SOUTHERN AFRICAN LARGE TELESCOPE

Annual Report - 2015-2016

SOUTHERN AFRICAN
LARGE TELESCOPE

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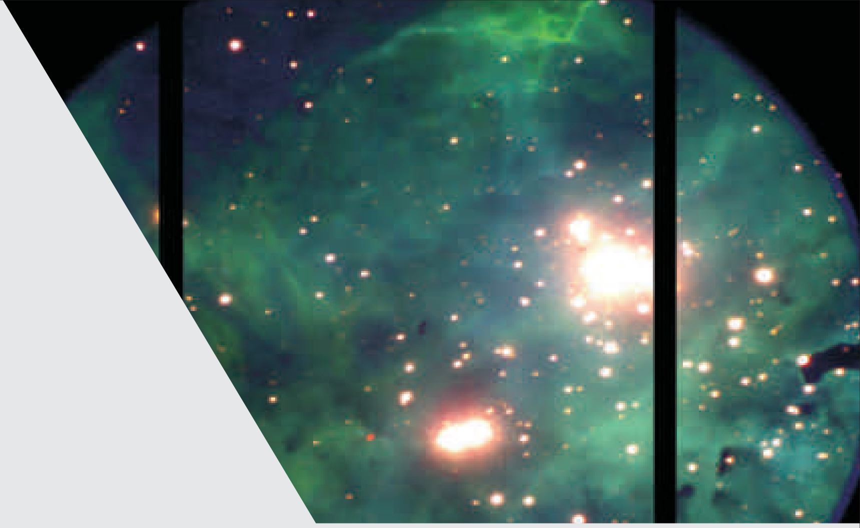
ABOUT SALT

The Board of the Southern African Large Telescope (SALT) is proud to present its Annual Performance Report for the period 1st January 2015 to 31st December 2016. This report offers an overview of the activities and performance of SALT, and highlights a selection of SALT research projects.

The Southern African Large Telescope (SALT) is the largest single optical telescope in the southern hemisphere and amongst the largest in the world. It has a hexagonal primary mirror array 11 meters across, comprising 91 individual 1m hexagonal mirrors. It is the non-identical twin of the Hobby- Eberly Telescope (HET) located at McDonald Observatory, Texas, USA. HET and SALT represent a completely new paradigm in the design of optical telescopes. The light gathered by its huge mirror is fed into a suite of instruments (an imager and two spectrographs) from which astronomers infer the properties of planets, stars and galaxies, as well as the structure of the Universe itself.

SALT is owned by the SALT Foundation, a private company registered in South Africa. The shareholders of this company include universities, institutions and science funding agencies from Africa, India, Europe, New Zealand and North America. The South African National Research Foundation is the major shareholder with a ~35 per cent stake. Other large shareholders are Dartmouth College, the University of Wisconsin-Madison, Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences and Rutgers University. Smaller shareholders include the American Museum of Natural History, the Indian Inter- University Centre for Astronomy and Astrophysics in India, the University of Canterbury (New Zealand), the University of North Carolina, Gottingen University (till November 2015) and the UK SALT Consortium, the latter representing the Universities of Central Lancashire, Keele, Nottingham and Southampton, the Open University and the Armagh Observatory. The size of the shareholding of each partner determines the access to the telescope which they enjoy. The HET Consortium, although not a shareholder, received ten percent of the telescope time for the first 10 years of operation, in return for providing all the designs and plans of the HET as well as assistance during the construction of SALT.

SALT is located at the observing site of the South African Astronomical Observatory, near the small town of Sutherland, about 380 km north-east of Cape Town in the Karoo. This site has been host to a number of other smaller telescopes since the early 1970s, and benefits from location in a semi-desert region with clear, dark skies. The quality of this site for optical astronomy is preserved by South African legislation.



VISION AND MISSION

VISION

Africa's Giant Eye on the Sky: Inspiring society by exploring the Universe.

MISSION

Provide a world-class large telescope research facility cost-effectively to astronomers in an international community.

Lead the advancement and development of optical astronomy on the African continent and inspire and educate new generations of scientists and engineers worldwide.

STRATEGIC OBJECTIVES OF SALT

Enable world leading astrophysical research: To provide high quality data that result in highly cited published papers in front rank journals;

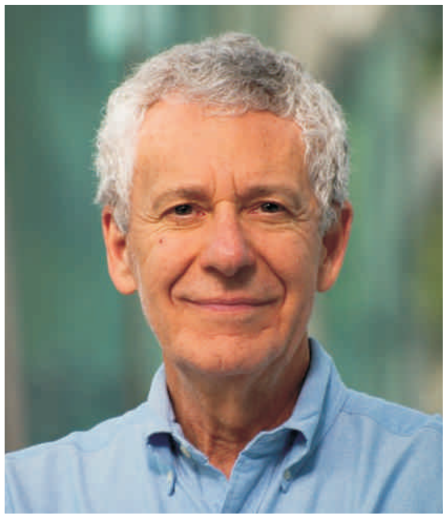
Optimize science operations: To maximize science efficiency and productivity while minimizing technical downtime;

Continuous improvement: To find and focus on science and operational areas of best performance; to enable and strengthen a creative staff; to secure financial support for operations and new developments;

Instrumentation development: To develop the skills and capacity needed for designing and building instrumentation and telescope functionality to keep SALT competitive in the future;

Human Capital Development: To use SALT for graduate student training, outreach to undergraduates, schools and the general public; to have a special focus on developing professional astronomy on the African continent;

To promote SALT a global flagship optical telescope: To increase SALT visibility and positive image in the international community and national and international media.



CHAIRPERSON'S OVERVIEW

Dear Colleagues,

We are proud to state that SALT is currently producing large amounts of excellent science data every night, and that its future productivity is only likely to increase. The telescope itself is finally in healthy mechanical, optical, electronic and software shape. The first generation instruments – SALTICAM, RSS and the HRS – are stable, exhibit high throughput and are functioning as designed. This high level of quality and productivity has been hard-won, through the dedicated and professional efforts of its staff and faculty.

61 peer-reviewed SALT science papers were published during 2015-2016, including SALT's first Science paper.

A critical improvement in 2016 has been the edge-sensor system (SAMS), which keeps the 91 SALT mirror segments aligned. It was completely replaced, tested, optimized and passed acceptance tests with flying colors. SAMS is designed to eliminate the need to realign the primary mirror segments more often than once every five nights, regardless of temperature changes and frequency or amplitude of telescope slews. SAMS is performing at spec or better, delivering sub-arcsecond images on many nights, and saving 1-2 hours every night that used to be spent on alignments.

An HRS data pipeline was produced, tested and is now fully functional. Several years of backlogged HRS data are being processed through it, and delivered to PIs. All raw and fully-processed data taken with HRS are now delivered within 24 hours.

A prototype Laser Frequency Comb produced at Heriot-Watt University in Edinburgh was installed and tested with HRS, producing excellent results. The lessons learned will be invaluable as SALT continues to improve HRS' stability and accuracy.

The next instrument to be delivered – the near-infrared arm of RSS – is currently scheduled for delivery in 2019. Intense discussion is underway about a next generation instrument to follow the NIR arm.

The month-long refurbishment in 2016 of many hardware and optical components was carried out with almost military precision, and precisely on schedule, by the operations team. This was the first time since SALT began normal operations that the telescope was shutdown deliberately for an extended period of time. The operations team is to be congratulated for their meticulous planning and excellent execution of the many tasks that they successfully carried out. Not a single goal was left unfulfilled. Consideration is already been given to the next shutdown, in 2017, for further mechanical and optical work. The mechanical and electronics shops are providing timely support as needed.

In October 2016 an intensive Five-Year-Review of all aspects of SALT was conducted by Catherine Cesarsky (Chair; French Alternative Energies and Atomic Energy Commission, France), Megan Donahue (Michigan State University, USA), Laura Ferrarese (National Research Council (NRC), Canada), Azwinndini Muronga (Nelson Mandela Metropolitan University, South Africa), Chris Smith (Association for Universities in Research in Astronomy (AURA), Chile) and Patrick Woudt (University of Cape Town, South Africa). The committee generated a series of recommendations that are being studied by the SALT Board, and which will be published in 2017 with the Board's responses.

SALT cost roughly 1/3 as much to build as other 10-meter class telescopes. Its operations budget is similarly smaller than that of all 10-meter telescopes. This is, in part, due to lower wages in South Africa than in, say, Hawaii or Chile. It is also due to the discipline of the CFO and Director, and determination of the Board to keep to a lean budget.

With the telescope and its instruments now in excellent condition, the Board is looking for one new partner interested in purchasing 10% of the shares in, and observing time on SALT.

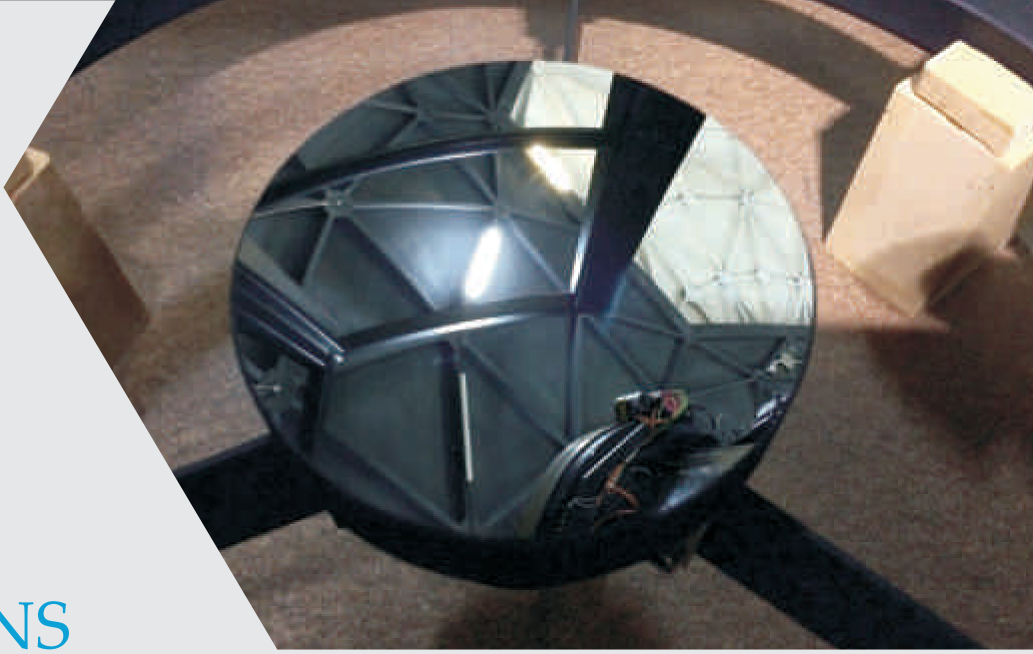
Prof. Michael Shara
Chairperson, SALT board

DARRAGH O'DONOGHUE, A REMEMBRANCE

On June 25 2015, Darragh O'Donoghue died from complications associated with viral pneumonia. His death brought shock, sorrow, and anguish to his family and to all of us who knew and loved him. Darragh was the heart and soul of SALT. He had more in-depth knowledge about the telescope than anyone else, and a passionate commitment to its success. When SALT's problems seemed bafflingly insurmountable, he was like a lighthouse on a stormy coast, saying "follow me and fear not, and all will be well". We did, and it was. He was a world-class scientist, specializing in observational studies of white dwarfs and variable stars. He was also a world-class instrumentalist, heading the SAAO instrumentation division, designing and building instruments for SALT and the other SAAO telescopes, and in the years before his untimely death working with Chris Clemens to invent a totally new and revolutionary astronomical spectrograph. He never lived by half-measures, bringing gusto and Irish humor to everything that he did. Darragh was my wise consigliere, schooling me in the intricacies of South Africa and providing unfailing advice. (Remember that Tom Hagen was part Irish.) With his passing I lost a valued friend and colleague, SALT lost a key leader and visionary, and South Africa lost a shining exemplar of integrity, excellence, and compassion. As we continue to struggle with the void he leaves behind, we should all resolve to bring our "inner Darragh" to the fore – we will be the better for it.

Darragh in Cape Town in February of 2011

Ted Williams
Director, SAAO



SALT OPERATIONS

SALT has achieved many significant milestones throughout 2015 and 2016 and the telescope's remarkable cost effectiveness in particular has come to the fore. The operations cost per refereed science paper is three to four times less than that associated with comparable large optical facilities. The opportunity for SALT to host a state-of-the-art calibration device (the laser frequency comb built by Heriot-Watt University) also demonstrated an exciting channel through which SALT can pursue world-class technological innovation, while forging international collaborations associated with highly specialised instrumentation.

SALT Operations Reorganisation

Following the decisions of the SALT Board made in November 2014, the management structure of SALT operations was reorganised early in 2015. Chris Coetzee took over responsibility for SALT operations, merging the former Technical Operations and Astronomy Operations divisions. SALT Astronomer Petri Vaisanen became the Head of Astronomy Operations, supervising the day-to-day functioning of the astronomy staff and advising Chris on scientific matters. This reorganisation has proven to be highly successful. The merged operations group became more efficient and the vital communications between the technical and scientific staff has been enhanced. There is great synergy between Chris and Petri, and their energy has inspired all the SALT personnel.

With the reorganisation, David Buckley ended his secondment to SALT effective 31 March 2015 and returned to his position at SAAO. David now has the title of SALT Scientist, and continues to devote 25% of his effort to SALT, working on developing global recognition of the success and effectiveness of the telescope. In his many years as SALT Astronomy Operations Manager, David laid the groundwork for the innovative and successful operation of the telescope in the queue-scheduled mode, and developed the position of SALT Astronomer. Much of the successful operation of the telescope today is due to David's hard work and insight, and SALT is deeply appreciative for his services.

Optimising SALT operations

Following the re-organisation of the SALT management structure in early 2015, the team's focus shifted towards optimising the telescope and instruments, as well as the processes associated with the gathering, reduction and distribution of data. The SALT Operations Manager (Chris Coetzee) opted to apply the Theory of Constraints in order to improve the efficiency of the entire process, from the proposals received from the partner time allocation committees to delivering the data products. In addition to increasing communication across all interfaces and enhancing coordination within the multidisciplinary team, SALT Ops also created a list of priority projects that will improve the quality and quantity of data delivered by the telescope. Furthermore, a comprehensive dashboard was developed to monitor and report on key performance metrics such as technical downtime, observing efficiency and completion rates for high priority blocks on various timescales (see Figure 1), while a fault tracker database was established to keep tabs on all technical issues.

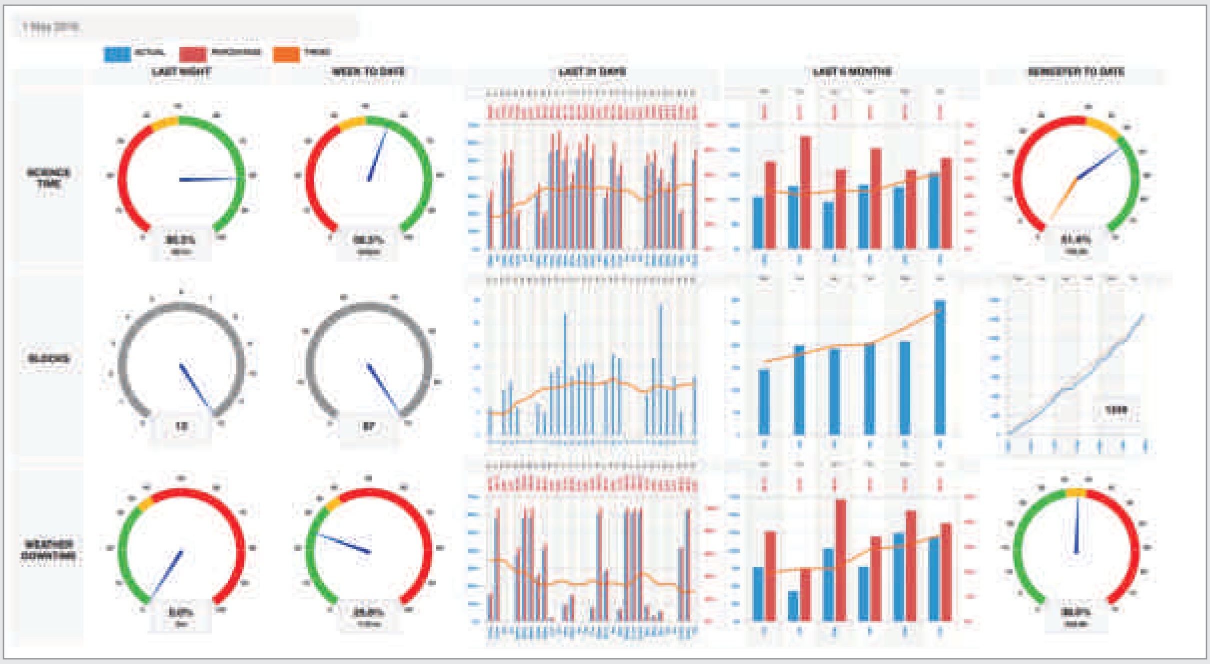


Fig. 1: Part of the SALT dashboard showing critical performance metrics on various timescales. In addition to the items shown, e.g. engineering time, technical downtime, operational efficiency, completion of different priority time, and published papers are also automatically tracked.

Results achieved up to the last quarter of 2016 (a year and a half after the organisational changes) were extremely pleasing, selected highlights are listed below:

- Downtime due to technical and other problems decreased from close to the ~10% level to ~5% (see Figure 2).
- Engineering downtime also went from more than 10% to less than 5% in the period, despite the installation of SALT Array Management System (SAMS) and the Laser Frequency Comb. By the end of semester 2016-1 engineering downtime has decreased to typical monthly levels of only ~3%.
- The completeness fraction of allocated observing time reached a record 88% in Semester 2016-1, having typically been in the 50%-60% range before 2015. The record fraction of P1 and P2 time completeness is now 87% and 69%, respectively, showing significant improvement over the past two years (see below, and Figure 3).
- The number of observing blocks completed per semester has increased from numbers less than 800 pre-2015, to about 1250 in both of the last two semesters.
- Observation efficiency, defined as the fraction of time used for science vs. the charged (i.e. planned) time, has reached nearly 100%, improving from historical percentage values in the 80s (see Figure 4 below).

From these results it is clear that the team significantly improved productivity in response to the daily monitoring of key metrics, dedicated focus on projects specifically selected to improve efficiency and data quality, as well as focus on communication.

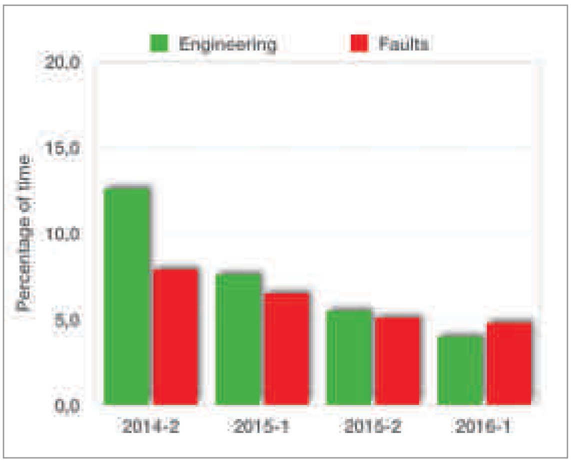


Fig. 2: The engineering and technical (faults) downtime over the last four semesters. Earlier values were at a similar or worse level than 2014-2. The 2016-1 fractions exclude a planned service shutdown period in August 2016.

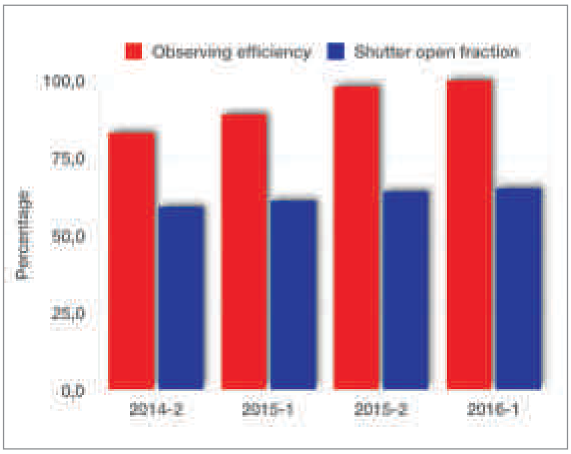


Fig. 4: Observing efficiency is defined as the ratio between charged time and actual science time spent. The shutter open metric is the fraction of science time that a science exposure is ongoing (i.e. excluding calibrations, readouts, and target acquisitions).

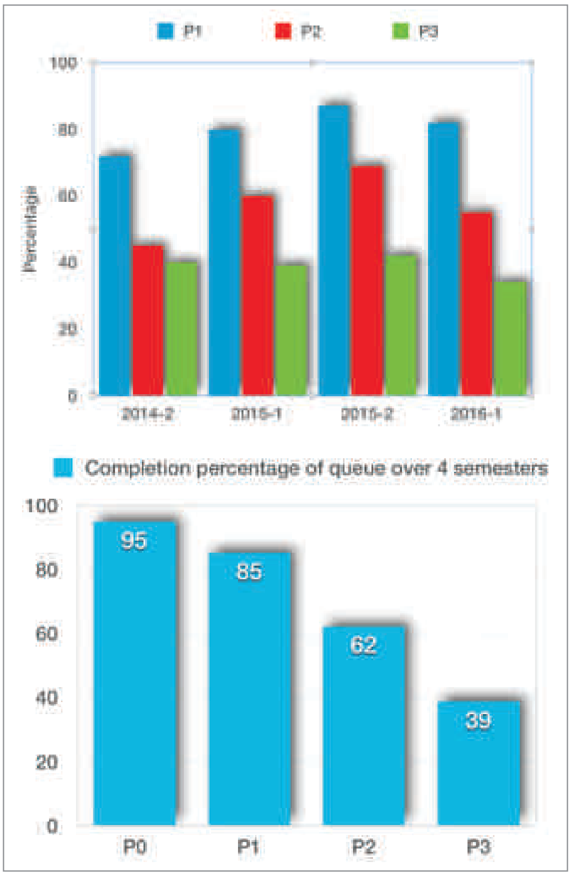


Fig. 3: *Top*: Observational completeness of allocated time, per priority. *Bottom*: The average completeness of PI-submitted observing blocks over the same 4 semester period. Note that the P3 time is overfilled in the queue by a factor of 3 to give more flexibility to the queue – the plotted fraction refers to the total times, and hence for example the 39% average completion means that 117% of actually expected P3 time was completed.

Science time usage and observing metrics

There were four SALT Semesters completed during the reporting period, 2014-2, ending in April 2015, 2015-1, 2015-2, and 2016-1, ending in October 2016. A total of 4177 Blocks were observed during these four Semesters. Of all the available on-sky time 42% was used for science (the best semester had 51% science), most of the balance being weather downtime. A total of 275 programs were allocated time by the various partner TACs in the period. Of these programs an average of 30% were fully completed, though the fraction rose to nearly 40% by 2016-1. The relatively low fraction is due to the practice of many TACs allocating mixed-priority time for programs, and the lower priority (P3) portions of the programs have lower completions, while the Priority 1 and 2 (P1-P2) portions are much higher. Thus, the main scientific observing metric at SALT is actually maximising the P1 and P2 time completeness. Figure 3 illustrates the trend over the past four semesters. The completeness fractions are, in fact, better by a few percentage points if defined as completeness of observing blocks in the queue, since not all allocated time gets triggered or submitted by the PIs in a given semester. The average completeness of submitted phase-2 blocks over the reporting period is shown in the right panel.

SALT Ops also monitors how well the charged time matches the actual time spent on the given observation. This can be defined as the "observing efficiency". We also calculate the "shutter open fraction", the fraction of time from all science time that an instrument is exposing a science frame. Both these metrics have been steadily increasing, as seen from Figure 4. Having maximised the observing efficiency, SALT Ops will next turn to looking for ways to make technical changes to decrease both the charged and spent time, e.g. by attempting to make target acquisitions faster.

Science output

The 2015 calendar year topped the annual count of refereed papers based on SALT data, with 36 publications. Calculating from the start of science operations (2011 for SALT) the rate is on par with other major international observatories. The number was lower for 2016, however, with only 24 papers. Nevertheless, an average of about 30 papers after 4-5 years of science operations, when normalised by annual operations costs, still means at least a factor of 3 more cost-effective science output compared to other 8-10m class telescopes worldwide. The goal of SALT is, however, to rise above 40 papers per year over 2017 and 2018 to keep on track with international trends.

In addition to selected highlights of science papers, all the 2015 and 2016 refereed publications are summarised in the lists presented at the end of this report.

A large contingent of SALT Operations staff participated in the prestigious 2016 SPIE Astronomical Telescopes and Instrumentation conference in Edinburgh in June. Our delegates presented eleven posters and gave four talks. The much-improved SALT operations figures made an impact on the audience and drew interest from other international observatory staff and management. The SAMS and Glycol Leak Detection System posters received much attention and the presentation of DDS as middleware of the Southern African Large Telescope control system was also well received. A full list of the 2016 SPIE SALT papers is presented at the end of this report.

TECHNICAL OPERATIONS

Major achievements during the course of 2016 included the successful completion of the Tracker Upgrade, installation and commissioning of the new SALT Array Management System (SAMS), implementation of the new Building Management System (BMS) software, as well as completion of the Robert Stobie Spectrograph (RSS) service and the associated cleaning of the Spherical Aberration Corrector (SAC; M4 and M5), RSS and payload optics. The cleaning of the various optical elements improved the telescope throughput by around 10% and the RSS optics gained a further 10%, resulting in a substantial boost for RSS programs in particular. The shutdown was completed on schedule and the subsequent on-sky re-commissioning took just a week. The whole project was thus completed within five weeks rather than the anticipated six.

After several years of development, the inductive edge sensors for the SAMS system were successfully produced by FOGALE Nanotech and its suppliers. The sensors were assembled, installed and commissioned by the Tech Ops team by the end of May 2016. The system continues to maintain excellent image quality performance under typical environmental conditions. Histograms comparing the external DIMM measurements with the FWHM values obtained from the guider images are shown below in Figure 5. The bottom graph illustrates measurements from June to October 2015, prior to SAMS becoming operational. The top plot shows the significantly improved image quality, indicated by the much closer agreement with the external seeing measurements provided by the DIMM once SAMS was introduced.

This agreement between the image quality delivered by the telescope and the seeing measurements from the DIMM is a significant accomplishment for the system, particularly since it is able to maintain excellent mirror alignment for several days at a time, even when large temperature and humidity excursions occur. In addition to saving the observing time that was previously wasted on mirror alignments during the night, the image quality is optimised and remains stable for all science observations, rather than only for those taken right after an alignment.

The Tracker Upgrade project was launched more than three years ago, to enable the tracker to carry significantly more mass, e.g. to allow the RSS-NIR instrument to be installed at prime focus. The installation began with the Y-upgrade in October 2015. Next was the introduction of the new Rho motor, which has substantially reduced the Rho following errors. The Hexapod Anti-Gravity System (HAGS), which reacts to the higher loads on the three tracker balls joints, was installed during the shutdown, and the ball joints were also replaced. During November 2016, the X-drive and all six of the original hexapod motors were replaced with new ones employing direct harmonic drives that work over the required slewing and tracking ranges. The final phase of the upgrade will be the installation of the new Rho cable wraps, which is planned for 2018. This upgrade being completed well within budget and with minimal slipping of the schedule is a testament to the more robust project management process that was implemented during this project. This has now become the project management standard for SALT.

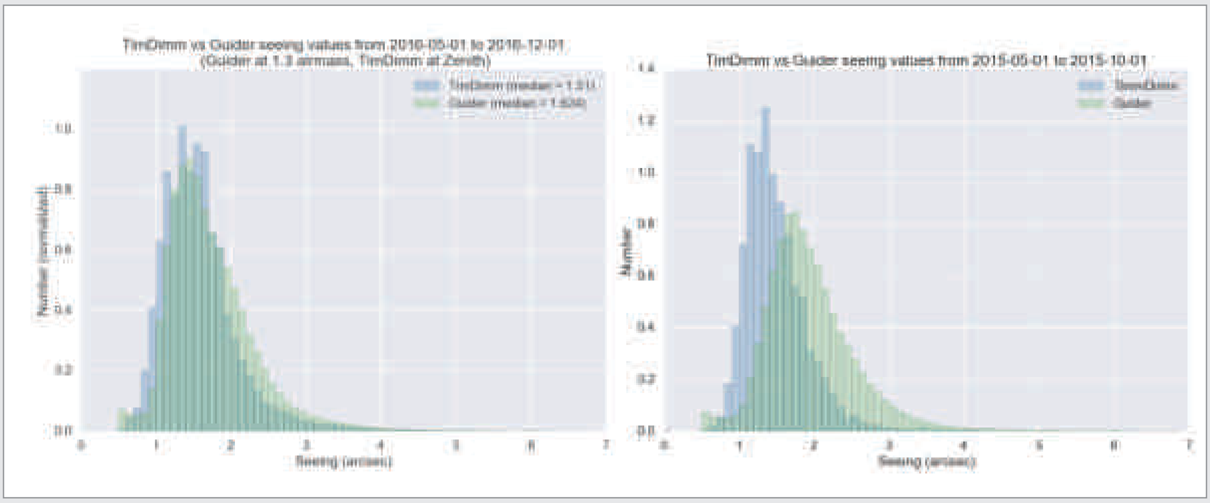


Fig. 5: Comparison between the seeing (measured with the DIMM, at zenith) and the delivered SALT image quality (measured from guider images at airmass ~ 1.3) before the introduction of SAMS (right) and since the edge sensor system became operational (left). The image quality (IQ) of SALT has drastically improved; the remaining poorer IQ tail is partially due to not excluding pre-focused values.

The SALT Prime Focus Guidance System Upgrade project is the current highest priority technical performance improvement initiative. It will deliver an upgraded guidance probe at the RSS instrument port. This will significantly improve the optical throughput of the guidance system, add rotational guidance functionality (using two guide stars) and introduce active telescope focus control. The preliminary design phase was successfully concluded and detailing of the design is now in progress. The project is currently within budget and scheduled for completion by 2018.

The dark Sutherland site

The Sutherland night sky brightness has been quantified with data obtained using a pair of specialised cameras set up on the plateau. These values confirm that Sutherland is a particularly dark astronomical site.It is among the darkest of any observatory worldwide, with average B,V,R and I zenith magnitudes per square arc second of 22.7, 22.0, 21.0 and 20.0, respectively.

Personnel

There was no turnover in the core SALT technical team during the past two years. One project team member left, as planned, at the end of the Tracker Upgrade project. Two staff members, from historically disadvantaged groups, have made progress in their studies towards becoming mechanical artisans by passing all of their theoretical examinations and a third has recently enrolled to qualify as an artisan. One female staff member is studying towards her Diploma in Supply Chain Management and will write her final exams in the second quarter of 2017. Another is being trained to clean the primary mirror using the sophisticated Mirror Cleaning System.

In the SALT Astronomy operations, one SALT Astronomer (SA) resigned, and a replacement was recruited. In addition, two more SAs were appointed, strengthening the whole team of SAs, software and data management personnel, and telescope operators, to 13 people.

Safety

There were no health and safety incidents during the past two years. A fire drill and a simulated search-and-rescue exercise were conducted during the third quarter of 2016. Some technical and procedural deficiencies were uncovered and most have since been rectified.

INSTRUMENTATION NEWS

All instruments have remained fully operational and progress was made in commissioning additional RSS modes. Low Resolution Fabry-Perot spectroscopy now works well, but dual etalon mode (employing both the High and Low Resolution etalons) still poses challenges due to thermally induced mechanical instabilities. The Medium Resolution etalon remains out of commission due to optical coating damage that will require a costly repair. A service of the RSS optics was performed in August 2016.

Figure 6 below shows the science usage fractions of the instruments in the 2015-2016 period, as well as the breakdown of the work-horse instrument RSS per mode.

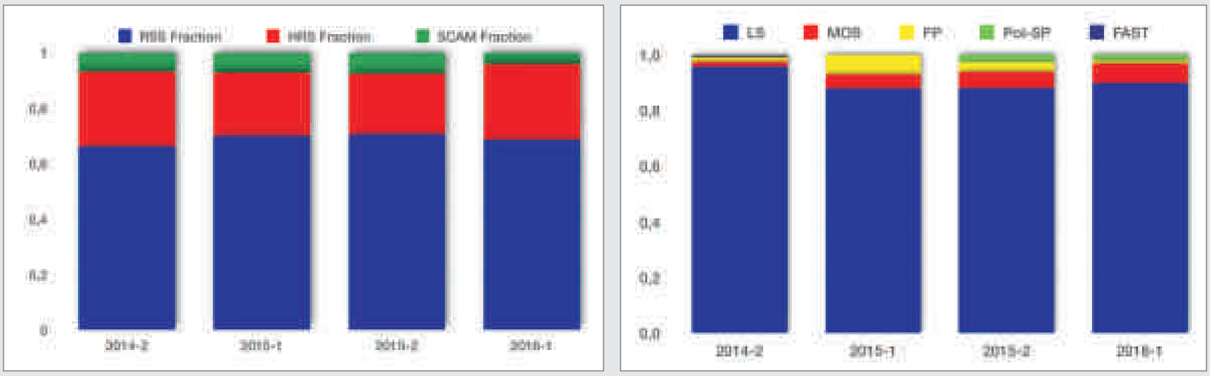


Fig. 6: Breakdown of SALT instrument usage over past four semesters (left), and the RSS modes (right). RSS is clearly the workhorse instrument, with long-slit remaining the most popular choice. HRS usage has stabilised to approximately quarter of all science time. The Fabry-Perot mode suffered from technical difficulties in 2016, so the usage does not reflect its actual demand, which is in fact similar to the MOS mode.

The highest priority project for Astronomy Operations during 2016 was developing the HRS data reduction pipeline and setting up tools for automatic data quality monitoring for all of the SALT instruments. The HRS pipeline has just started to deliver fully calibrated and extracted spectra to PIs at the end of 2016. With a robust HRS reduction pipeline in place, it was also possible to quantify the radial velocity accuracy of the various modes, approximately 300 m/s for all the HRS modes using default calibrations, i.e. arcs and radial velocity standards taken within days or weeks of the observations. Much higher accuracies will be achievable with dedicated calibrations. SALT was also able to experiment with a high-precision calibration device known as a Laser Frequency Comb (LFC) for the HRS for a few months during 2016.

SALT hosts an experimental laser frequency comb

Spectroscopic data are usually wavelength-calibrated using arc spectra of hollow-cathode lamps. High resolution data require better calibration, with the most demanding application being the search for low-mass exoplanets via the minute radial velocity perturbations they impose on spectra of their host stars. When such high precision velocity measurements are required, SALT HRS feeds light from a Thorium Argon (ThAr) arc lamp into the sky fibre of the instrument's High Stability mode. This allows the calibration data to be obtained during the course of the actual science exposure. The HRS also makes provision for employing an iodine cell, which results in a dense forest of iodine absorption lines being superimposed on part of the science spectrum to enhance the calibration accuracy. These options have significant limitations though, which may be overcome with a state-of-the-art calibration device known as a laser frequency comb (LFC). Unfortunately, these instruments tend to be prohibitively expensive and operationally demanding, so a LFC was not considered to be a viable prospect for SALT's High Resolution Spectrograph.

During the latter part of 2015, researchers in the Ultrafast Optics group at Heriot-Watt University in Edinburgh were referred to SALT by Ray Sharples, the PI for SALT's HRS. These laser physicists were keen to test an experimental LFC on a high resolution astronomical spectrograph. Naturally, SALT jumped at the opportunity to host and explore this extraordinary device and to establish a scientific collaboration with specialists in this rapidly-evolving field.

The laboratory-based system had to be extensively adapted to suit the HRS and then made to fit on a standard shipping pallet. Arrangements could then be made to safely transport the delicate optical and electronic components from Scotland to South Africa, and to ensure that all of the import/export paperwork was in order. The fragile crate cleared customs in Cape Town on 18 April 2016 and was transported to Sutherland the next day (see Figure 7). The Heriot-Watt duo of Derryck Reid and Richard McCracken then spent a week at the telescope, working closely with SALT Operations (specifically the local HRS team of Éric Depagne, Lisa Crause, Rudi Kuhn and Nic Erasmus) to get the comb set up and then to train the team to operate it over the coming months.

Once fully operational, the system could be fibre-coupled into the HRS via the instrument's High Stability bench. Great care was taken to avoid having the HRS CCDs damaged by the intense laser light from the comb. First spectra of the LFC were achieved later that night, and those were immediately followed by HRS observations of a radial velocity standard star with comb light simultaneously fed into the sky fibre (see Figure 8). This was a remarkable achievement just five days after the comb arrived at SALT!

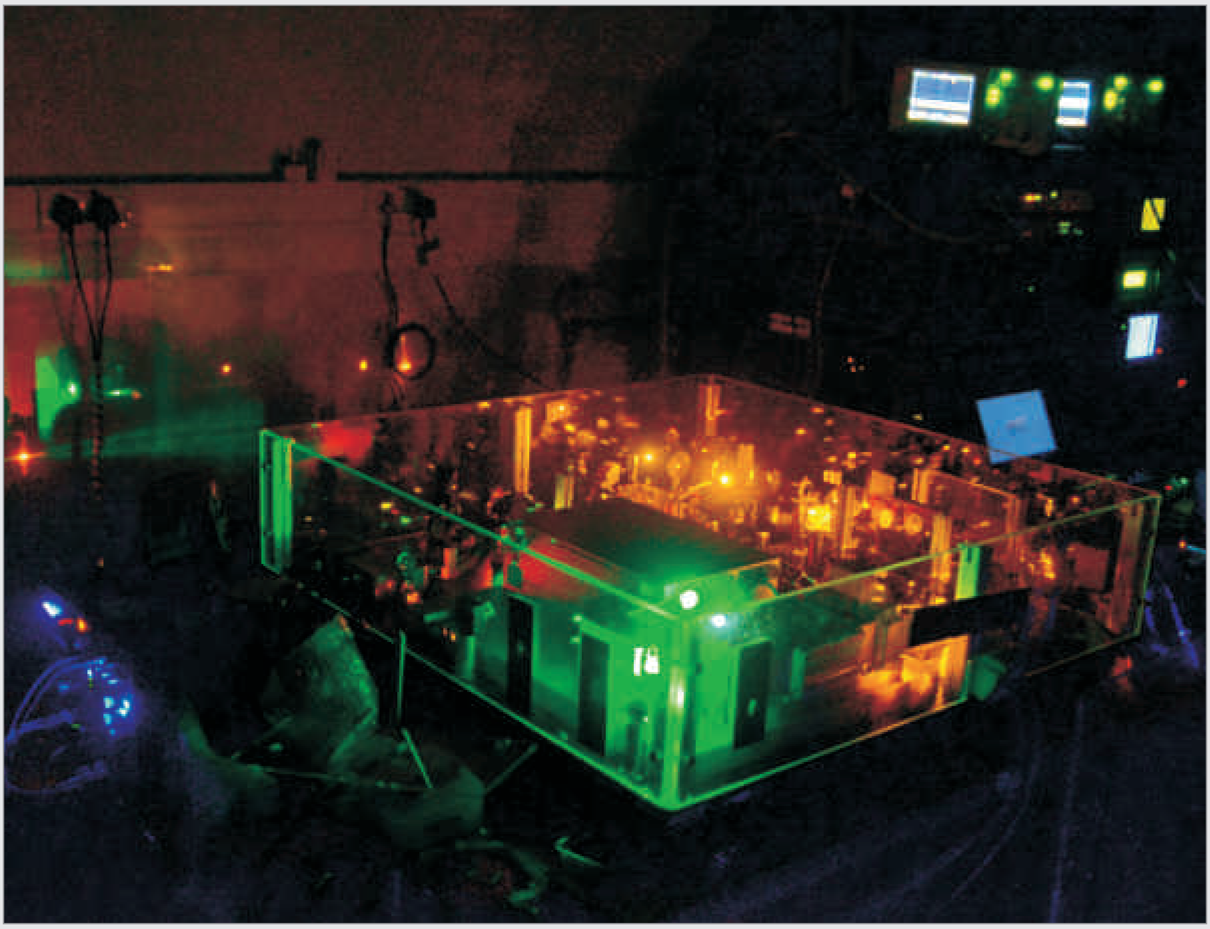


Fig. 7: The operational comb in the darkened HRS electronics room. The green glow is from the pump laser that drives the femtosecond pulsed laser at the heart of the instrument, while the yellow light indicates the peak of the comb spectrum. All of the other lights visible in this photo are due to various power supplies and electronic monitoring devices associated with the comb.

The LFC produces a spectacularly beautiful "super-continuum", which visually resembles a continuous spectrum when mildly dispersed. When the comb light is fed into a high resolution spectrograph, this band of colour is stretched out much further to reveal that it consists of thousands of uniquely defined laser spots, each with precisely defined wavelengths. This is superior in every respect to the calibration features from a conventional arc lamp, since the individual lines from the ThAr lamp are irregularly spaced and often quite sparsely distributed, saturation is inevitable for the brightest lines, others are impossibly faint and many are blended - none of which is conducive to reliable wavelength calibration. The comb provides about 50 times as many lines, without any blends or saturation, their frequency spacing is fixed and traceable, and each line can be absolutely referenced to an accurately known transition of Rubidium that gets included in the comb spectrum. The system thus yields an incredibly comprehensive, stable and traceable wavelength solution that allows minute velocity shifts to be measured from the spectra.

The deployment of an experimental LFC at SALT for a couple of months proved highly instructive for all concerned. This multi-disciplinary international collaboration introduced a cutting-edge calibration device to a high resolution spectrograph on a 10-m class telescope for the first time. It was immediately obvious that this would be an incredibly valuable addition to SALT as it would allow us to exploit the HRS's full potential for high-precision radial velocity work, specifically within the realm of exoplanet searches. We hope to pursue the collaboration with the Heriot-Watt team and to ultimately work with them to develop a suitable LFC for SALT.

See the various posts on the SALT Astronomy blog (http://saltastro.blogspot.co.za) in late April and early May 2016 for more technical information about the field trial of the Heriot-Watt LFC at SALT.

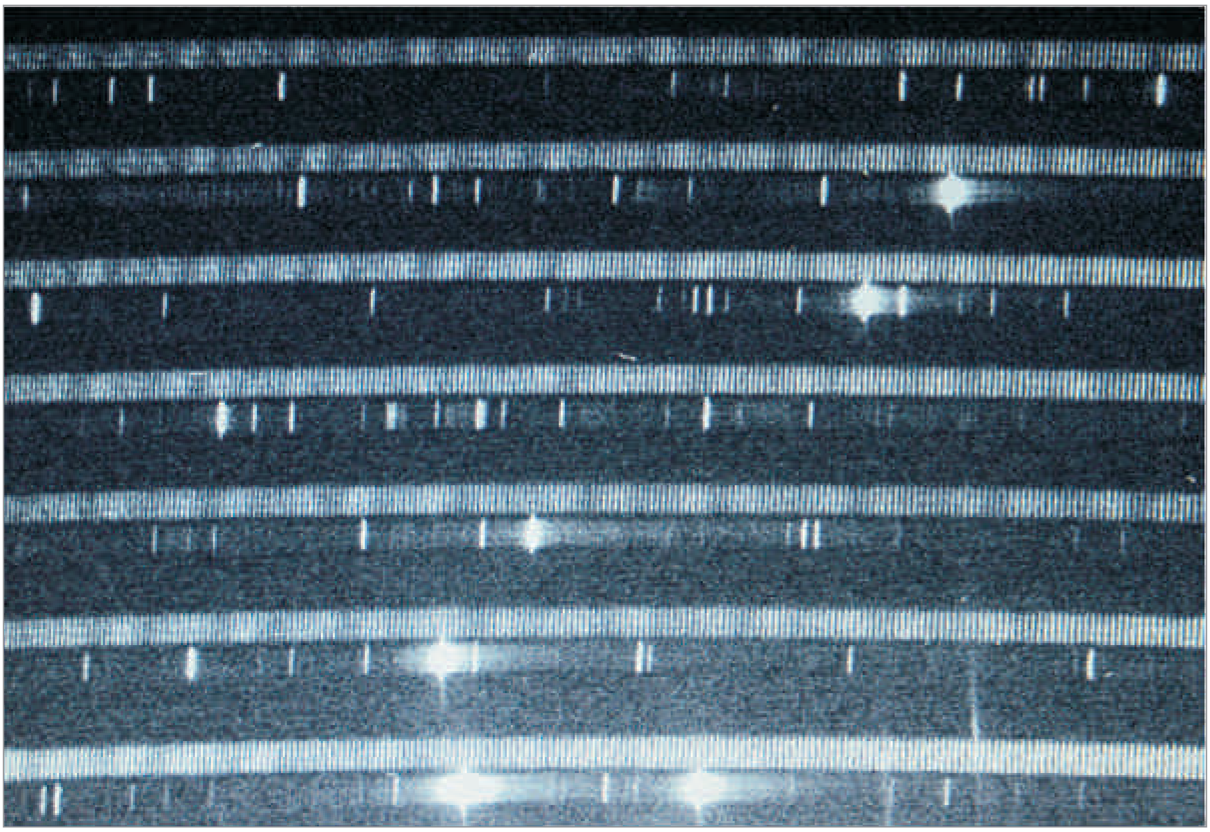


Fig. 8: Pairs of orders in a HRS image showing the comparison between the LFC (upper track) and the conventional ThAr arc spectrum (lower track). Note the huge number of comb lines compared to the sparse and irregularly spaces arc lines that also vary considerably in brightness.

RESEARCH HIGHLIGHTS

This section presents a number of research highlights from a range of salt observing programmes reported during 2015 and 2016.

STELLAR AND GALACTIC ASTRONOMY

The Spins of O-type stars in Wolf-Rayet + O Binaries

When massive stars rotate sufficiently rapidly (i.e. with equatorial velocities > 200-300 km/s) their rotation fundamentally influences their evolution. Furthermore, rapid rotation may critically affect the final collapse of a massive star, leading to ultra-luminous supernovae and long-duration gamma-ray bursts. The theoretically-predicted importance of rotation has motivated several observational studies to measure the distribution of rotational velocities of massive stars. All of these studies reached a similar conclusion: the distribution for both the early B-type stars and O-type stars is bimodal. The majority of these stars are relatively slow rotators with an average equatorial velocity ~100 km/s, while a smaller, but significant fraction of them are rapid rotators with equatorial velocities reaching up to 500-600 km/s. Many single O stars spin very rapidly; this can be explained if they accreted angular momentum from a mass-transferring companion before it blew up as a supernova. To test this hypothesis Michael Shara (AMNH), Steve Crawford and Lisa Crause (SAAO) used the LR mode of SALT's HRS to measure the spin rates of eight O stars in Wolf-Rayet (WR) + O binaries, increasing the total sample size of such O stars' measured spins from two to ten. They found an average equatorial rotation velocity from HeI (HeII) lines of equatorial velocities of 366 (185) km/s for these O stars (see Figure 9).

The authors have argued that the nearly 100% difference between measured HeI and HeII speeds is due to flattening of the rapidly spinning O stars in WR + O binaries, and that the hotter (cooler) poles (equators) of the O stars are the source of the HeII (HeI) lines. Super-synchronous spins, now observed in all 10 O stars in WR + O binaries where it has been measured, are strong evidence that Roche lobe

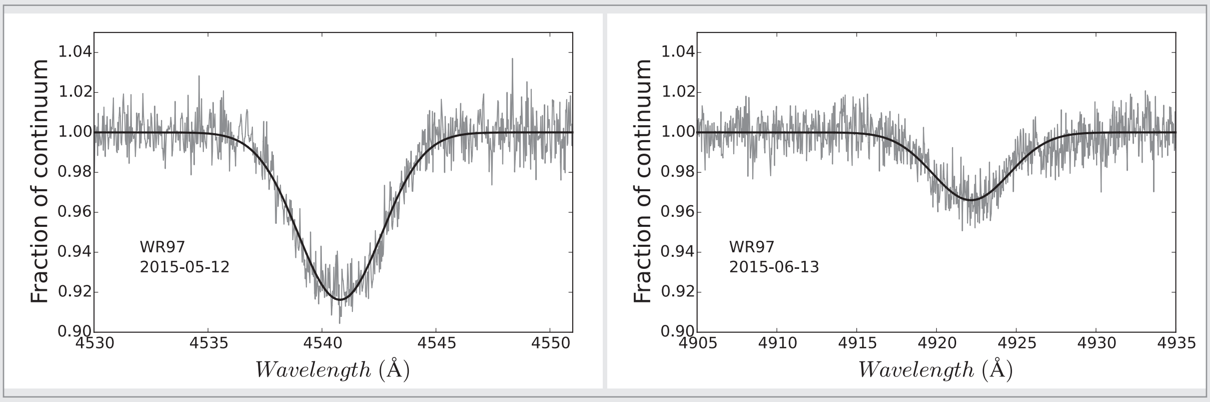


Fig 9: SALT High Resolution Spectrograph LR mode observations of HeI and HeII absorption lines in the O star of the binary Wolf-Rayet + O-star WR 97. The deduced rotational velocity of the O-star is 470 +/-35 km/s from the HeI line, and 280 +/-37 km/s from the HeII line.

overflow mass transfer has played a critical role in the evolution of these binaries. Theory predicts that this mass transfer rapidly spins-up the O-type mass gainer to a nearly break-up rotational velocity ~ 530 km/s: the observed average rotational speed of the O-type stars in their sample is 70% of that value. Thus even over the short WR-phase timescale, tidal and/or other effects causing spin-down must be efficient. A challenge to tidal synchronization theory is that the two longest-period binaries in their sample (with periods of 29.7 and 78.5 days) unexpectedly display super-synchronous rotation.

Ref: Shara, M. M., et al. 2017, MNRAS, 464, 2066

SALT reveals a rare post-common-envelope binary central star in the planetary nebula NGC 5189

In recent years it has become increasingly clear that many planetary nebulae are formed via an interaction with a stellar or perhaps even a planetary companion. The most readily observed cases are formed where a companion to the Asymptotic Giant Branch (AGB) star primary spirals into the atmosphere of the AGB star in a common-envelope interaction. The common envelope is ejected as the nebula, leaving two stars in a close orbit of a few days or less. This nebula often contains the hallmarks of

Fig 10: Hubble Space Telescope view of NGC 5189. The blue star at the centre is the central star around which SALT found an invisible companion orbiting every 4.04 days.

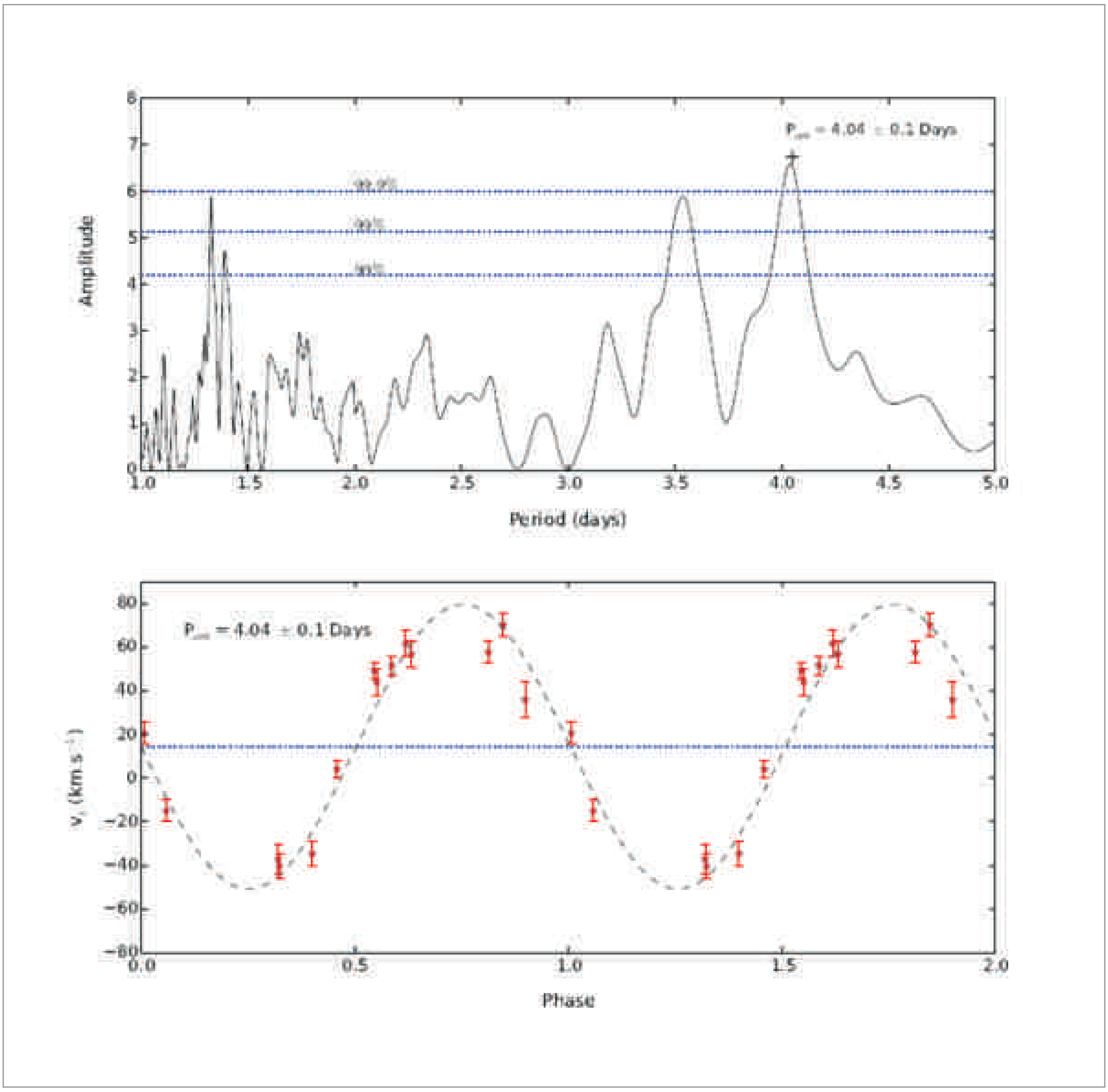


Fig 11. Lomb-Scargle periodogram (top) and phased radial velocity curve (bottom) of SALT RSS radial velocities measured from cross-correlation of the OVI 5290 emission feature in NGC 5189.

the interaction, with precessing outflows and other knot-like structures thought to be telltale signs that the binary interaction took place. NGC 5189 is a striking southern planetary nebula that ticks all of the boxes for having a binary companion (See Figure 10), however previous photometric studies found no evidence for a companion to the unusual [WO] Wolf-Rayet central star. Around 10% or so of planetary nebulae nuclei host low-mass analogues of Wolf-Rayet stars, but their formation is not well understood. Despite there being nearly 50 post-common-envelope central stars currently known, only one was previously identified to have a Wolf-Rayet component. Manick (SAAO), Miszalski (SALT) & McBride (UCT) used SALT to reveal the nucleus of NGC 5189 to be a 4.04 day spectroscopic binary (See Figure 11), with the companion most likely being a slightly more massive and evolved white dwarf, invisible at optical wavelengths. Repeat observations with SALT confirmed the binary motion is definitely real and allowed us to refine the orbital period to 4.05 days. Further work to find and characterise additional rare Wolf-Rayet binary central stars with SALT is ongoing.

Ref: Manick, R., Miszalski, B. and McBride, 2015, MNRAS, 448, 1789

Discovery of four new bona fide Galactic Luminous Blue Variables

Stars more massive than 20 solar masses experience the short-lived luminous blue variable (LBV) stage, which among other evolutionary stages of massive stars is the most interesting in terms of observational manifestations, and perhaps the most important in the evolutionary sense. The LBV phenomenon is still poorly understood, which is mostly because the LBV stars are very rare objects. The discovery of additional LBVs would, therefore, be of great importance for understanding their evolutionary status and their connection to other massive transient stars, as well as for unveiling the driving mechanism(s) of the LBV phenomenon.

Detection of LBV-like shells may be considered an indication that their associated stars are massive and evolved, and therefore could be used for the selection of candidate massive stars for follow-up spectroscopy. Many of these stars are extremely faint in the optical due to reddening, so 8-10-m class telescopes like SALT are required in order to obtain the necessary spectra.

A. Kniazev (SAAO/SALT) and collaborators have reported results of SALT optical spectroscopy of 55 central stars of compact mid-IR nebulae discovered with Spitzer and WISE (see Figure 12 for an example). To search for possible spectroscopic and photometric variability of the newly identified massive stars, they obtained additional spectra with SALT and performed photometric monitoring of these stars with the 0.75-m telescope of the SAAO. Subsequent spectroscopic and photometric monitoring of these stars allowed them to confirm the LBV status of four stars from their sample, thereby increasing the current census of the bona fide Galactic LBVs to eighteen stars in total.

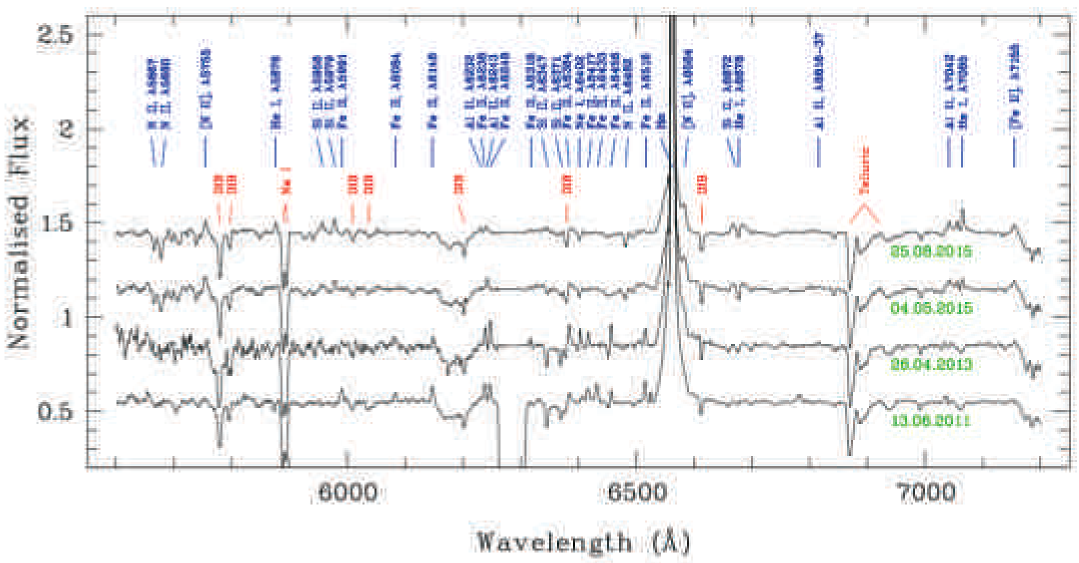


Fig 12: Evolution of the (normalized) spectrum of the new Galactic LBV MN48 from 2011—2015.

Ref: Kaniazev, A. Y., Gvaramadze, V. V., Berdikov, L. N., 2016, MNRAS, 459, 3068; Kaniazev, A. Y., Gvaramadze, V. V., Berdikov. L. N., 2015, MNRAS, 449, 60

2S 1553-542: a Be/X-ray binary pulsar on the far side of the Galaxy

Deep imaging of the region of space containing the elusive high-mass X-ray binary system 2S 1553-542 was conducted by Lee Townsend (UCT), David Buckley (SAAO) and collaborators using SALT in August 2015. This particular X-ray binary was discovered more than 40 years ago, though the exact position, distance and optical companion have yet to be identified. In 2015 it underwent a large X-ray outburst that allowed Swift and Chandra observations to improve the localisation of the source. When X-ray binaries of this nature go into outburst, it is usually accompanied by an increase in the light emanating from the optical counterpart. Director's Discretionary Time was used to take deep r', i' and H-alpha images of the position of 2S 1553-542, with the aim of finding what was likely an extremely faint optical counterpart within the positional error circle determined by the X-ray telescopes. On close inspection, and some precise astrometry, no less than 5 stars were found in the immediate region of the X-ray source (see Figure 13), where in archival imaging there was only one. Making use of the VISTA Variables in the Via Lactea (VVV) survey, the scientists were able to use the SALT imaging to confirm which star was the correct counterpart through careful examination of the optical magnitudes and colours. The team were also able to determine the distance of 15 kpc to the binary based on the shape of the spectral energy distribution of the optical star and the interstellar absorption derived from X-ray spectral information. With the estimated distance the target is the most distant X-ray binary known in our Galaxy.

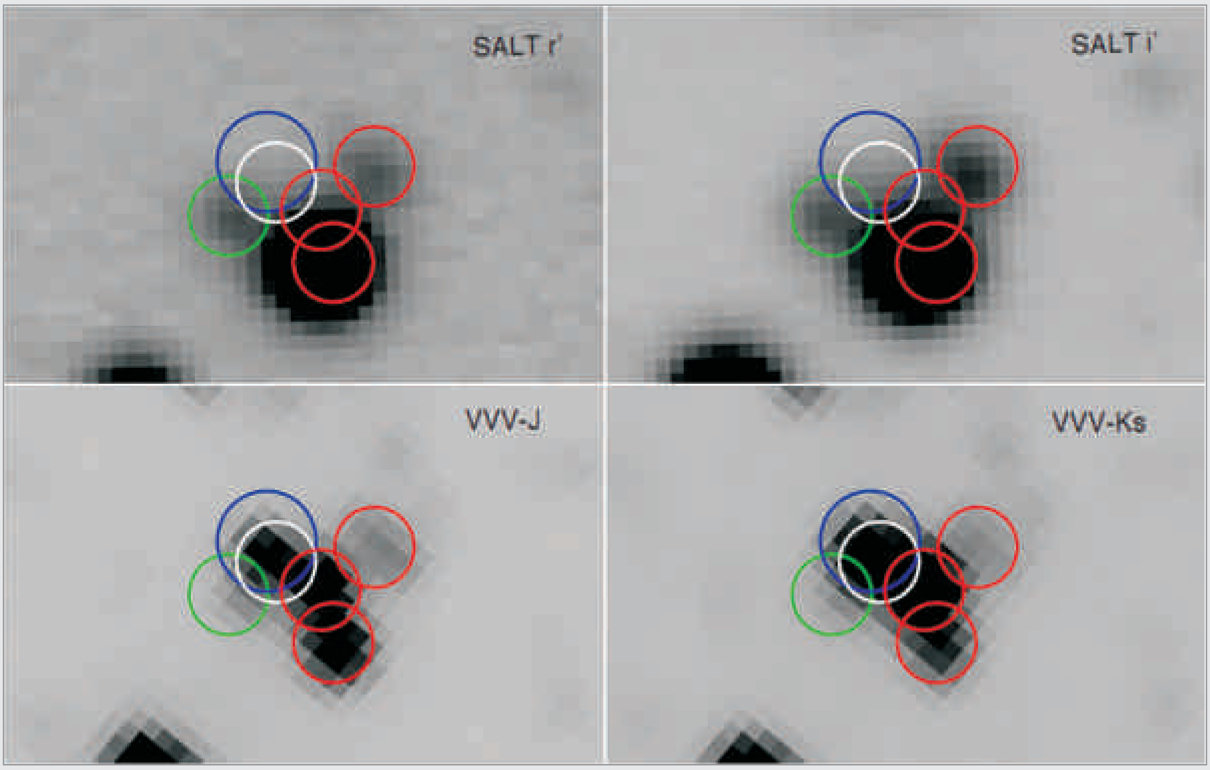


Fig 13: SALTICAM i' and r' and VVV-J and Ks images of the region around 2S 1553-542. The blue circle is the Chandra positional uncertainty (1 arcsec). The green circle is the position of the SALTICAM candidate counterpart. The red circles denote nearby NIR stars, detected in the VVV images. The white circle is the position of the newly proposed counterpart of 2S 1553-542, found in the near-infrared imaging and not present in the SALTICAM imaging.

Ref: Lutovinov, A. A,. et al., 2016, MNRAS, 462, 3823

SALT optical spectroscopy of PSR B1259-63/LS 2883 during the 2014 periastron passage

The gamma-ray binary system, PSR B1259-63/LS 2883 consists of a 48 ms pulsar in a 3.4 year orbit around a Be star. The system last went through periastron on the 4th of May 2014. This source is particularly interesting because it is the only one of the known gamma-ray binaries where the nature of the compact object is known. Therefore, understanding the details of the interaction in PSR B1259-63/LS 2883 is important for understanding how the other binary systems behave.

Most of the multi-wavelength observations find an increase in the non-thermal emission that peaks approximately 15-20 days before and after periastron, phases that are associated with the pulsar passing through the circumstellar disc. While this is seen in radio and X-ray observations and there is some indication of this in TeV gamma-ray observations, observations at GeV energies with Fermi-LAT showed a completely different light curve. The GeV observations show little or no emission around periastron, and a rapid increase around 30-40 days after periastron, a period during which the other emission is decreasing.

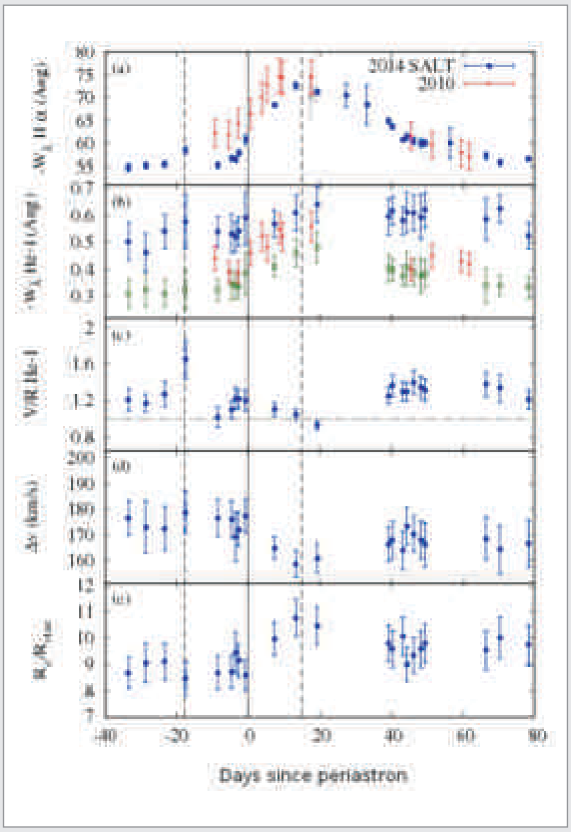


Fig 14: Blue circles show results from the RSS spectroscopic observations around the 2014 periastron passage, compared to the red crosses from observations around the 2010 periastron passage (Chernyakova et al. 2014). The two dashed vertical lines correspond to the last and first detection of the pulsar around the 2010 periastron passage, while the vertical solid line indicates periastron. (a) Equivalent width of the $H\alpha$ line. (b) The equivalent width of He I measured from the base of the emission line (solid blue circles) and from the line profile fit to the continuum (open green squares). (c) Ratio of the peaks of the violet to red (V/R) components of the He I line. (d) The peak separation of the He I line. (e) The emission location of He I assuming a Keplerian disc.

Using the RSS and SALT, the variation of the circumstellar disc from 33 days before, until 78 days after periastron was traced in a programme led by B. Van Soelen (UFS). All observations showed strong H and He-I emission lines that indicate that the disc was present throughout periastron, but was variable as reflected by the change in the equivalent width and shape of the emission lines. The equivalent width of both lines increased around periastron, peaking only after periastron, and decreasing around 30 days after periastron. The double-peaked He-I line showed a shift in the relative strength of the red and violet components and a change in the peak separation. This clearly indicates that the asymmetric structure of the disc was variable and if the disc is Keplerian, the decrease in the peak separation implies that the dominant emission region moves further out in the disc during periastron. These observations demonstrate that the disc presents considerable variability around periastron, but is always present. Remarkably, an increase in the H-alpha line was observed at the point of the disc crossing.

Combining the SALT results with multi-wavelength observations obtained through international collaborators, the dataset clearly showed that the equivalent width of the emission lines increases post-periastron and remains strong until after the peak in the Fermi emission is detected (see Figure 14). This strengthens the link between the variability in the circumstellar disc and the gamma-ray observations and may suggest some disruption of the disc around this period that could be linked to the cause of the flare. The Fermi-LAT observations showed a similar GeV gamma-ray light curve (though this was fainter than during the 2010 periastron) and the X-ray light curve (combined NuSTAR and Swift observations) showed a plateau in the fading X-ray light curve around the peak in the gamma-ray emission. This clearly shows that the Fermi-LAT event is not isolated at only GeV energies, but is connected to the multi-wavelength emission – results not known before this periastron passage.

Ref: Van Soelen, B. et al., 2016, MNRAS, 455, 3674; Chernyakova, M., et al. 2015, MNRAS, 454, 1358.

Discovery of an eclipsing dwarf nova in the ancient nova shell Te 11

When amateur astronomers found a peculiar looking nebula called Te 11 in the Orion constellation in 2010 (Figure15), astronomers were not quite sure what to make of it. It could have been a planetary nebula, or perhaps something more unusual. A detailed investigation led by Brent Miszalski (SALT/SAAO) and Patrick Woudt (UCT), shed new light on the perplexing object. Photometry collected by Woudt and colleagues clearly showed the nucleus of Te 11 to be an eclipsing dwarf nova with regular dwarf nova outbursts. The nebula seems to have been formed in a stellar explosion just over 1500 years ago according to ancient Chinese records. Te 11 therefore appears to be a particularly rare combination of dwarf nova and nova shell, with only two other examples well studied in the literature. Discoveries such as these are uniquely placed to tell us how the long term evolution of cataclysmic variables takes place over thousands of years. The distance to the object was also determined with the help of SALT spectroscopy (Figure 16), allowing the authors to estimate that at the time of the explosion, the star may have rivalled Jupiter in brightness, outshining all the other stars in the Orion constellation.

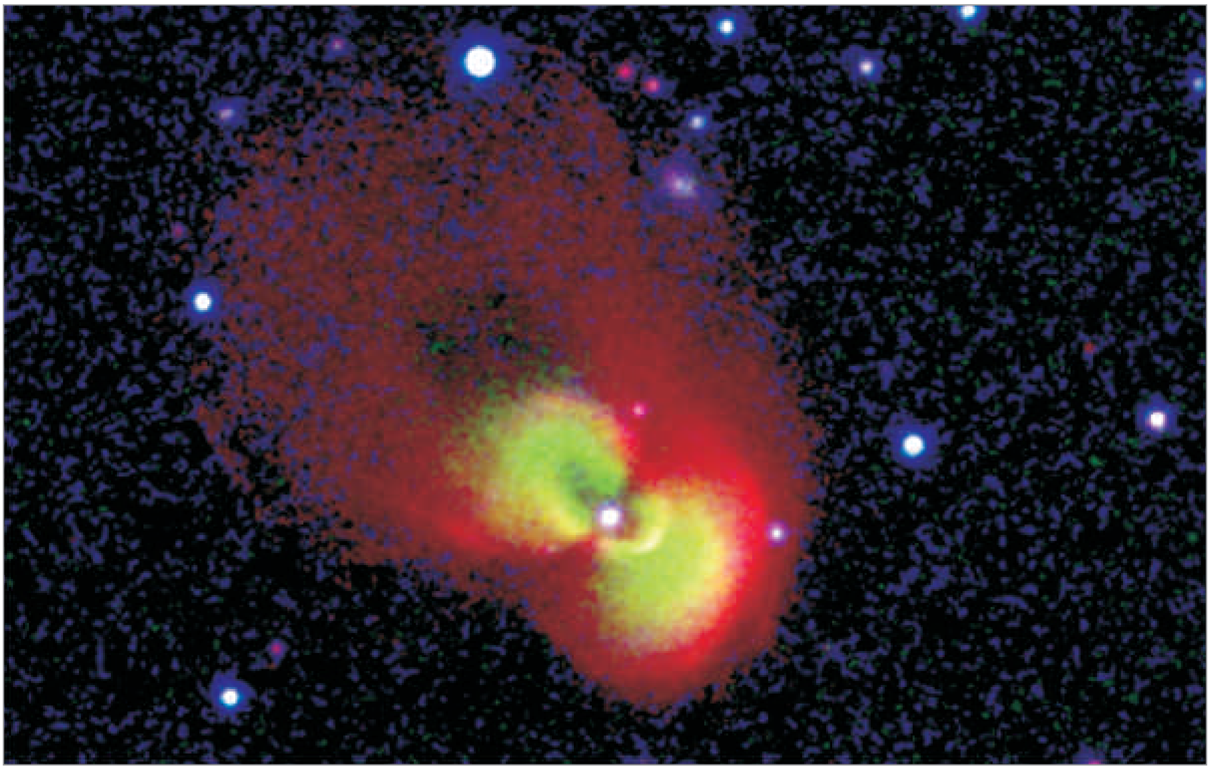


Fig 15: The peculiar nebula Te 11 surrounding its dwarf nova nucleus. A colour-composite image made from images taken with Halpha+[NII] (red, VLT FORS2), [OIII] (green, VLT FORS2) and SDSS g (blue, SDSS) filters. The image measures 2.5 x 2.0 arcmin^2 with north up and east to left.

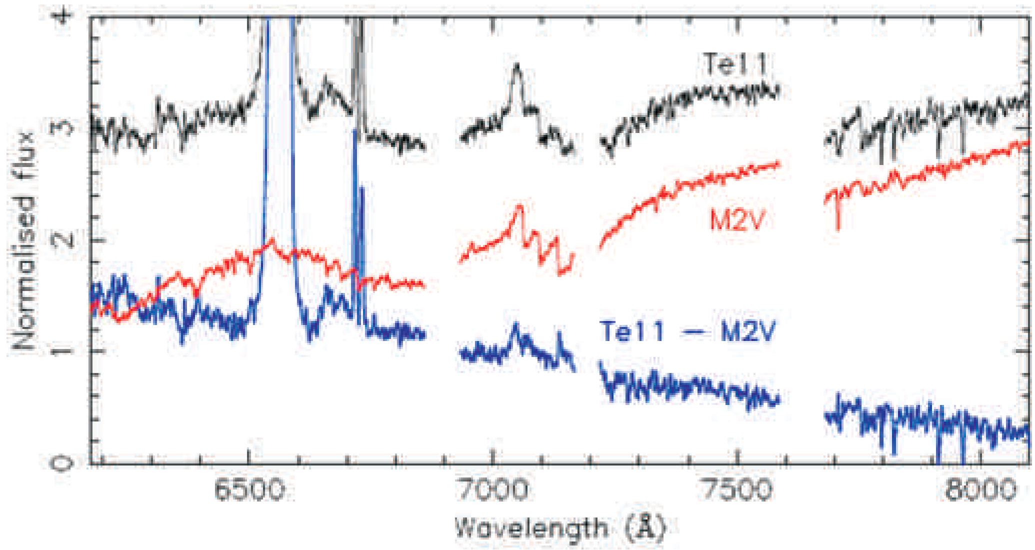
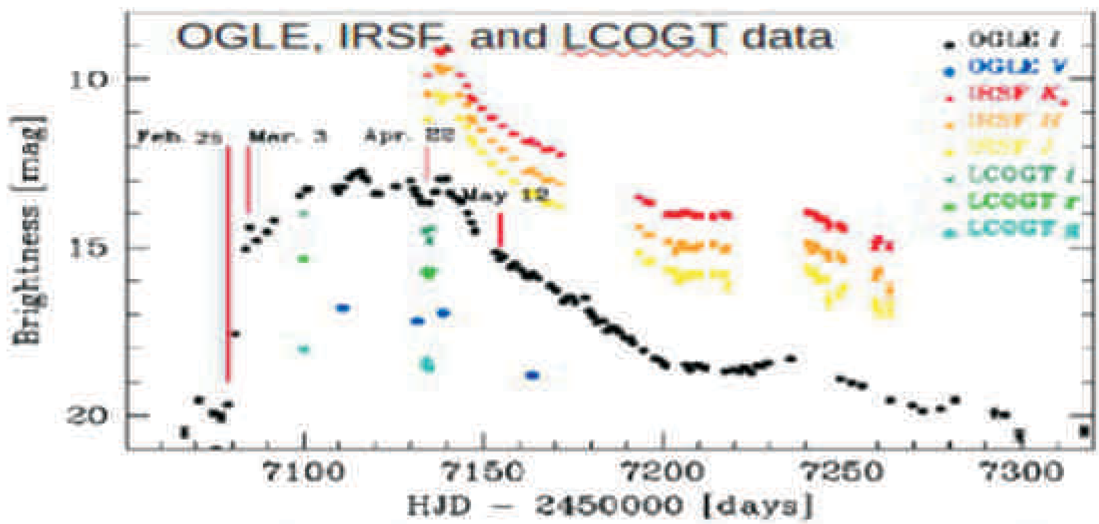


Fig 16: SALT RSS spectrum of the faint dwarf nova nucleus of Te 11 (black, SDSS r > 18 mag). The secondary is well matched by an M2 dwarf (red), which after subtraction shows the blue continuum resulting from the accretion disc (blue).

Ref: Miszalski, M. et al., 2016, MNRAS, 456, 633

V5852 Sgr: an unusual nova possibly associated with the Sagittarius stream

Novae are stellar explosions that take place in binary stellar systems. During these explosions, the star's brightness increases by many orders of magnitude, and then fades to its initial brightness, and the system survives the explosion. A team of SAAO astronomers, led by an SAAO PhD student Elias Aydi, heard of an increase in brightness of a star from their colleagues from Poland, who had used the OGLE telescope in Chile. Their first thoughts were of a classical nova explosion. However, after two months, the star's brightness was not fading like classical novae usually do. Hence, the team requested Director's Discretionary Time from SALT to obtain spectroscopic observations of the object in order to investigate



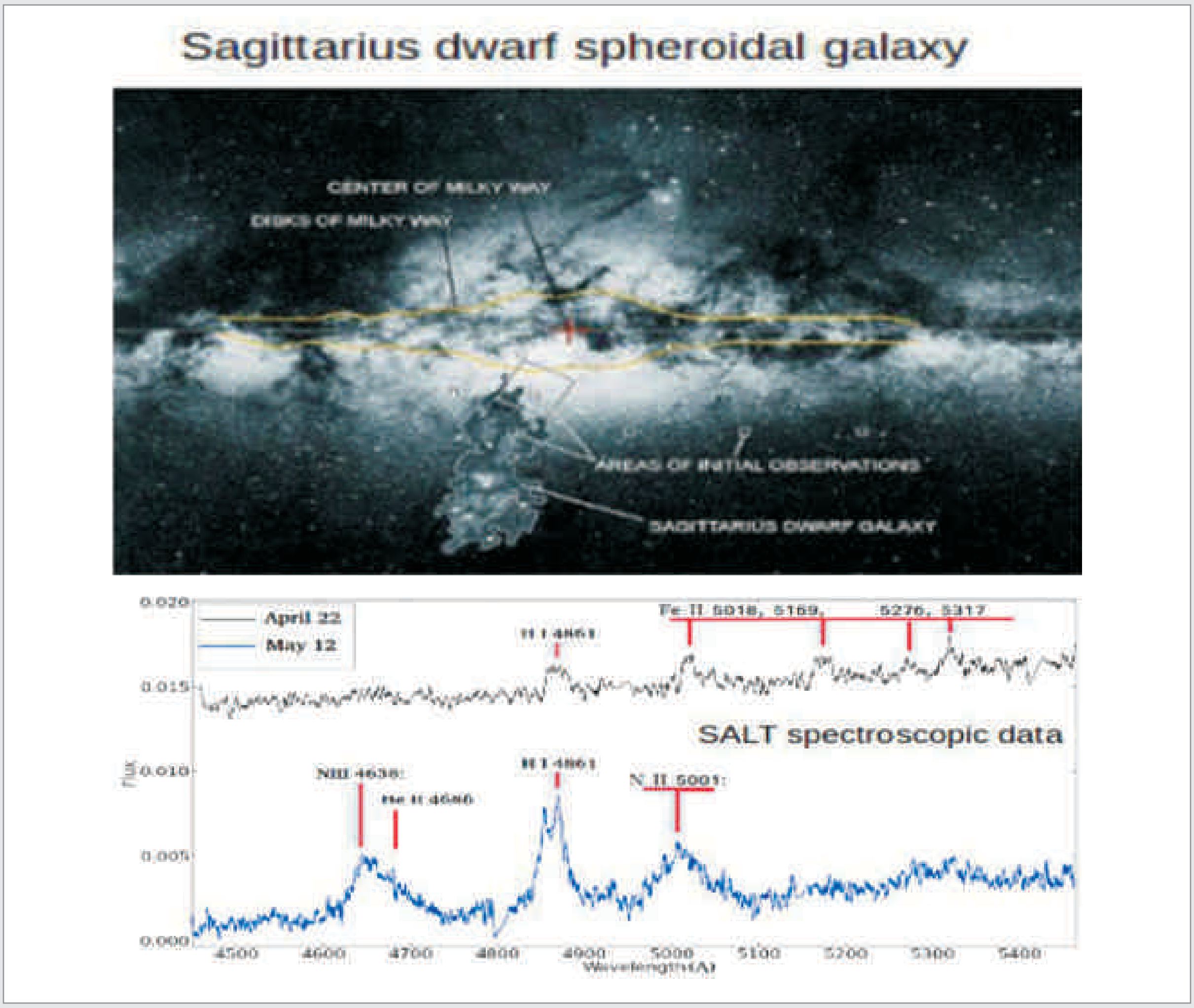


Fig 17: OGLE, IRSF and LCOGT photometry of the nova outburst and the object's subsequent evolution (top). Location of the Sagittarius dwarf spheroidal galaxy with respect to the Milky Way (middle). Spectra obtained with SALT's RSS showing the evolution of V5852 Sgr over a three week interval following the nova outburst (bottom).

its peculiar nature. The object was observed during two nights using the Robert Stobie Spectrograph on SALT in order to study its spectral evolution. At the same time, the object was followed-up with observations from the LCOGT telescopes (hosted in Sutherland) and infra-red observations using the Japanese-South African IRSF telescope also in Sutherland. The spectroscopy helped to confirm that the object did indeed undergo a nova explosion, but simultaneously the photometric OGLE, IRSF, and LCOGT data (see Figure 17) highlighted the peculiarity of the nova that showed a combination of signatures and features associated with different classes of novae (see Figure 17). Discovering and studying such unusual objects is key to understanding the mechanisms responsible for nova explosions and the post-explosion behaviour of such systems.

What added more intrigue and importance to the object was when the team derived an estimate of its distance. It was initially thought to be in the bulge of the Milky Way galaxy. However, using several methods, it was shown to be much further away. The location of the nova on the sky, its distance, and its spectroscopic features suggest that it is possibly located in the Sagittarius dwarf spheroidal galaxy, a dwarf satellite companion to our Milky Way. If so, this is the first nova explosion ever discovered in a dwarf spheroidal galaxy.

Ref: Aydi, E. et al., 2016, MNRAS, 461, 1529.

A semi-detached eclipsing binary that contains a delta Scuti star

As a result of a search through the SuperWASP archive for objects displaying multiply periodic photometric variations, Norton et al. of UK SALT consortium found evidence for an eclipsing binary star displaying a second, non-harmonically related, signal in its power spectrum. The object (1SWASP J050634.16-353648.4) was identified as a relatively bright (V ~ 11.5) semi-detached eclipsing binary with a

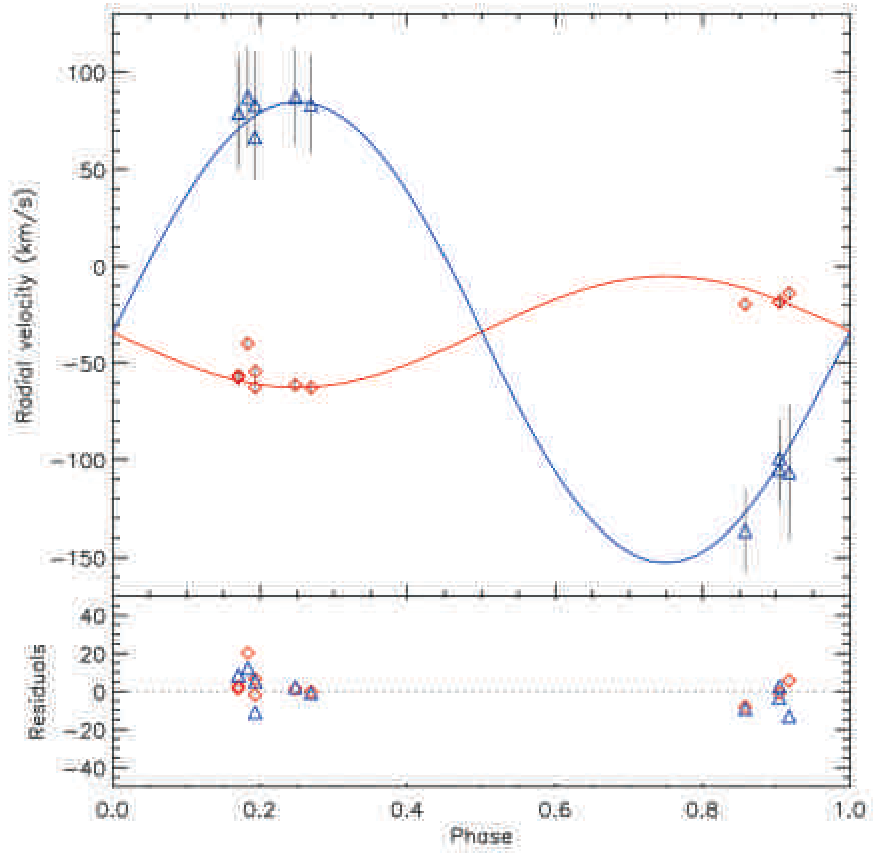


Fig 18: SALT RSS radial velocity curves of the two components of 1SWASP J050634.16-353648.4. The best-fitting model from phoebe is over-plotted showing the motion of the primary (red) and secondary (blue).

5.104 d orbital period that displays coherent pulsations with a semi-amplitude of 65 mmag at a period of 1.784 h (or frequency of 13.45 per day). Follow-up radial velocity spectroscopy was obtained with the RSS on SALT, and using these data they were able to confirm the binary nature of the system (see Figure 18). Using the phoebe code to model the radial velocity curve along with the SuperWASP photometry allowed parameters of both stellar components to be determined. This yielded a primary (pulsating) star with a mass of 1.73 +/- 0.11 solar mass and a radius of 2.41 +/- 0.06 solar radii plus a Roche-lobe filling secondary star with a mass of 0.41 +/- 0.03 solar mass and a radius of 4.21 +/- 0.11 solar radii. Thanks to the SALT observations, 1SWASP J050634.16-353648.4 was therefore identified as a bright delta Sct pulsator in a semi-detached eclipsing binary with one of the largest pulsation amplitudes of any such system known. The pulsation constant (Q = 0.026 +/- 0.002) indicates that the mode is likely a first overtone radial pulsation.

Ref: Norton, A. J., et al. 2016, A&A, 587, 54

A neighbourhood star's close shave with the Solar System

WISE J072003.20-084651.2, nicknamed Scholz's star after its discoverer in 2013, is a dim red dwarf type star in the constellation of Monoceros at a distance of 7 pc. SALT RSS spectroscopy by Ivanov, V., Vaisanen, P., Kniazev, A., and collaborators, and by Burgasser et al. using Keck, demonstrated that Scholz's star is actually a binary star system consisting of a M9.5 type star, and a T5 brown dwarf companion, with a combined mass of approximately 0.15 M_solar.

The most remarkable characteristic of Scholz's star turned out to be its past, however. The SALT and Keck spectra showed a radial velocity of about +80 km/s. Imaging revealed very low tangential motion, of the order 3 km/s. The same team that took the SALT observations, now led by E. Mamajek, estimated the past trajectory of the star. Using its present motion as a basis of dynamical Galactic orbit calculations, we found it had actually come close to our Solar System 70 000 years ago. At closest approach, it was just 52 kAU, or 0.25 pc away from the Sun. With 98% probability it travelled through the outer Oort Cloud.

This is the closest known stellar flyby to date. This is potentially significant, since it is thought that perturbations of the Oort Cloud may trigger comet showers down to the inner parts of our Solar System. These, in turn, can increase the probably of comet impact on Earth potentially causing extinction events as has happened several times in Earths history. In this case, we find the perturbation is too small to likely result in comet showers. However, it remains a very interesting coincidence that a stellar object would visit us so recently, previous work suggests such close flybys should happen only 0.1 Myr-1. Perhaps there are more ultra cool dwarf stars lurking in the neighbourhood than thought.

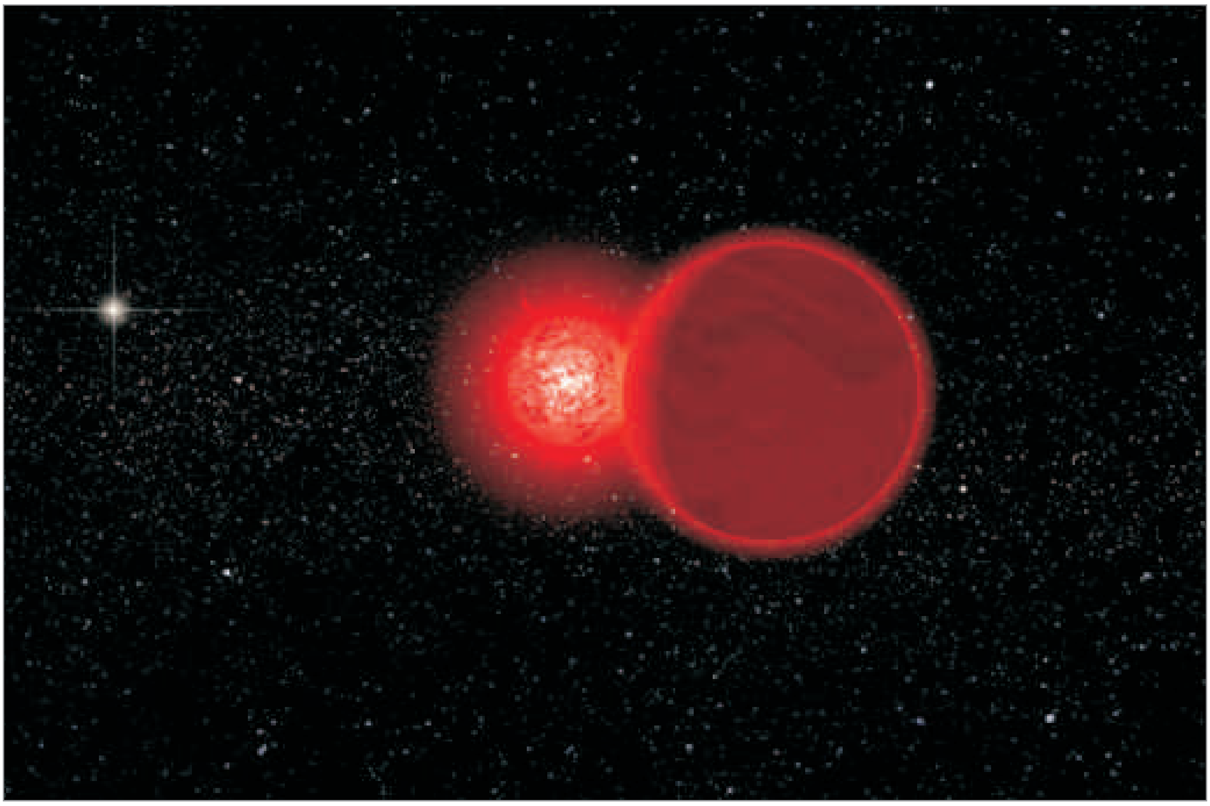
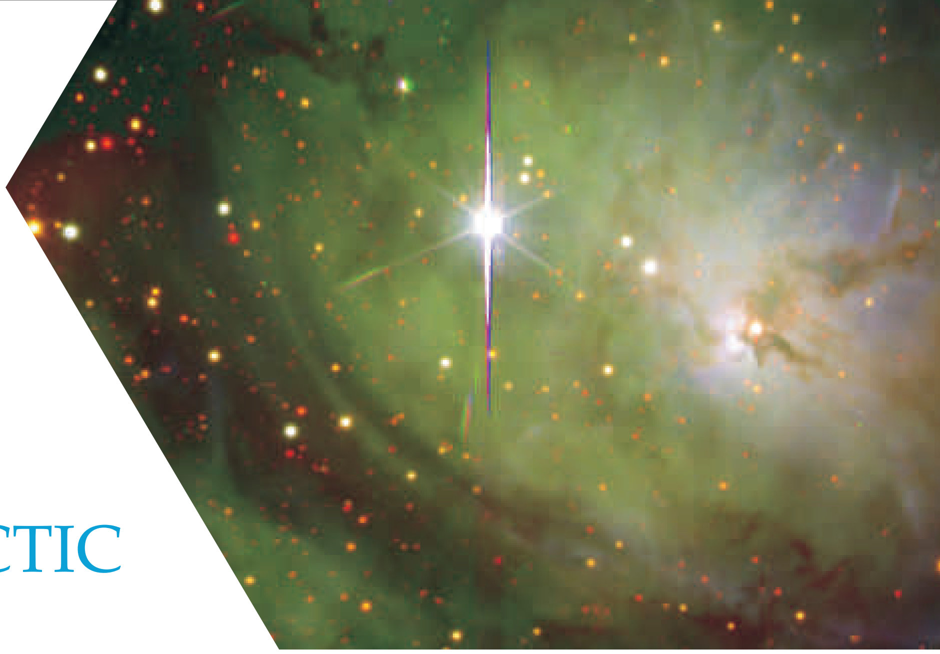


Fig. 19: Artist's impression of the Scholz's binary star, a small red star with a brown dwarf companion (at right), as it visited the outskirts of the solar system 70 000 years ago. The bright lone star to the left is the Sun 0.25 pc away at closest pass. (Credit: Michael Osadciw, University of Rochester).

Ref: Mamajek, E. E., et al., 2015, ApJ, 800, L17; Ivanov, V. D., et al., 2015, A&A, 574, A64



EXTRAGALACTIC ASTRONOMY

The SALT Strong Gravitational Lensing Legacy Project

The SALT Strong Gravitational Lensing Legacy Project (PI: S.Serjeant and Project Scientist: L.Marchetti, Open University of the UK SALT Consortium) is a long-term and multi-partner (involving RSA, UW and RU in addition to UKSC) observing program with SALT devoted to the spectroscopic identifications of one of the largest strong gravitational lens samples to date, selected using a new strong gravitational lens selection method via sub-mm surveys (Negrello et al. 2010 and Gonzalez-Nuevo et al. 2012).

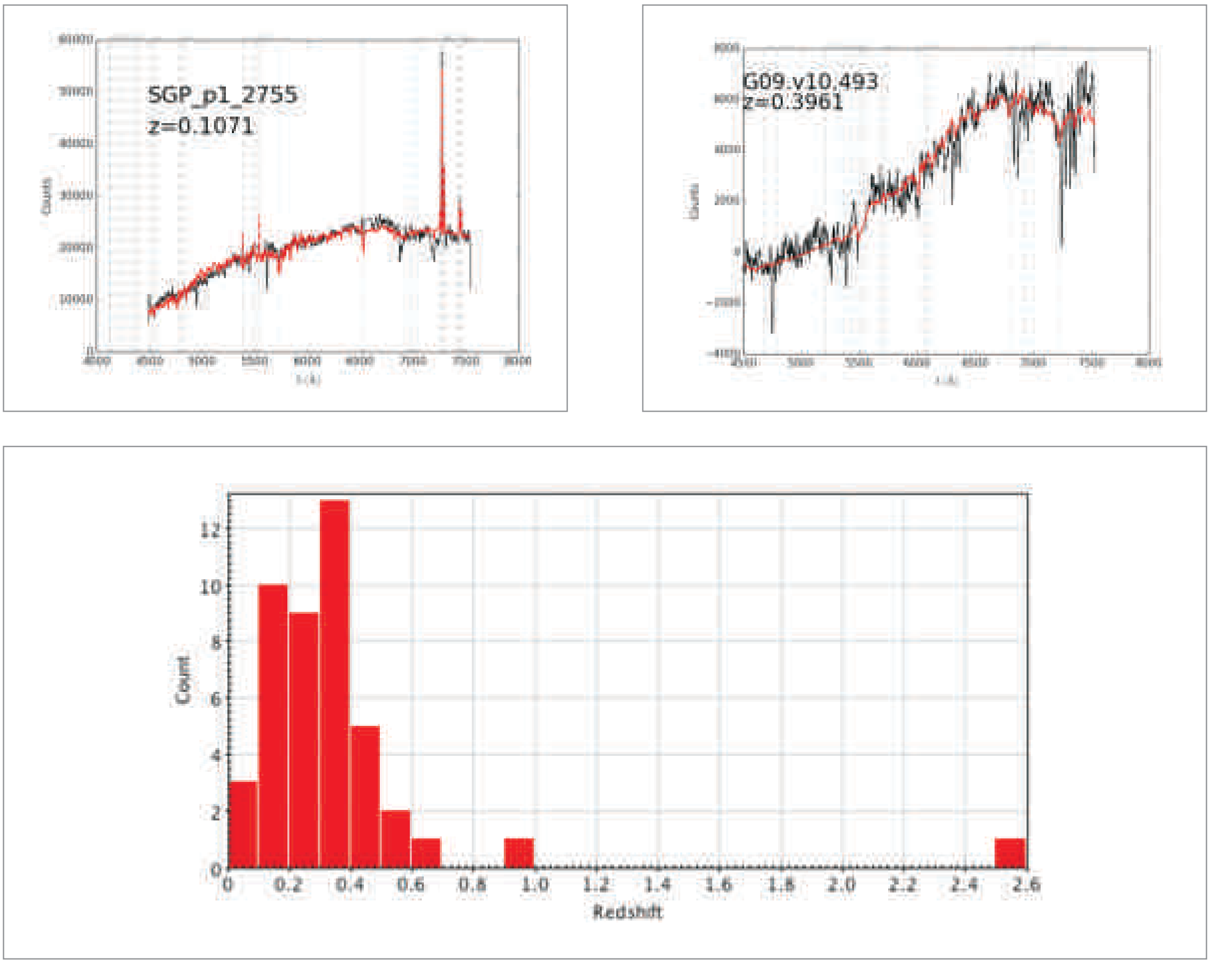


Fig 20: TOP: Examples of reduced spectra; BOTTOM: Redshift distribution of the objects observed with SALT to date. The vast majority of our lens sample is found at z<0.5, stretching up to z~1.0. The redshift distribution is peaking around z=0.4 as predicted from our lens selection. The source found at z~2.5 is a QSO for which we also obtained data with ALMA and HST.

The multi-year 300 hr SALT program started in late 2015 and will eventually allow identifying approximately up to 500 strong lensing systems which will be excellent candidates for multi-wavelength follow-up observations with ALMA, JWST and the E-ELT. The project will have a strong impact on the statistical characterization of strong gravitational lensing phenomena and has fostered the scientific collaboration between various SALT consortium partners (University of Wisconsin-Madison, Rutgers University and South African consortium members) and many external partners working in the field.

So far, more than 50 hours have been observed and the observing strategy and the data reduction pipeline is optimised to each target. The data analysis is on-going, and so far the project has successfully obtained redshifts for 100% of our targets down to a magnitude limit of r = 20 mag and for 75% of sources down to r ~ 21.5 mag (see Figure 20 for some examples of reduced spectra and for the spectroscopic redshift distribution obtained so far). These successful results validate the overall observing and data reduction strategy which have been implemented in collaboration with Co-Is working at SAAO in Cape Town. The project scientist was also awarded the "DST-NRF visiting fellowship for young researchers coming from the UK" and spends time in Cape Town and co-supervises students involved in the project further strengthening the SA / UK SALT collaboration.

Ref: Negrello, M., et al., 2017, MNRAS, 465, 3558

The Rings Survey. I. Hα and H I Velocity Maps of Galaxy NGC 2280

A team comprising of T. Williams (SAAO), C. Mitchell (RU) and J. Sellwood (RU) reported the first results from the RSS Imaging and Spectroscopy Nearby Galaxy Survey or RINGS. The aim of RINGS is to produce velocity maps from the H emission line of 19 nearby spiral galaxies at arcsecond angular resolutions over the 8' field of view of the Fabry-Perot imaging spectrometer on the Robert Stobie

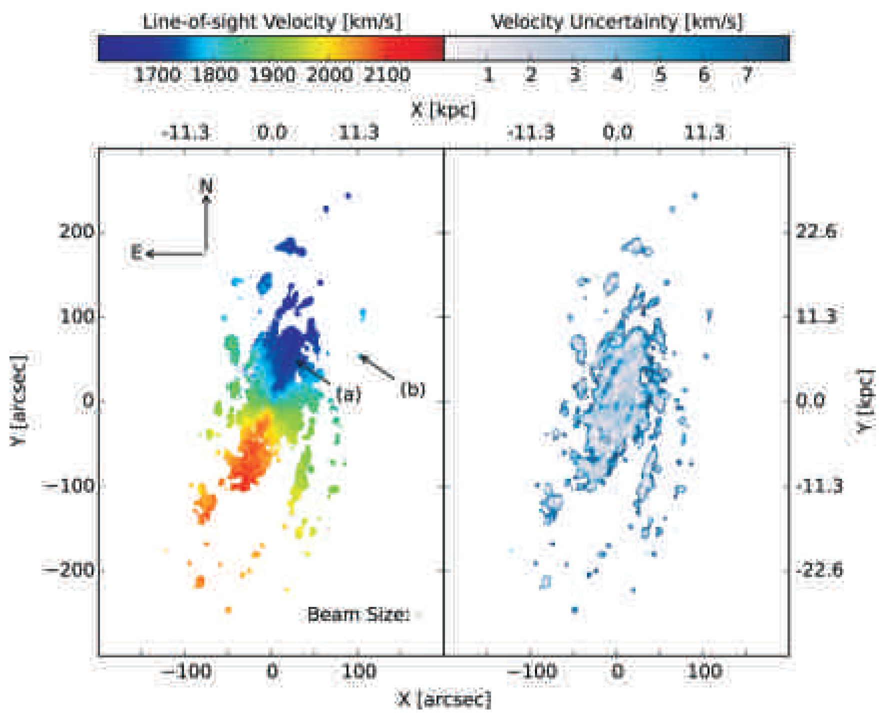


Fig 21: Maps of the velocity (left) and velocity uncertainties (right) produced from RSS FP H-alpha data for the RINGS galaxy NGC 2880 (Mitchell et al. 2015). Arrows indicate specific pixels with line detection signal-to-noise ratios of 50.2 (a) and 19.9 (b).

Spectrograph. The scientific goal of RINGS is to better constrain the dark and luminous matter distribution for comparison to cosmological models of structure formation.

Figure 21 shows the Hα velocity map (left) and uncertainties (right) for the RINGS galaxy NGC 2280. This map is at higher angular resolution than a complementary velocity map produced from radio H I observations. The better resolution of the RSS FP Hα velocity map allows for a more precise measurement of the inner slope of the rotation curve which in future papers will produce better constraints on the central mass distribution of the galaxy.

Ref: Mitchell, C., et al., 2015, AJ, 149, 3

Kinematics and stellar populations in isolated lenticular galaxies

Understanding processes of galaxy formation and evolution is the greatest challenge for modern extragalactic astrophysics. A huge variety of physical processes are involved in galaxy shaping, and it is a key problem to select the dominant agents driving evolution of galaxies of different morphological types.

Lenticular galaxies were introduced by Edwin Hubble when proposing his famous morphological scheme, the Hubble Tuning Fork, as a hypothetical intermediate type between ellipticals (to the left) and spirals (to the right). These S0s that he placed in the centre of the tuning fork diagram were to possess large-scale stellar disks (as found in spiral galaxies), but lack the HII-regions and spiral arms.

Lenticulars account for about 15% of the galaxy content of the nearby Universe, and some quite isolated lenticulars exist. What are the mechanisms of their formation? Can they be quite different from those acting in dense environments? This question has not even been considered.

A. Kniazev (SALT/SAAO) and collaborators reported on a study of a sample of isolated lenticular galaxies, where spectral data were obtained with SALT. They studied the stellar and gaseous kinematics, as well as radially resolved stellar population properties and ionized-gas metallicity and excitation for each galaxy in the sample. They found that there is no particular time frame of formation for the isolated lenticular galaxies: the mean stellar ages of the bulges and discs are distributed homogeneously between 1 and >13 Gyr. Furthermore, the bulge and the disk in every galaxy formed synchronously, as demonstrated by their similar stellar ages and magnesium-to-iron ratios. Extended ionized-gas disks are

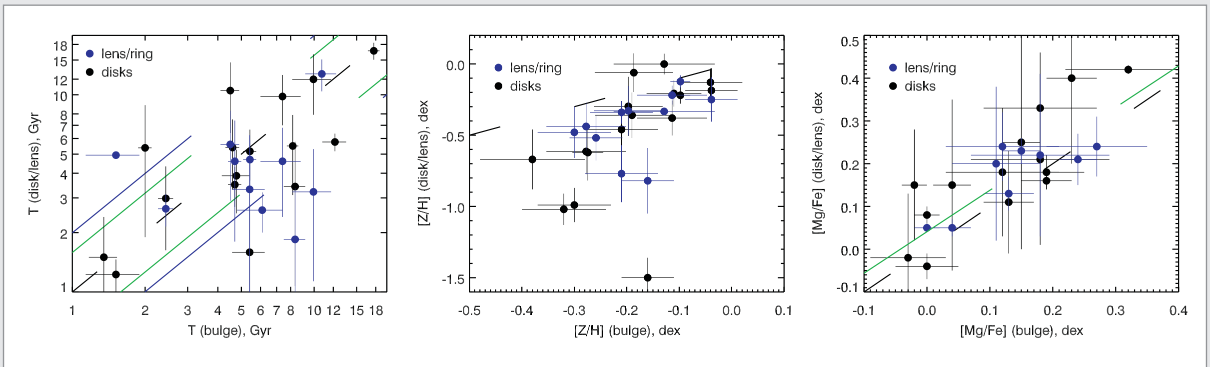


Fig 22: Comparison of the stellar populations in the bulges and in the disks: age-age diagram (left), metallicity-metallicity diagram (centre), and [Mg/Fe]-[Mg/Fe] (right). Green and blue dashed lines in the left panel correspond to deviation from bisector (dotted line) of value ±0.2 dex (by 1.5 times) and ±0.3 dex (by 2 times), respectively. Dotted lines show equality line. Green dashed line in the right panel shows linear fit of measurements

found in the majority of the isolated lenticular galaxies, in 72% ± 11%. They argued that all the gas in isolated lenticular galaxies is accreted from outside, (under the assumption of isotropically distributed external sources) and formulated a hypothesis that the morphological type of a field disk galaxy is completely determined by the outer cold-gas accretion regime.

Ref: Katkov, I. Y., et al., AJ, 150, 24.

Progressive redshifts in the late-time spectra of Type Ia supernovae

Late-time spectra of supernovae (SNe) Ia in the nebular phase (+70-100 days post-maximum brightness) are relatively uncommon. Building a stronger understanding of the late time features will hopefully lead to better insights into the nature of the nebular phase of SNe Ia. Christine Black and Robert Fesen (Dartmouth) used a large sample of late-time spectra of normal SNe Ia, including a spectrum of SN 2014lp obtained with the SALT RSS spectrograph, to show that several spectral features shift towards redder wavelengths as a SN Ia evolves (see Figure 23). SALT data of SN 2014lp also shows a few interesting spectral features at these later times that may be used as late-time spectroscopic identifiers for particularly slow declining, SN 1991T-like type Ia's.

Spectra of the Iax SN 2014dt have also been obtained with the RSS spectrograph. Iax SNe are a new rare subclass of Type Ia SN and as such, are still poorly understood. The spectra obtained here, in collaboration with the data collected by Saurabh Jha (Rutgers), will be used to further investigate the nature of these puzzling objects.

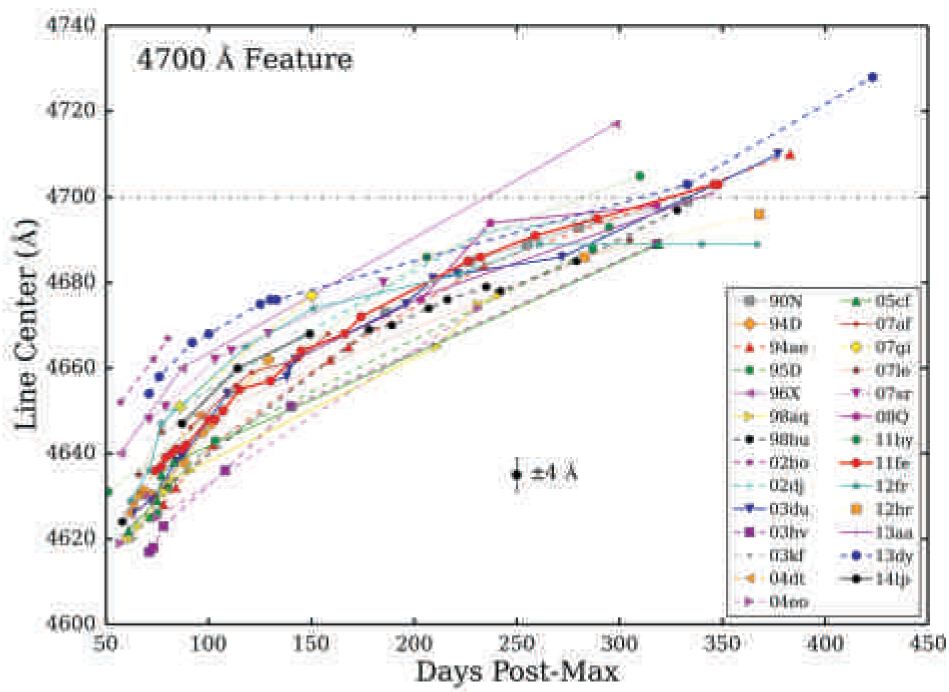


Fig 23: Central wavelength of the 4700 Å feature for all SN in this study versus days post-maximum light. This feature appears to follow the same evolution for all normal SNeIa. The horizontal black dot-dashed line marks 4700 Å.

Ref: Black, C. S., et al., 2016,MNRAS, 462, 659

ASASSN-15lh: A highly super-luminous supernova

SALT played a key role in the discovery and study of ASASSN-15lh, interpreted by Dong et al.as the most luminous supernova recorded. On 14 June 2015, ASASSN-15lh was discovered in a galaxy with unknown redshift by the All-Sky Automatic Survey for SuperNovae (ASAS-SN) using 14cm robotic telescopes stationed in Chile. The first spectrum of ASASSN-15lh showed a blue and mostly featureless continuum except for a broad absorption feature with a peculiar shape. Prof. Subo Dong (Peking University, China) and his colleagues found that if ASASSN-15lh were at redshift of 0.23 (see Figure 24), this spectral feature would be an exact match in shape and wavelength with an absorption line (attributed to OII) of a hydrogen-poor superluminous supernova SN 2010gx. A few days later, Prof. Saurabh Jha at Rutgers University (USA) used SALT to obtain a high quality spectrum and identified the Mg II absorption lines of the host galaxy exactly at the expected redshift of 0.23, confirming the prediction made by the superluminous supernova interpretation.

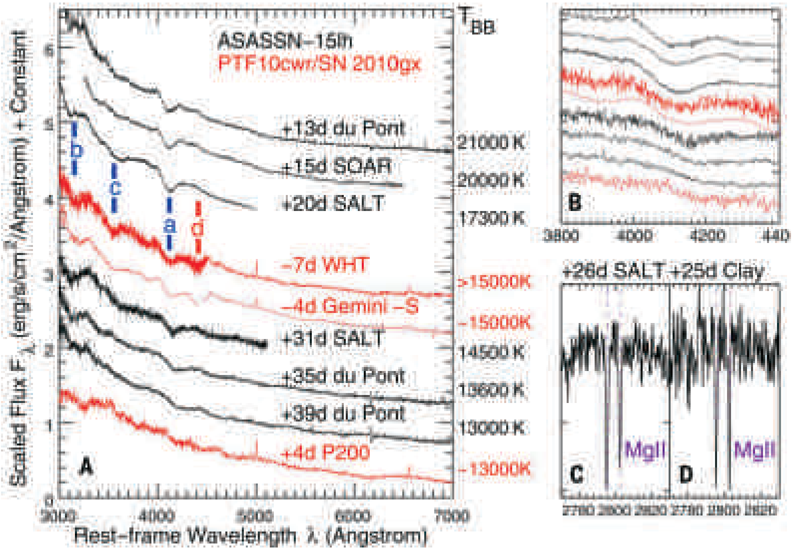


Fig 24: Rest frame spectra of ASASSN-15lh (black) compared with SLSN-1 PTF10cwr/SN 2010gx (red). (B) Close-ups of the 4100 features, whose evolution in shape ,depth, and velocity as a function of TBB is similar for both supernovae. (C and D) The ASASSN-15lh host redshift ($z = 0.2326$) is determined from the Mg II doublets seen in the SALT and Clay MagE spectra, with EW 0.55 ± 0.05 and 0.49 ± 0.05 in 1(C) and (D), respectively.

At a distance of 1.17 Gpc, ASASSN-15lh radiates at a whopping luminosity of 2.2×10^{45} erg s-1, which is about 200 times more powerful than a typical Type Ia supernova and more than twice as luminous as the previous record-holding supernova. Its high radiation energy exceeds the upper limit allowed by the popular magneta model and raises challenges to theoretical models for superluminous supernovae. This exceptional supernova has attracted a large number of follow-up works, both theoretical modeling to understand its mechanism as well as new observations using many space and ground-based telescopes covering wavelengths from X-ray, UV, optical to radio. UV observations by the Swift satellite revealed new surprises for ASASSN-15lh – 3 months after the discovery its UV emission started an unusual, 100-day-long re-brightening phase. Some astronomers (Leloudas et al. 2016, Nature Astronomy) proposed that ASASSN-15lh might be alternatively explained by a star disrupted by a supermassive black hole at the center of its host. However, using further follow-up data including those obtained by Swift and SALT, the ASAS-SN team concludes that the main observational properties of ASASSN-15lh are more consistent with that of a hydrogen-poor superluminous supernova.

Ref: Dong et al., 2016, Science, 351, 257; Godoy-Rivera, D., et al. 2017, MNRAS, 466, 1428

SCIENTIFIC MEETINGS

SALT Science Conference 2015

The SALT Foundation and SAAO were delighted with the success of the SALT Science Conference held in Stellenbosch from 1-5 June 2015. The programme was packed with talks, poster presentations, practical workshops and discussions showcasing SALT's capabilities. Over ninety astronomers and education professionals attended the conference representing over twenty nationalities. Delegates from international astronomical institutes from seven countries attended the conference to foster scientific collaborations and enhance partnerships with the South African astronomical community. Education and outreach professionals also contributed to the conference programme in recognition of the pivotal role that SALT has played in the advancement of astronomy and science education and in skills development within South Africa.

The event was formally opened by South Africa's Minister of Science and Technology, Naledi Pandor. Pandor's vision sees South Africa as a centre for research excellence in astronomy:

"Our aim is to position Africa as a global centre of research excellence for multi-wavelength astronomy, with optical, radio and gamma-ray telescopes working together to achieve common scientific goals."

The minister was keen to emphasise the importance of South Africa's experience in developing SALT in paving the way for South Africa's successful bid to host what will be the largest telescope ever built, the Square Kilometre Array (SKA) radio telescope, due to be completed in 2024:

"South Africa pursued the SKA project by using the lessons learnt from SALT as the basis for our planning and partnerships. The links we developed through the SALT project allowed us to build on existing networks and partnerships to secure the iconic SKA, an extremely important strategic initiative that puts science and technology to work for the benefit of all Africans."

As well as acknowledging the key role that SALT has played for science and technology development in South Africa, educators at the conference also stressed how the wonder and beauty of astronomy can be used to inspire and encourage young learners to pursue science and mathematics at school. Since its inception, the SALT project has placed a strong focus on education and public awareness programmes and Sivuyile Manxoyi, head of the SALT collateral benefits programme, summarised the work of the outreach department at the SAAO during his conference presentation:

"We have been very successful in training and supporting teachers and curriculum advisors in the teaching of Natural Science and particularly the theme 'Earth and Beyond'. Through programmes such as the national astronomy quiz we have succeeded in using astronomy to inspire curiosity and critical thinking among learners. Through our exciting job shadowing programme, we are spreading career information pertaining to astronomy and related science."

For the remainder of the conference the focus shifted to the practicalities of optimising the use of the telescope and showcasing the recent exciting and varied science conducted using SALT observations.

Dr Steve Crawford, SALT Science Data Manager pointed out:

"Since the start of science operations, SALT has been producing exciting science at a comparable rate to similar telescopes at the same stage in their operations, but at a fraction of the cost. This is a huge compliment to the SALT staff and the astronomers working with the observatory."

SALT operations staff also held several training workshops during the conference to help potential SALT users to apply for telescope time and to analyse SALT data products using software tools developed by the SALT team.

Scientific areas covered ranged from planetary science, to stellar astrophysics, to studies of galaxies and the distant universe. A large portion of the conference focused on the variable universe, a niche area for SALT as its instrumentation is tailored towards achieving high time resolution observations of varying and/or transient objects.

Dr Petri Vaisanen, Head of SALT Astronomy Operations commented:

"Listening to the talks at the conference from an operational point of view, it was extremely gratifying to see so many scientists, from students to professors, getting results from SALT. People are finding out exciting things about the Universe from analysis of the data we have been dishing out to them under the Sutherland night skies for years, it makes the work worthwhile."

Dr David Buckley, SALT Scientist and chair of the scientific organising committee for the conference added:

"SALT has really come of age. This is demonstrated by the breadth and quality of the science results presented. Over the past couple of years there has been a steady improvement in the efficiency and productivity and SALT's community of users have learned how to best exploit it to their advantage. This has resulted in a ramping up of science publications showing that SALT is beginning to make a significant contribution in forefront astronomy, partly due to some of the competitive advantages that it has."

Finally, the conference finished with considerations and prospects for future SALT science. Dr Marsha Wolf from the University of Wisconsin detailed the proposed extension of SALT's capabilities into the near-Infrared region of the electromagnetic spectrum. This will allow astronomers to observe even more distant objects than is presently possible with SALT due to light from distant galaxies being red-shifted into the near-Infrared by the expansion of the Universe. Extending into the near-Infrared will also allow observations of objects enshrouded by gas and dust, which visible light cannot penetrate.

Prof. Bruce Bassett, joint Professor at SAAO, UCT and AIMS in Cape Town introduced methods that he has developed employing computer algorithms to automate the classification of transient objects. The volume of data that astronomers will need to analyse will increase significantly once the SKA comes online and automating data analysis wherever possible will be crucial in order to fully exploit SALT and SKA in the future.

One of the key take home messages from the conference was the importance of using SALT together with other ground based and space based observatories such as the SKA radio telescope and the European Space Agency's Euclid satellite mission.

Dr David Buckley, commented:

"The meeting was well attended by SALT users, both within South Africa and abroad. Importantly many graduate students whose early careers are taking full advantage of SALT attended. The future for SALT looks assured, particularly with planned new developments and synergies with emerging facilities in South Africa and globally."

SALT Science Conference 2015 delegates at the Stellenbosch Institute for Advanced Studies

EDUCATION & PUBLIC OUTREACH

Southern African Large Telescope Collateral Benefits Programme (SCBP) activities

In an effort to fulfil its mandate, the SCBP unit has managed to reach 293 465 people in 2015/2016. This was completed through various activities, which include teacher training and development, school visits and learner workshops, competitions and quizzes, a job shadowing programme, public tours, public lectures and stargazing sessions. A total of 247 559 members of the public participated in our public programmes, 1823 teachers received training in Earth and Beyond related activities and 46 083 learners were reached through learner workshops and school visits.

Teacher Training

SCBP as a unit is committed to contributing to the improvement and development of teacher quality and classroom practice. The unit is collaborating with various provincial education departments throughout South Africa, including the Western Cape, Eastern Cape, Northern Cape, Mpumalanga, Limpopo and KwaZulu-Natal. The unit is also worked with the University of Cape Town's School of Education, the School Development Unit, Stellenbosch University, the Cape Peninsula University of Technology, Siyavula and the Primary Science Project in the training and development of teachers. A total of 1823 teachers were trained in the form of 2-7 day long teacher training workshops.

The workshops were based on pedagogical approaches and Earth and Beyond content which forms part of the South African Natural Science syllabus. Furthermore, the SCBP unit has conducted workshops on astronomy software and has been encouraging the teachers and learners to use the tools provided in exploring and understanding the Earth and Beyond content. In this vein, training workshops on Stellarium, World Wide Telescope and Aladdin have been completed and these were well received by all our audiences. Teachers have also been encouraged to utilise astronomy to provide context for teaching mathematics and science, and as a way to demonstrate the application and relevance of these subjects by establishing a connection to the "real" world.

Further teacher support has been in the form of team teaching with classroom based teachers and also assisting with conducting practical and laboratory experiments with the high school teachers and learners.

With Siyavula, a Mark Shuttleworth foundation supported organisation, SCBP managed to train all Natural Science subject advisers in the teaching of Earth and Beyond. It was our hope that the curriculum advisers would be able to support the teachers nationally. The SCBP-Siyavula workshops were held in Johannesburg, Durban and Cape Town.

Learner Activities

A total of 46 083 learners were reached through curricular, co-curricular and extra-curricular activities. These included: an astronomy quiz, an astronomy essay competition, science clubs and job shadowing. Learners were also reached through participation in science festivals, exhibitions, public stargazing sessions, learner workshops and school outreach activities.

Learner Workshops

The SCBP learner and school outreach still remains popular with the schools. Our learner workshops attract learner visitors to the Observatory, both in Cape Town and Sutherland. All of our workshops are based on the natural science school curriculum and include hands on activities, which learners can take home. This has a ripple effect as it encourages learners to engage in conversations with each other and also with their family members following these activities. All of our activities utilise simple, cheap and accessible materials, and all Tuesdays and Wednesdays are fully booked throughout the year.

Due to socio-economic challenges and large distances, some schools are unable to visit the Observatory and the SCBP staff strive to fulfil the learners and teacher wishes by visiting those schools. These school visits are linked to stargazing and the running of shows in an inflatable planetarium dome.

Astronomy Quiz

Since the introduction of the online version of the astronomy quiz for grade 7 learners, unprecedented numbers have been reached – 934 schools are currently participating in the quiz. In 2015, we introduced an Afrikaans version of the quiz after translating the questions into Afrikaans.

The online version of the quiz is cost effective and encourages participation of learners from rural and under-developed areas in the Northern Cape. The Sci Bono Science Centre (the largest science centre in South Africa) has requested using our online program to conduct the quiz in Gauteng in 2017.

Job Shadowing

We have hosted six sessions of job shadowing during the period under review. These reached 60 learners and involved astronomers, software developers, Information Technology staff, engineers, education and outreach personnel. Our job shadowing programme has been transformed from an exclusive astronomy focus into a more holistic programme that also highlights related careers and the roles they play in the field of astronomy. It is an intensive two day programme that takes learners through experiences of both observers and theorists, and provides exposure to the continuum of observations/data collection, analysis and interpretation. Suggestions have been made by Mr Chris Coetzee to include a visit to Sutherland and an experience of actual observation using research telescopes.

Science Clubs

The SCBP unit continues to encourage the establishment of science clubs across this country. In collaboration with the South African Agency of Science and Technology Advancement (SAASTA), two science clubs in Cape Town, at Thandokhulu and Luhlaza High Schools, are currently being supported closely. Ms Buzani Khumalo and Mr Sivuyile Manxoyi were invited to assist the Eastern Cape Education Department in the training of teachers and learners from 35 schools selected across that province in the establishment of Science Clubs.

Science Festivals

In collaboration with Square Kilometre Array (SKA) and Hartebeesthoek Radio Astronomy Observatory (HartRAO), the SCBP team has facilitated workshops and mounted an exhibition at the country's two major science festivals, SciFest and TechnoX. SCBP won the prize for the best exhibition at the 2015 TechnoX festival.

In an effort to popularise astronomy, SCBP continues to participate in provincial and regional science festivals such as the ones held in Limpopo and Kuruman.

Thousands of learners and members of the general public are reached through participation in these festivals. Audiences from outside the Western Cape and the Northern Cape also have the opportunity to personally interact with Observatory staff via these festivals.

Open Nights

A total of 46 open nights have been held in 2015 and 2016. The open nights include a public lecture, a tour of the Cape Town Museum and a stargazing session. 40 different astronomers from SAAO, UCT, UWC and SKA have given these lectures and the audience ranges from 60 to 140, depending on the title or topic of the lecture.

The historical McClean Telescope (built in 1897) remains the major attraction during the open nights. However, it is proving difficult to maintain this beautiful old telescope due to financial constraints.

We are considering holding a revolving open night outside of the Observatory, to allow township residents the experience of an astronomy talk and stargazing.

Sutherland Visitor centre and Community Development Centre

Visitor Centre

The Sutherland Tours remain extremely popular and the number of visitors is constantly increasing. In 2015 and 2016, we hosted 13 548 and 14 378 visitors at our Sutherland site. We have embarked on a vigorous marketing campaign to increase awareness of Sutherland as a tourist destination. Sutherland and our telescopes feature in the South African National Tourism video and we have also included Sutherland in all of the tourist marketing publications.

Our Photo Booth exhibit is also a hit with Social Media, particularly Facebook and Twitter. The booth generates a number of conversations and is also a source of attraction to Sutherland and our Visitor Centre in particular.

In 2016, we included SKA and MeerKAT based exhibits in a bid to promote a multi-wavelength astronomy experience. There is a need to develop new exhibits for our visitor centre, particularly exhibits based on the solar system and near Earth objects as these are closely related to the school curriculum.

Community development Centre

The community development centre continues to serve as a rallying point of development in the community of Sutherland. In 2015/16 we received a generous grant from the Department of Arts and Culture, to the tune of R500 000. This was used in conducting research into business opportunities based on culture and tourism in the community of Sutherland and the Karoo Hoogland region. The second phase has begun with the training of identified members of the community in business development and management. The last phase of the programme will be assisting the members of the community to develop successful businesses.

SALT partners

We would like to thank our SALT partners for all their enthusiastic assistance in the execution of education and outreach programmes.

Thanks to Göttingen University for their visits and collaboration in conducting outreach activities in Cape Town and in Sutherland. Going forward, our intention is to include mini research programmes for learners and teachers using the MONET telescope. Following discussions between the relevant parties, the plan is to implement this in 2017.

Thanks to Dartmouth College (Professor Brian Chaboyer in particular) for their contributions to education and outreach in Cape Town.

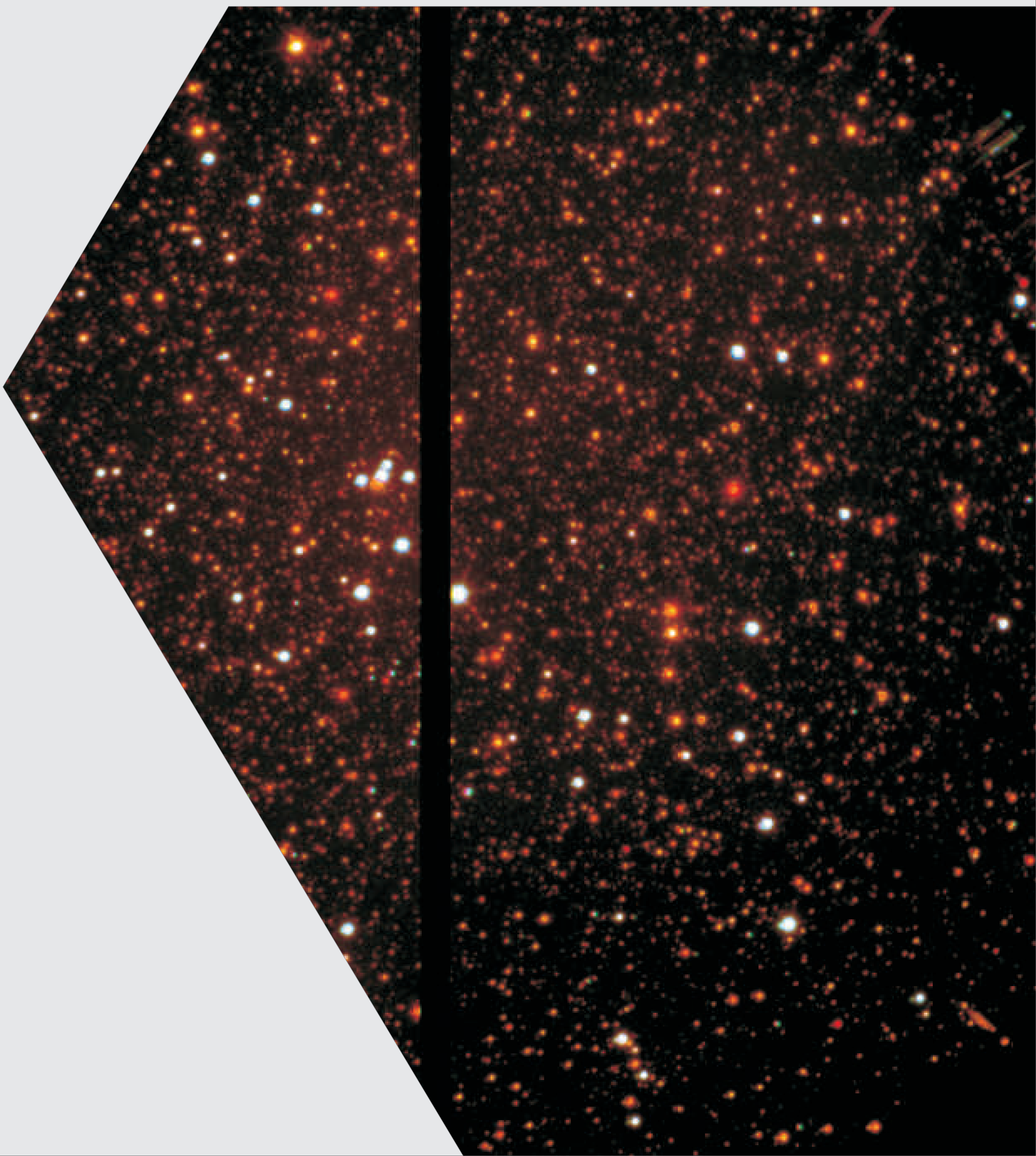
Thanks also to Professor Malcolm Coe of the University of Southampton for the student competition based on astronomy, and all his attempts to obtain an inflatable planetarium for SCBP. And to Professor Phil Charles, also of Southampton, for his continued support which is geared towards fundraising and education programme development.

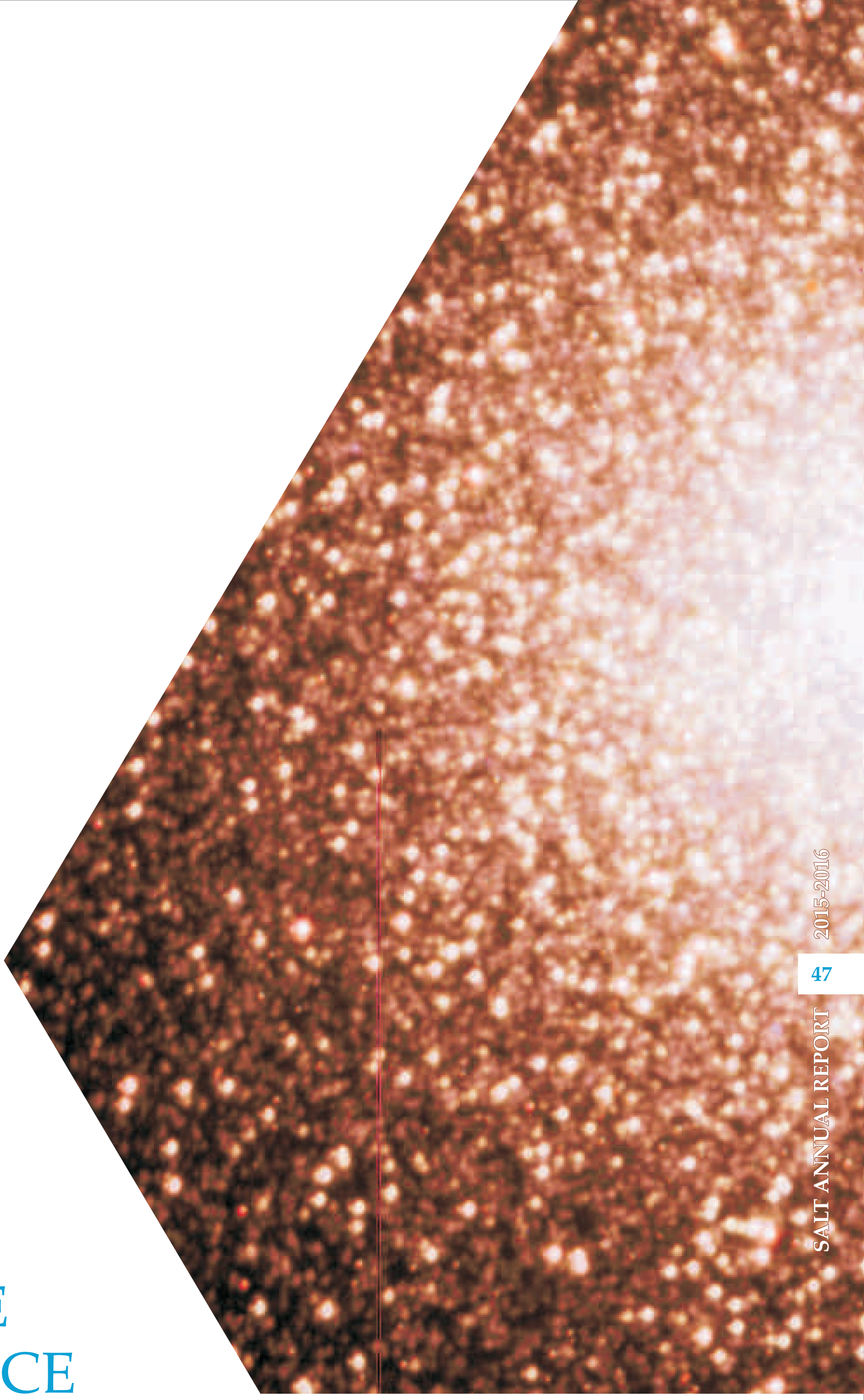
Thanks to Dr Samir Dhurde of IUCAA for his support on education and outreach resources and ideas.

Thanks to AMNH for all the resources in the form of shows for our science centres and planetarium. Thanks to Professors Ted Williams and Mike Shara for giving a talk to South African science communicators at SAASTA in Pretoria.

We would love to revive the teacher programme from Rutgers University, the teacher development programme with the University of Wisconsin and also the collaborations with the University of Central Lancashire.

Thanks to all our partners for all their support. Let's take astronomy to the people!





CORPORATE GOVERNANCE

The affairs of the SALT Foundation are regulated by the Shareholder's Agreement, signed at the formation of the Company.

In terms of this agreement, the Company is controlled by a Board of Directors comprising two members from the National Research Foundation and one member from all the remaining partner institutions. The Directors are elected at the Annual General Meeting of the Company and serve for a period of three years, following which they may be re-elected.

With the exception of Dr. Darragh O'Donoghue, all Board members are independent, Non-Executive Directors. In this reporting period, the Board comprised of the following members:

Prof. Michael Shara
(Chair) American Museum of Natural History

Prof. Brian Chaboyer
Dartmouth University

Prof. Gordon Ernest Bromage
(resigned 12/11/2015)
United Kingdom SALT Consortium

Prof. Phil Charles
(appointed 12/11/2015)
United Kingdom SALT Consortium

Prof. Chris Clemens
(resigned 9/11/2015)
University of North Carolina

Prof. Gerald Cecil
(appointed 9/11/2015)
University of North Carolina

Prof. John P. Hughes
Rutgers University

Prof. Ajit Kembhavi
(Resigned 9/11/2015)
Inter-University Centre for Astronomy & Astrophysics

Prof Somak Raychaudhury
(appointed 9/11/2015)
Inter-University Centre for Astronomy & Astrophysics

Prof. Wolfram Kollatschny
(resigned 9/11/2015)
Göttingen University

Dr. Darragh O'Donoghue
(passed away 25/6/2015)
National Research Foundation

Dr. Lisa Crause
(appointed 9/11/2015)
National Research Foundation

Prof. Marek Sarna
Nicolaus Copernicus Astronomical Centre

Prof. Nithaya Chetty
National Research Foundation

Other officers of the Company include **Mrs. Lizette Labuschagne** (Chief Financial Officer) who was also appointed as Company Secretary and Business Manager on 1/6/2015, when Mr Ismail Osman resigned.

The Board meets twice a year, usually in May and November. The SAAO Director and senior staff involved in the operations of the telescope also attend the Board meetings.

OPERATIONS CONTRACT

In terms of the Shareholder's Agreement, SALT is operated on behalf of the SALT Foundation by the SAAO and managed by the SAAO Director. With the exception of Mrs. Lizette Labuschagne, the staff who carry out the day-to-day operational activities are SAAO employees. Engineering operations are managed by the SALT Technical Operations Manager, Mr. Chris Coetzee, while Dr. Petri Vaisanen heads the Astronomy Operations..

The operations plan and budget are presented by the SAAO Director at the November Board meeting for the following financial year.

THE BOARD EXECUTIVE COMMITTEE

The Board has delegated authority to the Board Executive Committee (BEC) to manage the Company during the period between Board meetings. The BEC meets every 6 weeks and receives reports on the operations and development of the telescope from the SAAO Director and other senior staff with the relevant responsibility. The BEC comprises 4 Board members. In this reporting period, they were: Prof. Mike Shara (Chair), Prof. Brian Chaboyer, Dr. Darragh O'Donoghue and Prof. Eric Wilcots.

THE FINANCE AND AUDIT COMMITTEE

Although the full Board takes responsibility for the Annual Financial Statements of the Company, the Board has appointed a Finance and Audit Committee (FAC) to interrogate the management of the financial affairs of the Company at a detailed level. This committee meets at least twice a year, shortly before Board meetings, and presents a report at the Board meeting. In this reporting period, the members of the FAC were: Prof E. Wilcots (Chair), Prof M. Wybourne, Prof G. Bromage and Prof J. Hughes.

Technical Operations Team – 2015

Adelaide Malan

Anthony Koeslag

Chris Coetzee

Deneys Maartens

Denville Gibbons

Deon Bester

Eben Wiid

Etienne Simon

Grant Nelson

Hitesh Gajjar

Janus Brink

Johan Hendricks

John Menzies

Jonathan Love

Keith Browne

Martin Wilkinson

Nicolaas Jacobs

Ockert Strydom

Paul Rabe

Raoul van den Berg

Stephen Hulme

Thabelo Makananise

Timothy Fransman

Vic Moore

Willa de Water

Wouter Lochner*

Astronomy Operations Team – 2015

Alexei Kniazev

Anja Schroeder

Brent Miszalski

Christian Hettlage

David Buckley

Encarni Romero-Colmenero

Éric Depagne

Fred Marang

Luke Tyas

Paul Kotze

Petri Vaisanen

Steve Crawford

Thea Koen

Veronica van Wyk

Corporate Governance Team - 2015

Lizette Labuschagne

Surayda Moosa

Technical Operations Team – 2016

Adelaide Malan

Anthony Koeslag

Chris Coetzee

Deneys Maartens

Denville Gibbons

Deon Bester*

Eben Wiid

Etienne Simon

Hitesh Gajjar

Janus Brink

Johan Hendricks

John Menzies*

Jonathan Love

Keith Browne

Nicolaas Jacobs

Ockert Strydom

Paul Rabe

Raoul van den Berg*

Stephen Hulme

Thabelo Makananise

Timothy Fransman

Vic Moore*

Willa de Water

Wouter Lochner*

Astronomy Operations Team – 2016

Alexei Kniazev

Anja Schroeder

Brent Miszalski

Christian Hettlage

Encarni Romero-Colmenero

Éric Depagne

Fred Marang

Marissa Kotze

Nhlavutelo Macebele

Paul Kotze

Petri Vaisanen

Rosalind Skelton

Rudi Kuhn

Steve Crawford

Thea Koen

Veronica van Wyk

Corporate Governance Team - 2016

Lizette Labuschagne

Surayda Moosa

* part-time

LIST OF PUBLICATIONS

SALT Refereed publications – 2015

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