and a variety of observations were undertaken. UV spectroscopy with RSS has confirmed the instrument's improved response following the optics repair, with a clear detection of spectral features down to the atmospheric cutoff (e.g. HeII 320.4 nm and the Bowen fluorescence line at 313.3 nm). Spectropolarimetry (still under analysis) has revealed P Cyg line depolarization and an unusally low value for the interestellar polarization (0.5–0.7%, given its purported distance (3 kpc).

7. Discussion

MARCOS DIAZ: What is the spectral resolution in Frame Transfer mode?
DAVID BUCKLEY'S Comment: Maximum resolution, with a narrow slit (~0.6 arcsec), is R ~12,000 for RSS.

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