S·A·L·T

SOUTHERN **A**FRICAN **L**ARGE **T**ELESCOPE

AFRICA'S GIANT EYE

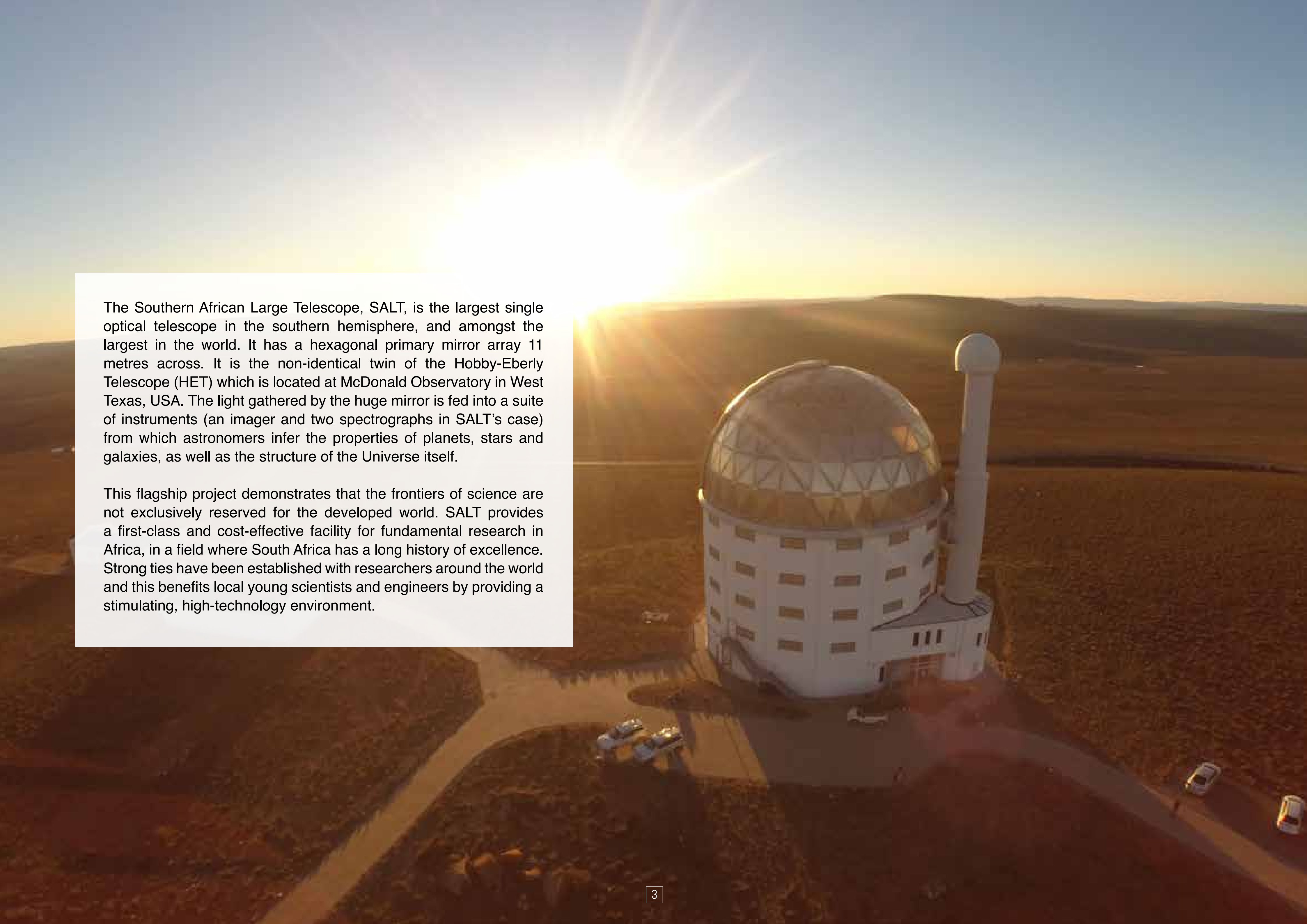
EXPLORES THE UNIVERSE

SALT SCIENCE

SALT'S MISSION

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

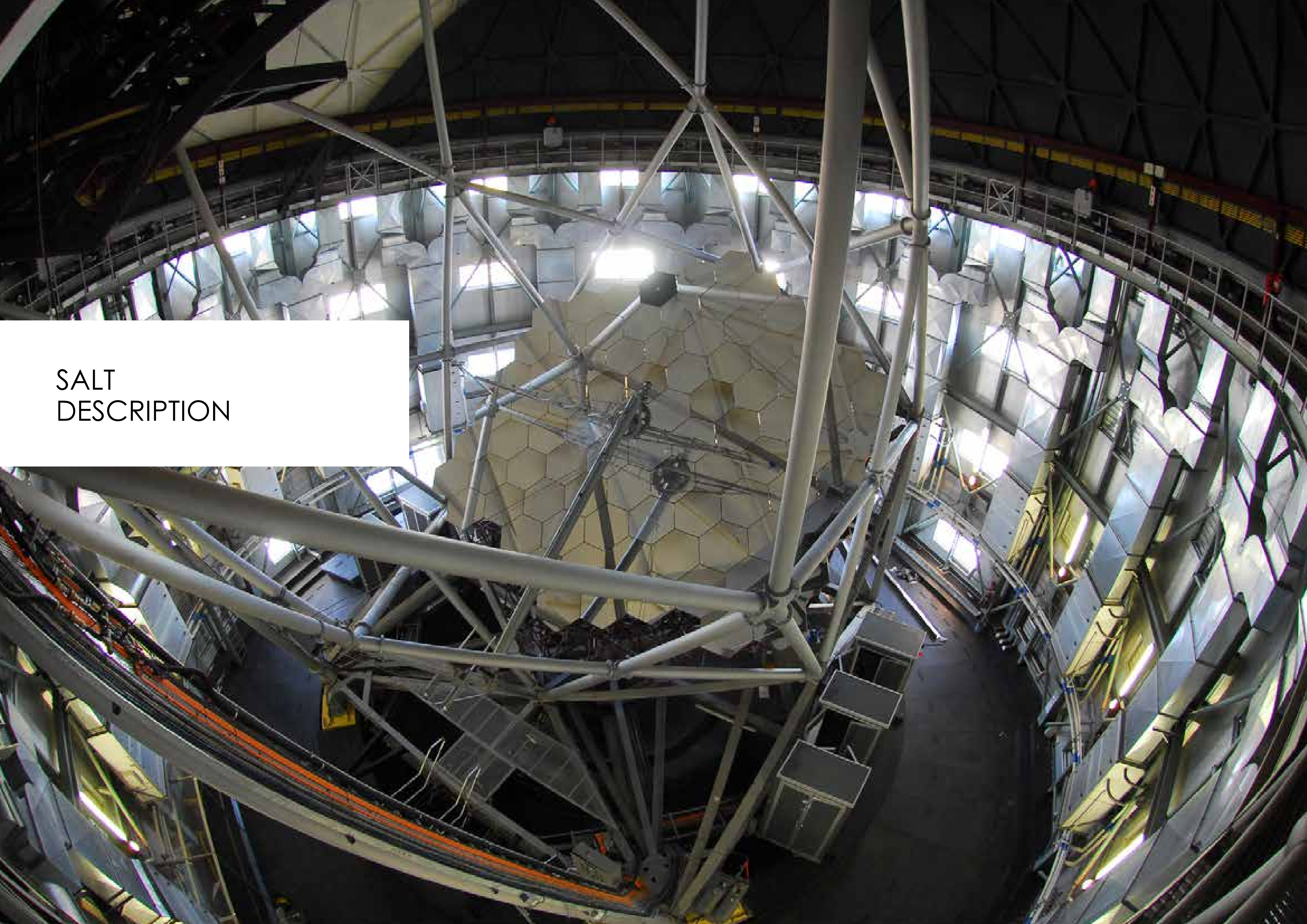
Provide a world-class large telescope research facility cost-effectively to astronomers in an international community.



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 metres across. It is the non-identical twin of the Hobby-Eberly Telescope (HET) which is located at McDonald Observatory in West Texas, USA. The light gathered by the huge mirror is fed into a suite of instruments (an imager and two spectrographs in SALT's case) from which astronomers infer the properties of planets, stars and galaxies, as well as the structure of the Universe itself.

This flagship project demonstrates that the frontiers of science are not exclusively reserved for the developed world. SALT provides a first-class and cost-effective facility for fundamental research in Africa, in a field where South Africa has a long history of excellence. Strong ties have been established with researchers around the world and this benefits local young scientists and engineers by providing a stimulating, high-technology environment.

SALT DESCRIPTION



SALT'S TECHNOLOGY

SALT has a hexagonal primary mirror array measuring 11 x 9 metres, consisting of 91 individual 1-metre hexagonal mirrors. Older telescopes typically employed the "equatorial" mounting scheme that made it easy to track a star in the sky. However, today's larger optical telescopes are are more often of the "alt-az" variety, in which the telescope simultaneously rotates in azimuth and tilts in elevation to follow celestial objects as the Earth's rotation carries them across the sky. Like its older twin, the Hobby-Eberly Telescope (HET), SALT has the additional simplification of a fixed elevation angle (37 degrees from the vertical, compared to 35 degrees for the HET) and is only rotated in azimuth when acquiring a target. The telescope structure remains stationary during the course of an observation and a tracker assembly at the top of the telescope follows the image of the target as it moves along the focal surface of the spherical primary mirror. This greatly simplifies the mechanical design of the telescope structure and therefore significantly reduces the cost. The complexity resides in the prime-focus tracker assembly that carries the secondary optics and instruments, constantly making incredibly small, and precise, movements during the course of an observation.

The SALT Array Management System (SAMS) comprises a set of inductive edge-sensors mounted on the backs of the mirror segments. This system is designed to maintain the overall shape of the SALT mirror array once all the mirrors have been aligned to an ideal spherical surface. The edge-sensor transmitter-receiver pairs provide feedback for closed-loop control of the segment attitudes, compensating for the underlying steel truss expanding and contracting differentially due to thermal variations. SALT previously required several mirror alignments per night, but SAMS now maintains an optimal array for a week or more, saving a considerable amount of observing time and significantly improving the delivered image-quality of the telescope.

SALT is operated as a queue-scheduled telescope: there is a dedicated group of eight SALT Astronomers that observe the targets for scientists all over the world. On any given night, the observations are selected according to the current weather conditions and the specific requirements/constraints imposed by the scientists. A SALT data pipeline reduces the data immediately, and they are electronically sent to the scientist's home institution within 24 hours of the observation being made.

The queue-scheduled mode of operation allows extremely rapid response to targets of opportunity (typically within a matter of hours). This, together with the fact that the full suite of instruments is available at all times, allows observers to quickly switch between observing modes, depending on the specific science requirements. This capability makes SALT a powerful instrument for transient follow-up work, as was demonstrated with the first multi-messenger event, GrW170817.

...SAMS now maintains an optimal array for a week or more, saving a considerable amount of observing time and significantly improving the delivered image-quality of the telescope.

SALT control room

SALT LOCATION

SALT is located alongside the telescopes of the South African Astronomical Observatory (SAAO) in the Karoo semi-desert, 20 km from the small town of Sutherland and about 370 km north-east of Cape Town. The observing site is 1783 m above sea level. Being far from city lights and pollution, it is one of the darkest observatory locations in the world. It is ideally placed in longitude between the other large optical observatories of the southern hemisphere (in Chile and Australia) to allow continuous coverage for time-critical observations.

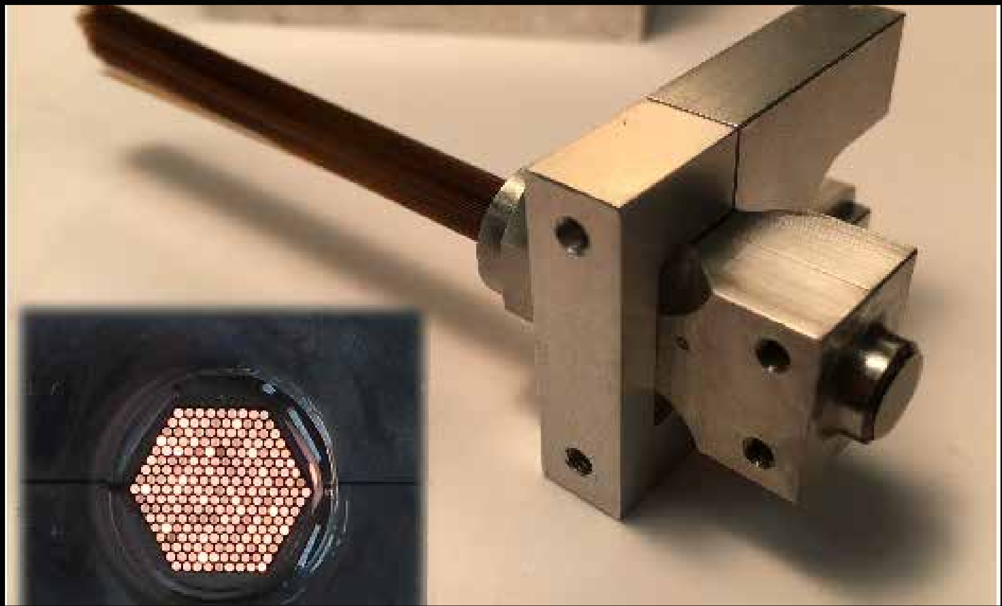
SALT INSTRUMENTATION

SALTICAM serves as the acquisition and imaging camera for the telescope with a science field-of-view of 8 arcminutes. It operates from 320 to 950 nm and also offers high-speed observing modes.

The low- to medium-resolution Robert-Stobie Spectrograph (RSS) offers long-slit and multi-object capabilities, along with various (linear and circular) polarimetric imaging and spectroscopic modes, Fabry-Pérot (FP) imaging-spectroscopy and narrow-band imaging options. The spectrograph operates from 320 to 900 nm and also includes high-speed options for the different modes.

The fibre-fed High-Resolution Spectrograph (HRS) permits high-resolution single-object spectroscopy from 370 to 890 nm, divided into blue and red channels with a cross-over wavelength of 555 nm. The Low-, Medium- and High-Resolution modes yield resolving powers of 15, 40 and 65 thousand, while the High-Stability mode (also with R = 65,000) for precision radial velocity calibration offers the choice of an Iodine Cell or simultaneous Thorium-Argon injection for exoplanet science.

SALT INSTRUMENTATION
COMING SOON



A laboratory prototype IFU head constructed using a MaNGA-style hexagonal ferrule. – Credit: University of Wisconsin-Madison

SALT's science focus areas call for complementary new SALT instruments and software development in the short- and medium-term:

The NIR spectrograph (due in 2020) will extend the wavelength range of the telescope into the near-infrared (out to 1.7 microns).

The HRS High-Stability mode is being optimised for exoplanet science, with new pipelines and enhanced calibration facilities being developed.

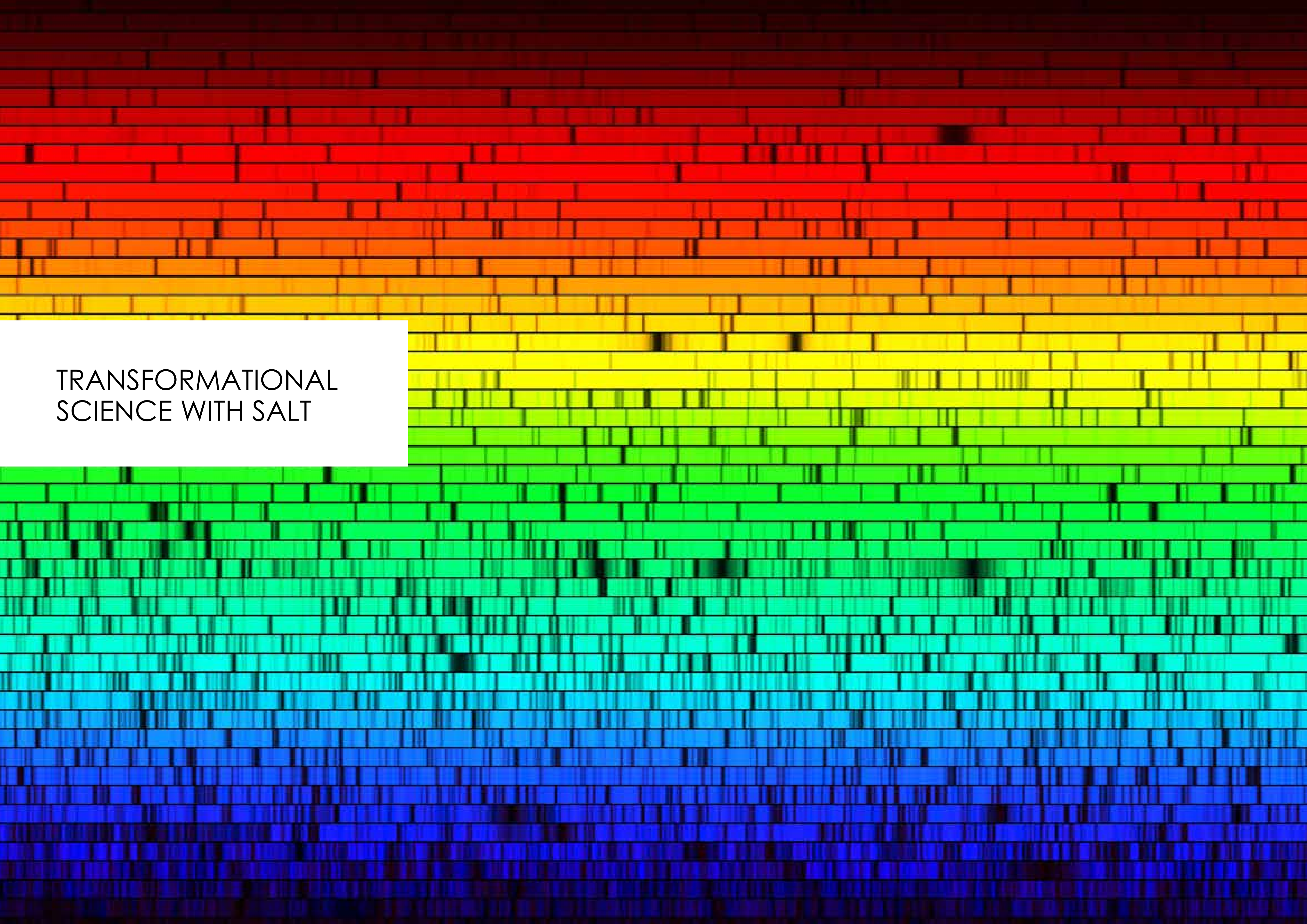
MaxE (Maximum Efficiency Spectrograph), an extremely efficient single-object spectrograph, will serve the transient science domain. As a 1.5-generation SALT instrument, MaxE development is being fast-tracked in order to overlap with MeerKAT and to capitalise on the enormous scientific potential associated with local multi-wavelength synergies. Assembly is due to start in 2020.

MaxE as a transient spectrograph has to be ready to receive automatic triggers from a number of sources and to be intelligently combined with other Sutherland-based telescopes and instruments. The first part of this project will concentrate on linking the SAAO telescopes with SALT through versatile remote and/or robotic operations, while the longer term goal involves an innovative and powerful "Sutherland Intelligent Plateau" concept.

For the 1.5-generation package, significant software engineering development will enhance SALT's capabilities in the fields of time-domain/transient science and exoplanets.

A large-area integral field unit (IFU) spectrograph is envisioned as a 2nd-generation instrument, to enable spatially-resolved spectroscopy over a field-of-view competitive with similar instruments at other major observatories.

TRANSFORMATIONAL SCIENCE WITH SALT



SALT'S FORTÉ

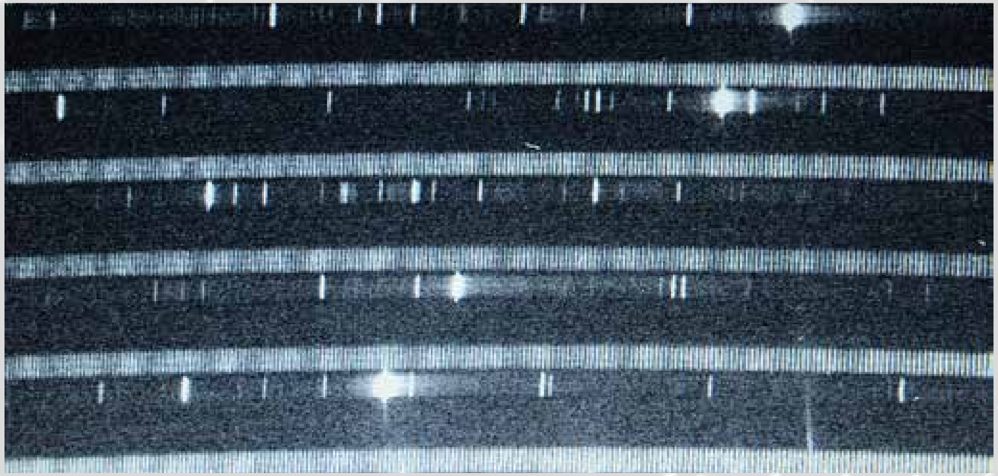
SALT is, first and foremost, a spectroscopic telescope. Due to its operating mode and design, it is most efficient when employed as a survey telescope, with a wide range of targets available in the observing queue.

The telescope's large collecting area and Sutherland's dark skies mean that highly competitive results can be obtained for diffuse, low surface brightness objects.

Brighter targets – where most of the light is above the sky background, regardless of the seeing – can be observed very efficiently.

There are several spectroscopic options available, including multi-object and Fabry-Pérot capabilities, as well as polarimetric modes, some of which are rare on large telescopes.

Operationally, SALT is capable of rapidly changing modes and instruments on-the-fly, and can respond to sudden events and requests (e.g., targets of opportunity) during the course of a night.



SALT SYNERGIES

SALT's strengths in rapid follow-up, its wide variety of spectroscopic instruments and its proficiency in observing small, diffuse objects are sought-after characteristics for an observatory.

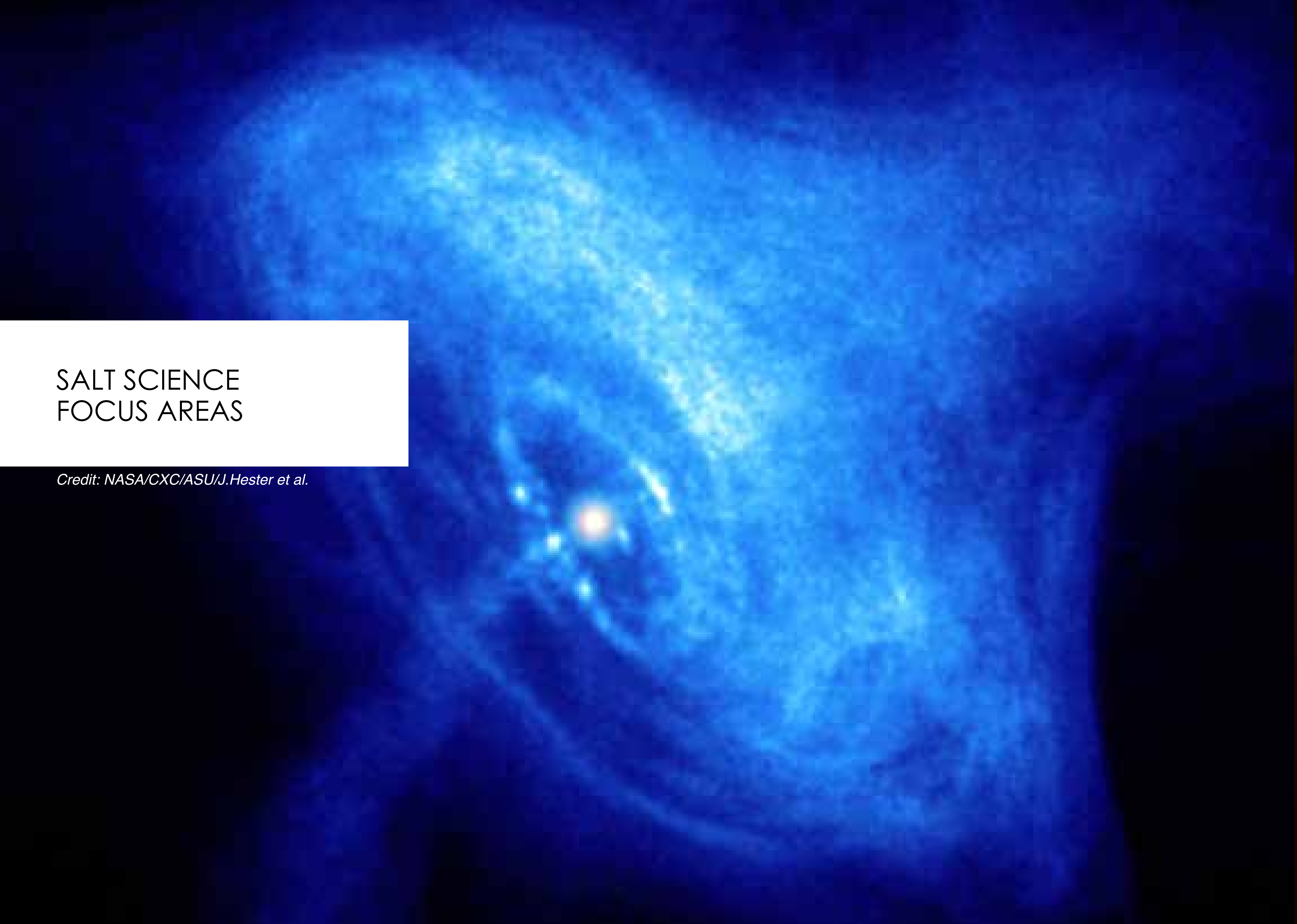
As a world-leading radio-transient follow-up machine, SALT will capitalise on MeerLICHT and MeerKAT synergies.

Cutting-edge science projects are due to start with the upcoming LSST and SKA telescopes.

SALT will participate in multi-wavelength surveys together with MeerKAT programs in all the science focus fields.

SALT could become a key player in southern-hemisphere exoplanet work by establishing precision radial velocity capability with the HRS and providing follow-up observations for TESS and other Exoplanet space missions.

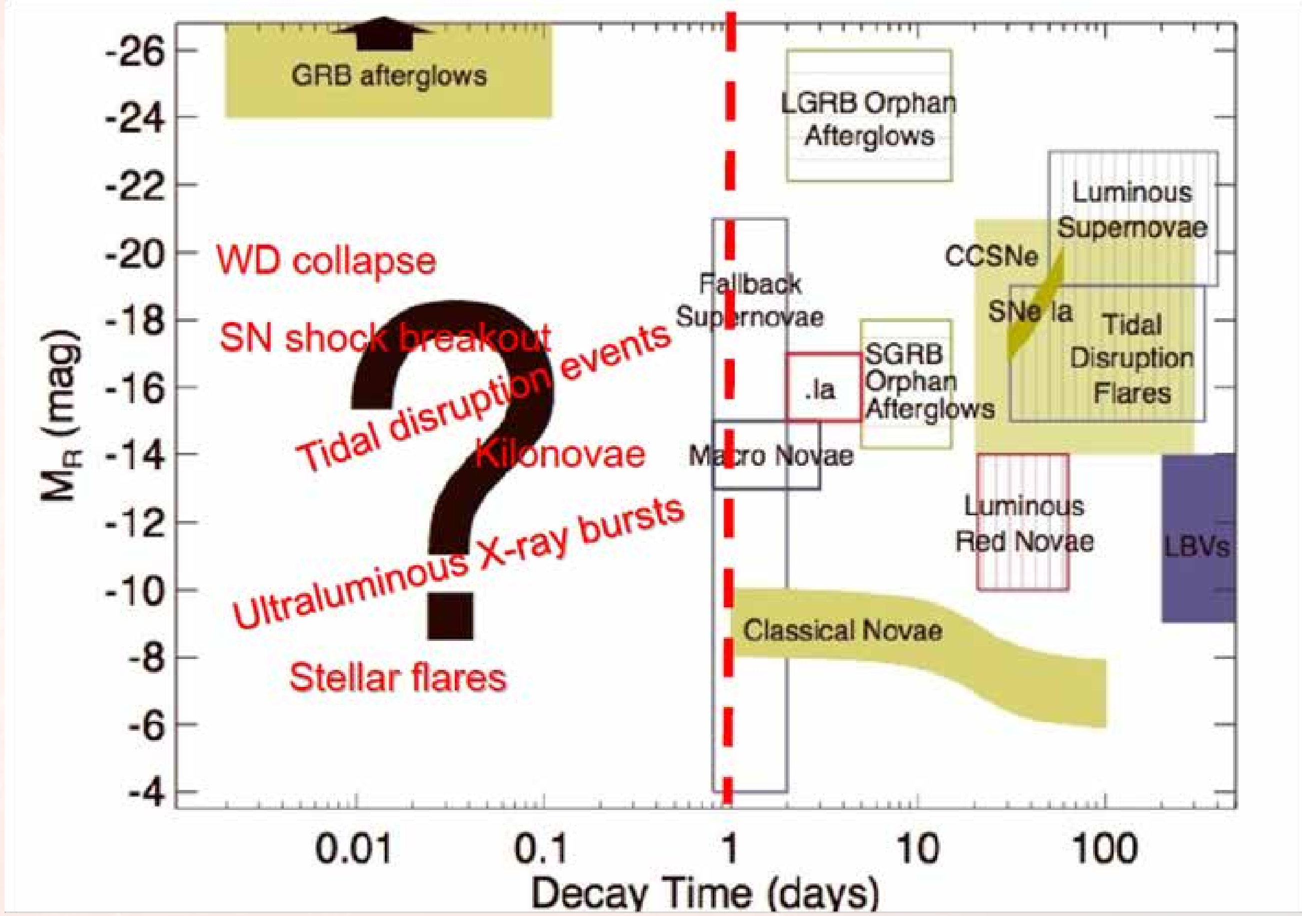
SALT SCIENCE FOCUS AREAS



Credit: NASA/CXC/ASU/J.Hester et al.

TRANSIENT AND TIME-DOMAIN ASTROPHYSICS

The SALT community has a firmly established interest in this area. Extremely energetic events can probe the laws of physics under conditions that cannot be reproduced in a laboratory or particle accelerator on Earth. There are many known source classes of such events and objects. Some of these classes are rare and still inherently enigmatic and thus need rapid follow-up to establish their nature. SALT can play a key role in finding, following-up, and characterising the transients themselves, or the hosts thereof. Surveys and projects feeding SALT are expected to come from many wavelengths and many observatories, including space-based observatories (at X-ray and gamma-ray wavelengths). The new instruments and the planned "Sutherland Intelligent Plateau" will increase SALT's output enormously and make SALT one of the key players in transient science, particularly in light of the increased detection rate facilitated by the upcoming global large-area observatories like LSST and SKA. Due to its rapid response capability, SALT can catch explosive events in their crucial early phases where data is notoriously sparse. SALT's rapid spectroscopic follow-up of the recent LIGO gravitational wave event, which resulted in one of the earliest spectra, is a high-impact example of such a successful observation.



Zwicky diagram: The brightness (optical) of the transient source is plotted versus the time it takes for the transient source to fade away. – Credit: David Buckley

1 CATACLYSMIC VARIABLES

Double degenerate cataclysmic variable stars (CVs), the AM CVns, are arguably the favoured pathway for supernova Type Ia (SN Ia) progenitors and a more detailed understanding of existing systems, as well as the identification of new systems, will be crucial for testing this hypothesis. These rare, low-luminosity objects are usually discovered during their infrequent high-amplitude outbursts as optical transients. To advance our understanding of fainter CVs with the lowest luminosities and the shortest orbital periods (the CV "graveyard", where they reside as a result of gravitational radiation-induced angular momentum loss), a significant sample of such objects is needed with well-determined spectral and photometric properties, rather than the mere handful currently known. Most known CVs, though, are high-luminosity systems (in quiescence). Among these objects are the so-called period bouncers which evolve to longer orbital periods. Follow-up SALT spectroscopy, combined with photometric monitoring programs with LCOGT, MONET-South and Lesedi, is crucial for the study of these typically faint ($V \sim 20^m$) objects. These relatively nearby systems are also expected to be an important class of persistent low frequency gravitational waves, detectable in the coming decades with space-based laser interferometry missions.

Artist's impression of the recurrent nova RS Oph – Credit: David Hardy/PPARC

2 ERUPTIVE TRANSIENTS

This transient class comprises novae, recurrent novae, luminous red novae, symbiotic novae and supernovae.

Early spectroscopic follow-up is vital to understand the mechanism of mass ejection and dust production in novae.

Artist's impression of a supernova: The white area is the explosion, orange depicts gasses and yellow the collision of fragments of the star, heating the gas rapidly. – Credit: supernovae.net

Recurrent novae with evolved secondaries are considered promising candidates for SN Ia progenitors. Luminous red novae and other "gap" transients (with luminosities between supernovae and ordinary novae) are rare, but LSST and the SPIRITS survey (a systematic NIR search by Spitzer) will find vast numbers of such objects. Though only a handful will typically be visible at optical wavelengths, critical diagnostics can be obtained from these which will greatly improve our understanding of this class. The existing suite of SALT instruments, particularly the HRS, is well suited to such observations and to continuously monitor these outbursts from discovery to decline. Significant insights into novae have already been achieved with SALT, particularly with the discovery and study of the fastest and most luminous yet detected, which appears to be in the Small Magellanic Cloud.

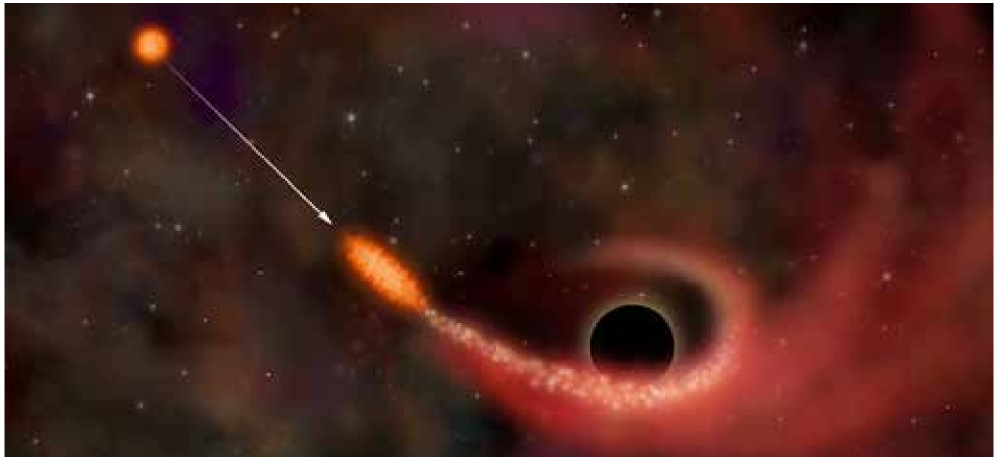
3 X-RAY TRANSIENTS

X-ray transients (XRTs) include low- and high-mass X-ray binaries (LMXBs and HMXBs) and black hole (BH) binaries. They all have rather different properties, but all benefit from optical observations obtained during the outburst cycle, which can last from days to months. Accreting millisecond X-ray pulsars (AMXPs) can constrain the equation of state of super-dense matter and are the "missing link" in the evolutionary sequence from X-ray binaries to millisecond radio pulsars. Thus far they have only been detected as XRTs. Two such systems have been observed by SALT, with supporting multi-wavelength observations

Low-resolution spectroscopy of XRTs can be used to both classify the type of object and characterise the nature of the accretion processes. Combined with other, multi-wavelength observations, spectral energy distributions can be determined and the evolution of the outburst monitored, but only if the observations are quasi-simultaneous. This requires coordination of different facilities, both ground- and space-based. The long-term SALT transient program has already observed a number of systems during their outburst cycle and has ably demonstrated that this type of synoptic monitoring, contemporaneous with observations at other wavelengths, is a compelling capability.

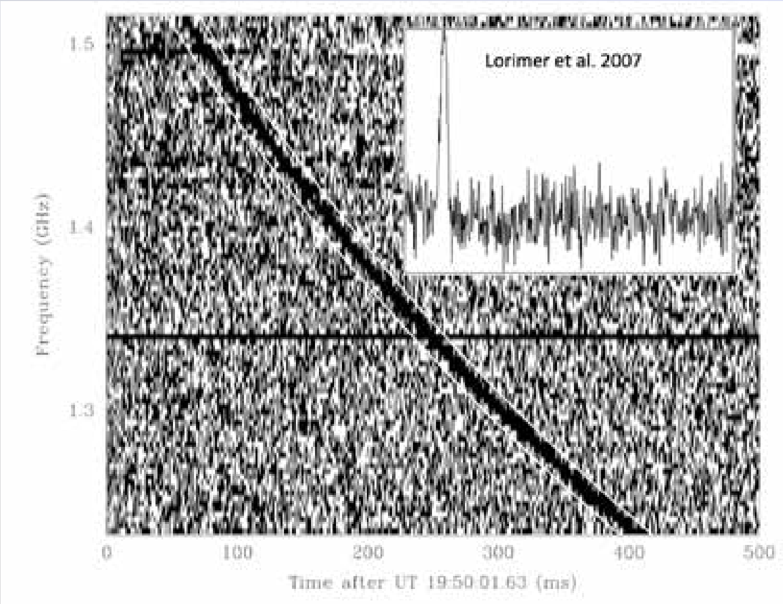
SALT's ability to undertake high time resolution observations (sub-second), often a rare feature of large telescopes, has allowed studies of fast variability and the discovery of low frequency optical quasi-periodic oscillations (QPOs) in some newly identified XRTs.

4 GAIA AND OGLE TRANSIENTS



Both the OGLE and the Gaia surveys provide candidates for long-lasting BH microlensing events as well as Tidal Disruption Events (TDEs), which are flares resulting from the total or partial disruption of a star orbiting close to a central BH. Detection of single BHs from microlensing events is crucial for understanding late phases of stellar evolution, the dynamics of the Galaxy and dark matter distribution. Confirmation of a BH lens in a microlensing event is very difficult due to numerous degeneracies in the microlensing model. TDEs, on the other hand, offer a unique opportunity to study the low-mass end of the stellar mass BH distribution. Spectroscopic follow-up observations with SALT will help to determine source distances to constrain the mass of a lens and to understand its nature. The first spectropolarimetric observations of a TDE was recently undertaken with SALT as part of the transients programme.

Left: *Artist's impression of a stellar mass black hole accreting material from its large companion star and producing powerful jets. – Credit: M.Weiss/NASA/CXC*
Above: *Artist's illustration of a tidal disruption event: a star on an orbit taking it close to a supermassive black hole will be torn apart by tidal forces. – Credit: NASA/CXC/M.Weiss*



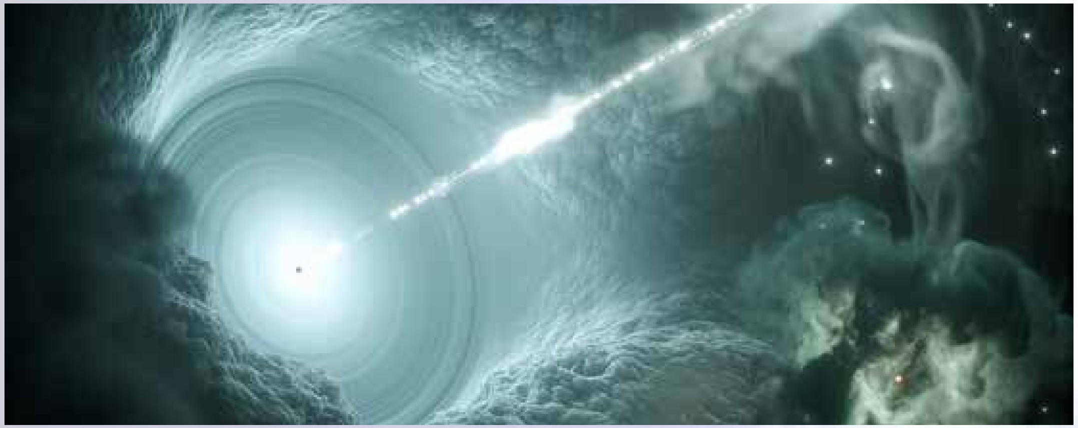
5 RADIO TRANSIENTS

The MeerKAT large survey for radio transients, ThunderKAT, will find transients on a range of timescales from seconds to days, from fast radio bursts, dwarf nova outbursts, XRBs, and TDEs, all of which require spectroscopic characterisation by SALT. To assist with optical counterpart identification, the MeerLICHT optical telescope will simultaneously cover the entire MeerKAT field-of-view for every observation conducted. Apart from the potential to observe optical counterparts of radio transients, it is also expected to discover optical transients (e.g., CVs, intra-day variables, novae) in its own right. The new discovery space, which the combined radio-optical observations of transients will enable, cannot be overstated. Apart from SALT helping to shed light on the nature of known objects, like the enigmatic fast radio bursts (FRBs) and rotating radio transients (RRATs), the very real possibility exists for the discovery of new phenomena and classes of transients.

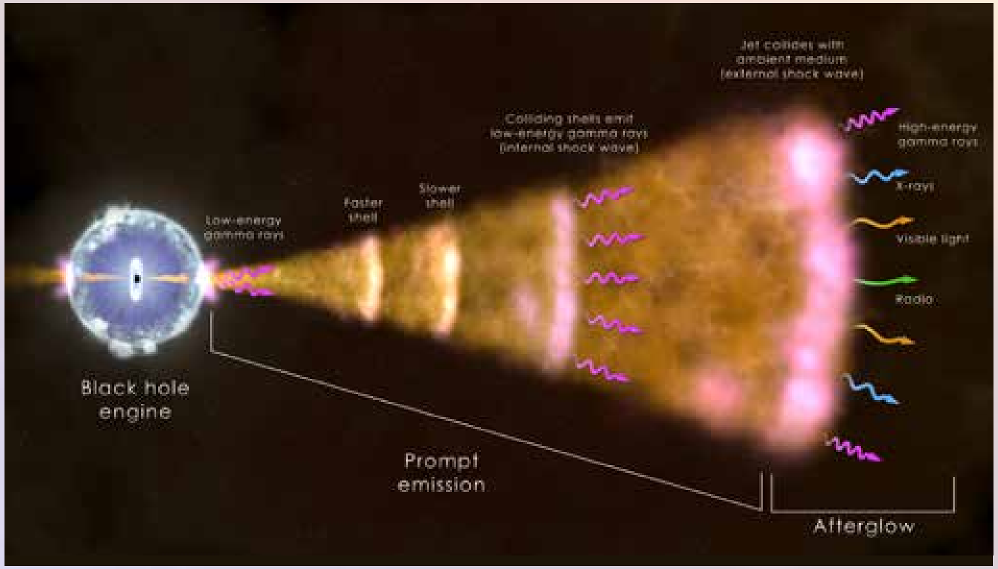
'Waterfall plot' of the famous Lorimer burst showing the characteristic dispersion sweep expected from pulses of radio emission that have travelled cosmological distances. The inset shows the pulse after adding all of the frequency channels and correcting for the sweep. – Credit: Lorimer+ 2007

6 FLARING BLAZARS

Understanding radiation mechanisms of blazars requires simultaneous multi-wavelength observations (radio, IR, optical, UV, X-ray, γ-ray) of their flares. Correlated multiband variability (sometimes associated with changes of polarimetric properties), when compared to detailed radiation modeling, is key to identifying the particle acceleration, radiation mechanisms and physical conditions in the jet. SALT spectra are used to detect spectral features from which redshifts and luminosities of spectral lines and of the continuum are determined, resulting in the characterisation of the flaring state. Spectropolarimetry probes the role of magnetic fields in the particle acceleration and radiation processes. The typically higher degree of linear polarisation detected during a flare event is indicative of synchrotron radiation in a rather highly ordered magnetic field. In addition, the observed decline of the degree of polarisation towards shorter wavelengths may be a result of an unpolarised component from the accretion disc. Observations of the changing angle of the linear polarisation over time can directly lead to knowledge of the geometry of evolving jets in blazars.



*Artist's impression of a blazar: The supermassive black hole at the centre of the accretion disc and dusty torus sends a narrow high-energy jet of matter towards the observer.
– Credit: DESY, Science Communication Lab*



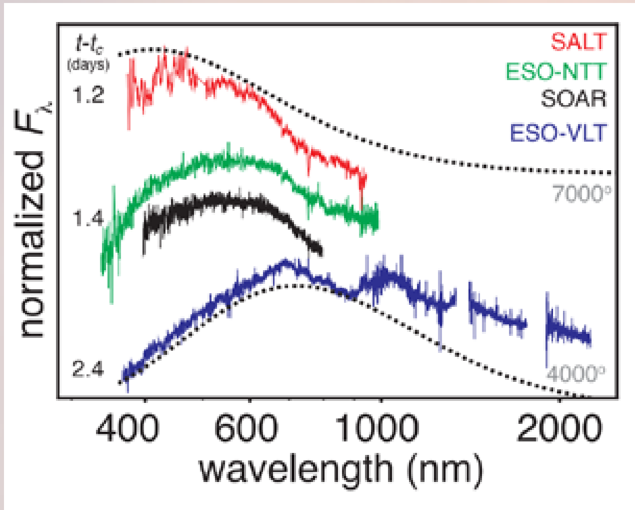
A dying massive star forms a black hole which drives a particle jet into space, resulting in a long gamma-ray burst. Light emission across the full spectrum comes from hot gas near the black hole, from collisions within the jet and from the jet's interaction with its surroundings. – Credit: NASA

7 GAMMA-RAY BURSTS

The prospects to observe gamma-ray bursts (GRBs) with SALT have improved significantly with the advent of the local MASTER-SAAO and Watcher-Boyden facilities. Both play a role in the prompt detection of optical afterglows, e.g., MASTER-SAAO detected polarised emission in the prompt emission from GRB 150301, which has been important in probing the physics of the GRB explosion. SALT spectroscopy can help to build multi-wavelength spectral energy distributions which are used to determine the GRB energy and to test the fireball models. SALT's follow-up redshift measurements of very high energy (>100 GeV) gamma-ray triggers from HESS can be used to constrain the GRB model parameters and probe the extragalactic background light, as well as the Lorentz Invariance Violation.

8 MULTI-MESSENGER TRANSIENTS

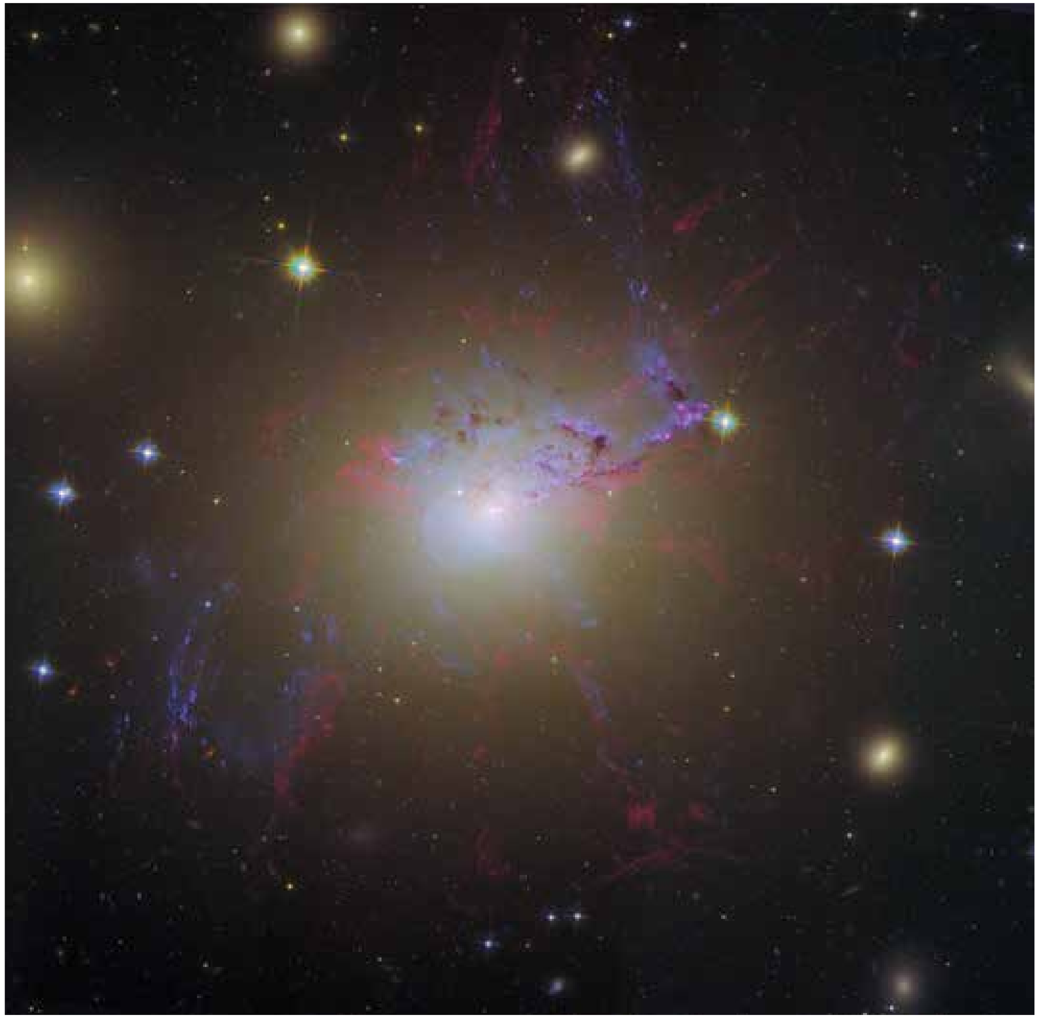
The age of gravitational wave astronomy has dawned with the first confirmed event (GrW150914) from merging black holes, followed by the success in detecting electromagnetic counterparts from a neutron star merger (GrW170817). The detection and study of electromagnetic counterparts of gravitational wave sources will be a major new area of investigation in the coming years. With the improvement in source location by survey telescopes, coupled with South Africa's ability to undertake multi-wavelength transient detection and follow-up observations with local facilities like SALT, HESS and MeerKAT, among others, South African researchers will not only participate, but potentially lead in this emerging new field of exploration. Similar arguments hold for the development of neutrino astronomy, with the establishment of global facilities like IceCube and KM3Net. In 2017, SALT observed the first confirmed optical counterpart of an IceCube neutrino detection (IC170922A), namely the bright blazar TXS 0506+056.



Four early spectra of GrW170817, taken with SALT (red), ESO-NTT (green), the SOAR 4-m telescope (black) and ESO-VLT-XShooter (blue). – Credit: Abbott+ 2017

TRACKING THE FLOW OF MATTER FROM STARS AND GALAXIES:

THE BARYON CYCLE AND THE LOW SURFACE BRIGHTNESS UNIVERSE

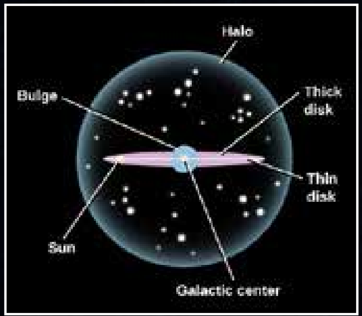


Galaxy formation and evolution remains one of the largest and most active fields in astronomy.

By combining insight from our own galaxy and its closest neighbours in the Local Group with knowledge gleaned from more distant galaxies, astronomers have built up a picture of hierarchical galaxy formation within a Lambda Cold Dark Matter (Λ-CDM) cosmology, whereby structures in the Universe build up over time through the merger of smaller components. Although the stability of the atmosphere (seeing) is modest, South Africa's Karoo night sky is extremely dark and so studying the nearby Universe to extremely faint levels and in great detail is a global niche that SALT is well placed to exploit, given its massive light-gathering power. Galaxy evolution is also a key science driver for the SKA and MeerKAT and hence offers potential for powerful multi-wavelength synergies.

Colour composite image of NGC 1275 which hosts an active supermassive black hole. The lacy filaments are composed of cool gas suspended by a magnetic field and are surrounded by the hot gas in the center of the Perseus galaxy cluster.
– Credit: NASA/ESA/Hubble Legacy Archive and Al Kelly

1 RESOLVED STARS IN THE MILKY WAY AND IN NEARBY GALAXIES



For many years our own Galaxy was believed to be built of three main components: a disc of young and intermediate-age stars (including spiral arms), a bulge of old and very old stars, and a very old halo. Such a simple structure could apparently be seen in many galaxies and formed the basis for formation theories. This basic model, however, is misleading and much work is needed to reveal the true structure of our Galaxy in detail and its implications for formation and evolution theories. LSST, MeerKAT and SKA will be essential in investigating numerous variable stars, tracers of the now-proposed five major structures halo, thick disc, thin disc, bulge and galaxian centre. In synergy with these observatories, SALT is most suitable to determine radial velocities and spectral characteristics. Its high-resolution spectroscopic capability is also required to measure abundances.

2 THE LOW SURFACE BRIGHTNESS UNIVERSE

A number of low surface brightness (LSB) features in the outskirts of galaxies are evidence of past build-up and evolution of galaxies: bridges and tails between merging galaxies, shells of stars around elliptical galaxies, streams of stars in halos of our own and nearby galaxies, and intracluster light in galaxy groups and clusters. These very diffuse structures are challenging to observe beyond the local Universe, yet provide essential constraints on models of galaxy formation. Ultra-diffuse galaxies and radio-detected HI-rich but optically dark galaxies are examples of exotic, little-understood targets in this difficult-to-observe regime. While MeerKAT and SKA will study the widely distributed reservoirs of neutral gas outside the bright discs of galaxies, SALT can combine these with faint extended ionised gas measurements in the optical and thus constrain models of accretion and outflow of gas. Due to its large collecting area and very dark location, SALT is the ideal telescope to study these features, in particular since high spatial resolution is not required. The future spectroscopic capabilities of IFU instruments will make SALT very competitive in this field.

Image above: SDSS image of the elliptical galaxy NGC 474 (centre) and the spiral galaxy NGC 470 (right), imaged to a very low surface brightness with the MegaCam camera on CFHT. The colours indicate stars of various ages forming a complex and extended stellar halo. – Credit: Duc/Cuillandre/CFHT/Cole

3 STAR FORMATION AND THE BARYON CYCLE

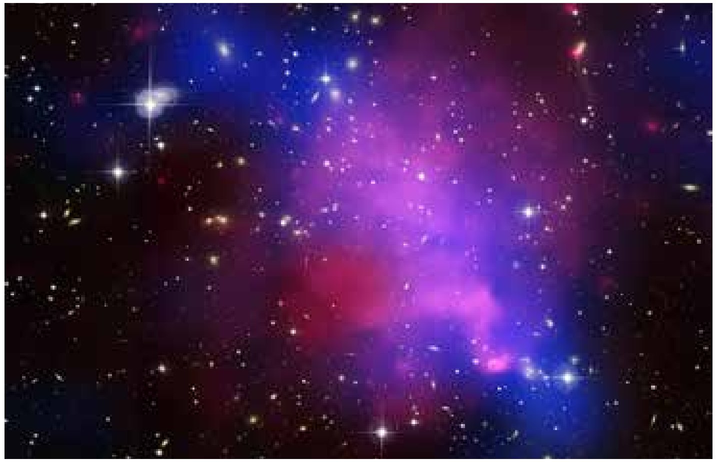
The observed star formation history of the Universe in combination with simulations suggest that to maintain the current observed star formation rate galaxies need to accrete gas; the gas is also heated and ejected, and some of it falls back onto the galaxy – this is the baryon cycle. The origins, properties and fate of extraplanar gas are diverse, complex and not well studied, but they are crucial to understand the triggering, feedback and fueling of star formation in galaxies. This topic is also one of the key science drivers of MeerKAT and SKA, and optical/NIR spectroscopy would be highly complementary to the radio observations. Spatially resolved studies of galaxies in different environments are needed to quantify the nature of interstellar and intergalactic material, galactic gas outflows, gas accretion from the cosmic web, star formation feedback, and gas turbulence. Such spectroscopic observations target the properties and dynamics of ionised, warm atomic and warm molecular gas within galaxies. SALT's future IFU instruments will be used for detailed observations of spectral lines and continua of the diffuse ISM. Their analysis will provide information about the chemistry, metallicity, star formation rates, star formation history and sources of gas heating and thus help to determine the origin and history of the gas and how it is being affected by its environment (i.e., feedback).

Credit: spica-mission.org

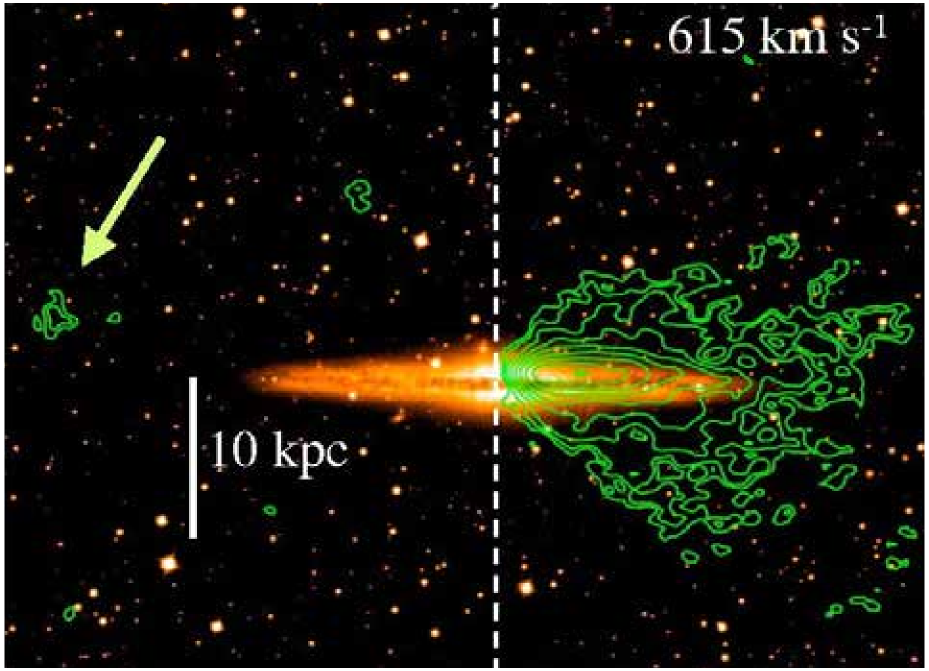
Background image: NASA, ESA, P. van Dokkum

4 DARK MATTER STRUCTURE

The Λ-CDM model has been successful at interpreting astrophysical phenomena on a wide range of scales, but it remains unclear whether the internal structures of simulated galaxies, formed in a CDM framework, are consistent with observations of real galaxies. Typically, an observed rotation curve is decomposed into contributions from stars and gas and any remaining velocity is attributed to dark matter. SALT is well positioned to address the issue of dark matter in galaxies. Seeing-limited two-dimensional imaging spectroscopy, either by the current RSS Fabry-Pérot system, or by a new IFU spectrograph, is required. SALT's 8-arcminute field-of-view is ideal for all but the nearest galaxies, and the telescope has the sensitivity to survey a moderate to large sample of targets in a reasonable amount of time.



Credit: X-ray: NASA/CXC/UVic./Mahdavi et al.; Optical/Lensing: CFHT/UVic./Mahdavi et al.



The channel map of NGC 891 at a radial velocity of 615 km/s (v_{sys}=528 km/s) shows gas on the receding side of the disc (to the right of the vertical dashed line). The cloud in isolation on the left side of the galaxy (arrow) is counter-rotating. – Credit: Oosterloo+ 2007

5 GALACTIC DISCS

Details of the evolution of disc galaxies remain unclear. The commonly accepted global picture of evolution provided by the Λ-CDM theory requires hierarchical assembly of galaxies dominated by major mergers. However, observations contradict this picture: giant disc galaxies demonstrate a peak of their star formation about 10–11 Gyr ago, while small disc galaxies continue their main star formation even now. Any merger must dynamically heat stellar discs and, in the case of major mergers, even destroy them, while giant spirals have rather thin, dynamically cold stellar discs, evidently unaffected by mergers over the last ~8 Gyr. An empirically motivated addition of outer cold gas accretion onto galactic discs into the global evolution picture can be built into the Λ-CDM models, but also has difficulties with observational support: despite many efforts, the sources of this accretion remain hypothetical and controversial. Diffuse extraplanar gas is found around many galaxies and intragroup/-cluster environments, but direct evidence of hot or cold accretion from the cosmic web remains elusive. SALT with its large aperture and modest spatial resolution is an ideal instrument for spectral studies of galactic large-scale stellar discs with rather low surface brightness at their edges. Kinematical studies, on the other hand, require panoramic spectroscopy, as offered by the Fabry-Pérot mode of the RSS.

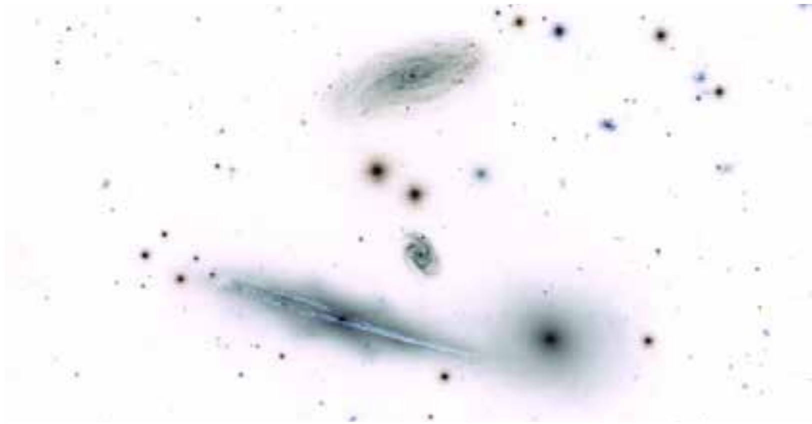
6 GALAXIES IN VERY LOW DENSITY ENVIRONMENTS: IN-DEPTH STUDIES OF FORMATION AND EVOLUTION

Voids as large-scale structure elements occupy more than half of the modern Universe's volume. State-of-the-art theories and N-body simulations indicate that properties and evolution of low-mass galaxies residing in voids can differ significantly from those in the more extensively studied environments of filaments and clusters. Rather subtle differences in galaxy properties have been found for distant voids and walls, including bluer colours and higher SFRs. This is considered an indirect indication of larger gas mass reservoirs in void objects. Knowledge of the evolutionary parameters like gas O/H, gas mass fraction and optical colours of galaxies in local voids (z=0), though, is still rather fragmentary. SALT's HRS observations of faint HII regions in low-mass galaxies in the Local Void can help obtain estimates of gas O/H ratios. This, in combination with HI studies (e.g., with MeerKAT), as well as deep multi-colour surface photometry, can shed light on the nature of unusual dwarf galaxies, such as those discovered recently in voids, that resemble galaxies at the beginning of their evolution.

7 LOW MASS GALAXY EVOLUTION IN GROUPS

Growth and evolution of galaxies is regulated by the baryon cycle, that is, the transformation of gas to stars through replenishment of the base fuel (namely neutral hydrogen) and balanced by secular and feedback mechanisms. Our understanding of this cycle is yet incomplete at best, particularly for low mass galaxies where the models and data are in very poor agreement. We know very little of how low mass galaxies assemble, grow and evolve. Galaxy groups are most interesting in this field of study since they contain a variety of low mass galaxies. In combination with the TAIPAN survey, which will identify a large number of galaxy groups out to redshifts of z = 0.05, SALT can be used to detect and identify group members with masses below TAIPAN's threshold of $\sim10^{9.6}$ M_{sol} and hence help to obtain sufficient statistics to cover a diversity of groups.

Image left: *Hubble image of the dwarf galaxy Pisces B. Most of the stars are old except for some young, blue stars that were born in the last few hundred million years. – Credit: NASA/ESA/E. Tollerud (STScI).* ***Image bottom:*** *Galaxy group HGC-87, composed of a three massive galaxies and a number of low-mass members.*



Abell 370 parallel field: while statistics to cover a diversity of groups. one eye of Hubble was observing the galaxy cluster Abell 370, the second eye – another instrument – was looking at a part of the sky right next to the cluster. – Credit: NASA, ESA/Hubble, HST Frontier Fields

8 HIGH REDSHIFT

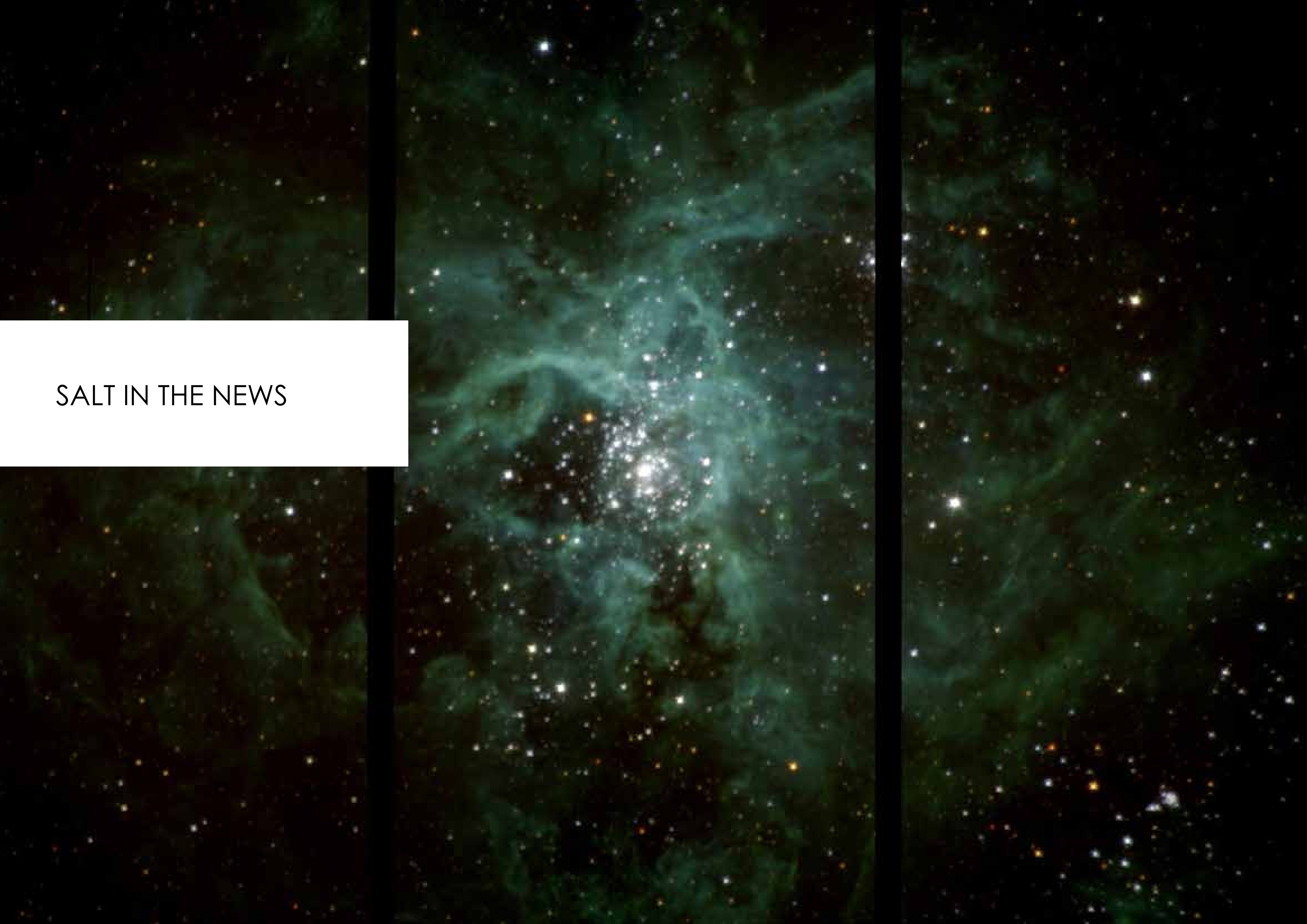
Over the past two decades, photometric redshift surveys have opened up the high-redshift Universe by providing good redshift estimates for statistical samples of galaxies. Spectroscopic follow-up is still essential, however, to train and test the accuracy of the photometric redshifts, to unambiguously identify members of groups and clusters, to measure environmental indicators, dynamical masses, chemical abundances and ages, etc. Deep observations at radio wavelengths require optical redshifts as input to identify and classify sources, as well as to allow the stacking of radio spectra (e.g., in collaboration with MeerKAT's LADUMA survey). SALT is also a useful resource for follow-up observations of cosmological probes, including Type Ia supernovae detected by LSST, and Luminous Red Galaxies (LRGs) used as cosmic chronometers. SALT's high-efficiency spectroscopic modes (MOS, MaxE and future IFUs) can efficiently obtain high-precision redshifts for distant galaxies and galaxy clusters detected with other surveys (e.g., HST deep fields, Herschel, Sunyaev-Zeldovich clusters). The RSS's 8-arcminute field-of-view is well matched to moderate-sized, deep survey fields at high redshift and is ample to cover the entire virial radius of high-redshift (z~1) galaxy clusters.

FINDING LIFE IN THE UNIVERSE:

EXOPLANETS AND THEIR CHARACTERISTICS

The highest-profile astronomy research in future decades may well be dominated by the search for life outside the Solar System – in similar ways as the largest international astronomy projects of decades past were dominated by the drive to understand the beginning of the Universe. SALT has an instrument capable of detecting and characterising classes of exoplanets in the form of the HRS and the relevant modes are undergoing commissioning and refinement. In addition, the SKA will make a significant impact in studying complex molecules in “cradles of life”. This area of research is therefore a must for the SALT community in the decades to come.

Exoplanets, though predicted for a long time, ever since man speculated about other stars being similar to our sun, were not discovered until 1992. Since then there has been a multitude of detections, in particular since the Kepler space telescope was launched. Today, almost 4000 confirmed exoplanets are known, with many more candidates to investigate. These numbers will multiply with the new space missions like NASA’s recently launched TESS and the near-future JWST and WFIRST space observatories, as well as ESA’s exoplanet missions CHEOPS and PLATO. All of these will require ground-based high-precision radial velocity measurements to characterise the planetary candidates. One of the highest priorities for SALT is to make the High-Stability mode of the HRS available. Together with a new pipeline and upgraded calibration facilities (e.g., a new Iodine Cell and possibly a Laser Frequency Comb), this mode will enable SALT to competitively measure radial velocities in the required <5 m/s range for exoplanet search and follow-up studies.



SALT IN THE NEWS

SALT PLAYS A KEY ROLE IN THE GLOBAL HUNT FOR DARK ENERGY

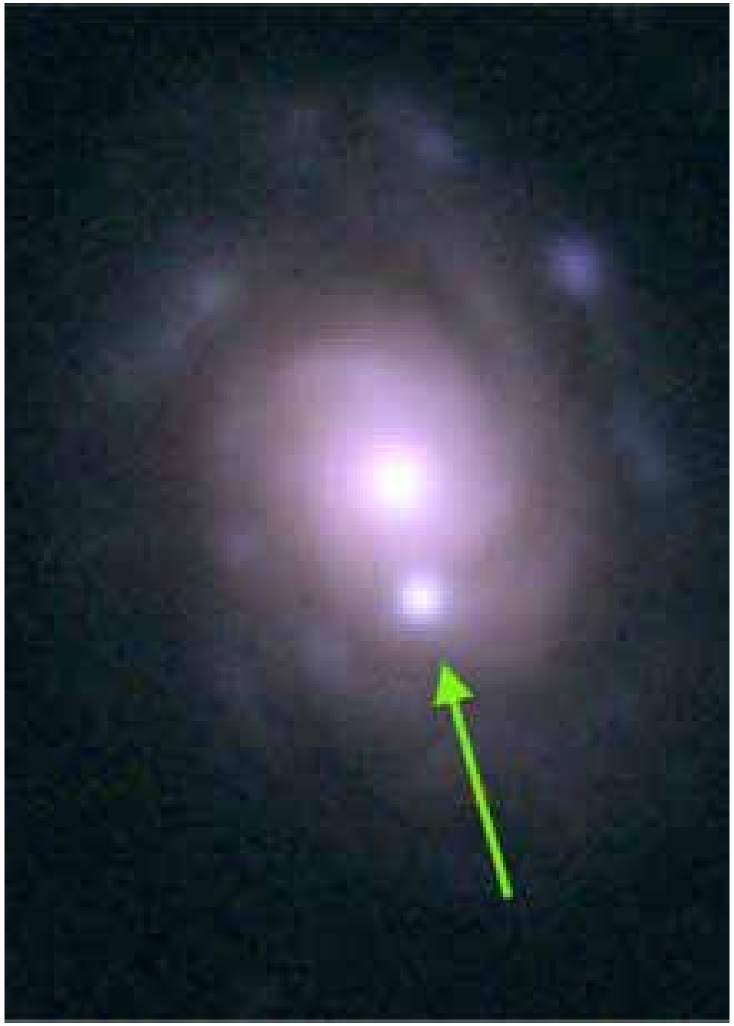
(Dec 2018) The international Dark Energy Survey (DES) is the most sophisticated study of Dark Energy so far, the mysterious force that accelerates the expansion of the Universe. Twenty years ago, this acceleration was discovered by carefully observing supernovae. Two decades later, Dark Energy is still one of the great mysteries of our time. To remedy this, DES began science observations in 2013 in Chile, South America, with the overall goal of measuring the expansion history of the Universe by placing tight constraints on the quantity and properties of Dark Energy. To have confidence in the conclusions it is most important to control systematic uncertainties to a very high precision. DES employs several methods of constraining the elusive Dark Energy, of which supernova observations are a primary tool.

Supernovae are stars that explode at the end of their lives; they become so bright that they can be seen on the other side of the Universe. Astronomers can accurately calculate the distances to a subclass of them, the so-called Type Ia supernovae. Once their distances are known, Type Ia supernovae can be used to measure the acceleration of the expansion of the Universe. The more supernovae are observed accurately and the more distant they are, the higher the precision.

SALT, with its large mirror and its ability to rapidly target new candidates, allows spectra to be taken when the supernova candidate is still at its brightest. A number of such detailed spectra, together with spectra from other large telescopes in DES, as well as the images in which these selected candidates were discovered, were analysed by machine-learning algorithms. Subsequently, these algorithms, now using only the discovery images, were able to successfully classify and determine distances of all the supernova candidates discovered by DES, most of which were too faint to observe spectroscopically. While this new type of classification and redshift determination is less accurate in comparison to that performed with spectroscopic data from SALT and other telescopes, it provides the purest sample of supernovae to date and the large numbers required for DES to succeed.

The results from the first three out of six years confirmed independently the existence of Dark Energy by combining four different cosmic probes: (1) supernova observations, (2) baryonic acoustic oscillations, (3) weak gravitational lensing and (4) galaxy clustering. The combination of these four probes means that for the first time there is strong evidence for cosmic acceleration and Dark Energy from a single experiment, instead of combining results from many different telescopes and different analyses.

Image: An example image depicting one of the supernovae that SALT took spectra of. The supernova lies in one of the host galaxy's spiral arms. For a brief time the supernova can be as bright as the 100 billion stars of the host galaxy. – Credit: SALT/SAAO



SALT CONTRIBUTES
TO THE DISCOVERY OF A BINGEING WHITE DWARF

A new binary star system has been discovered where a small white dwarf star is cannibalising its larger Sun-like companion.

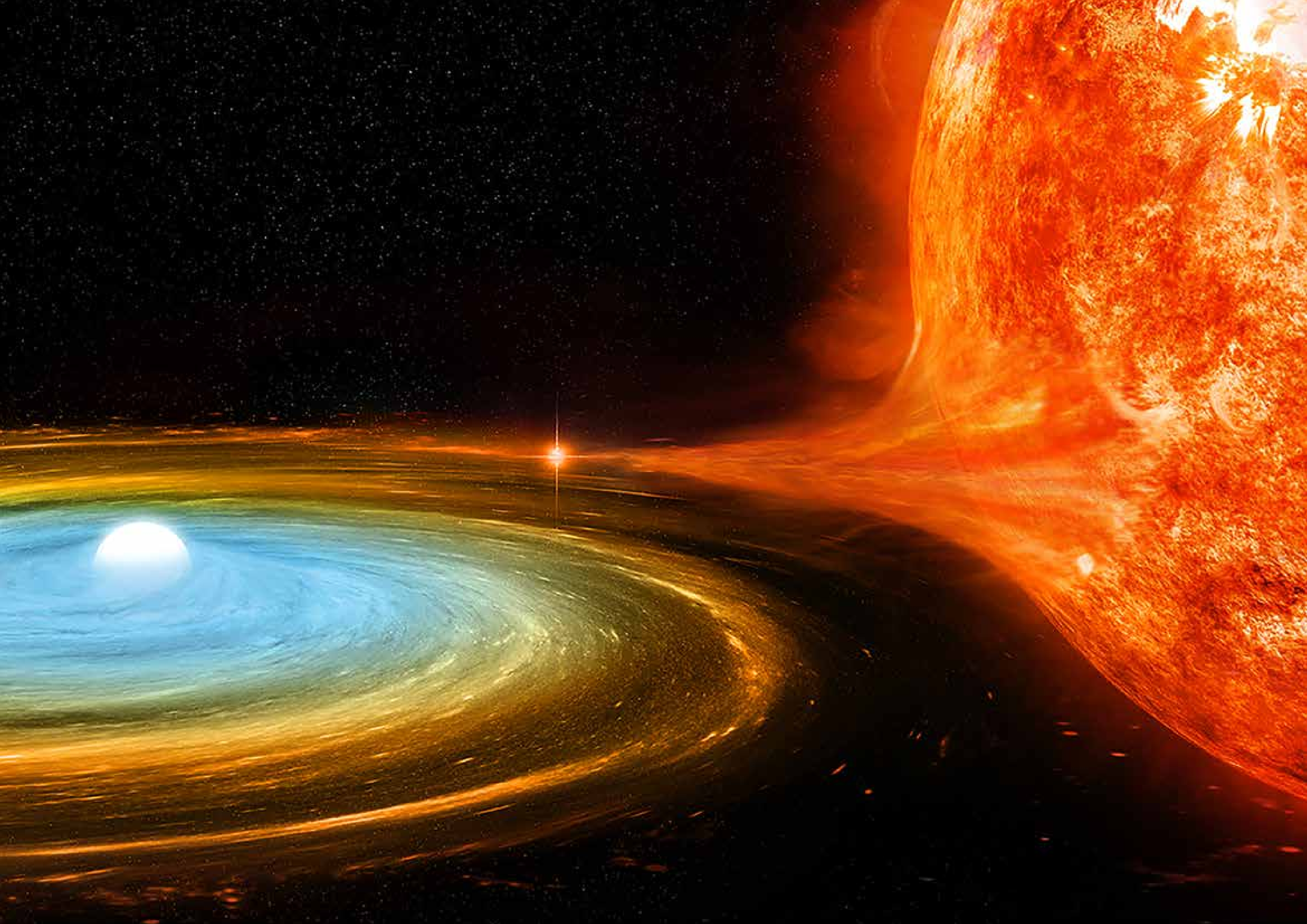
(Dec 2018) Such objects are actually quite common, but for this new object the white dwarf binged on its neighbour at a prodigious rate, thereby heating part of it to nearly a million degrees. The object, named ASASSN-16oh, was found on 2 December 2016 by the All-Sky Automated Survey for Supernovae (ASASSN), a network of about 20 optical cameras, distributed around the globe, which automatically surveys the entire sky every night in search of transient events; that is, of objects which suddenly appear.

Optical follow-up observations were conducted with SALT, with the Polish OGLE telescope in Chile and with the Las Cumbres Observatory (LCO) telescope network. The binary system was also discovered to be a so-called “supersoft” X-ray source by the Swift and Chandra X-ray satellites. Such supersoft systems have always been associated with a thermonuclear runaway explosion on the surface of a white dwarf, brought on by the accumulation of hot and dense accreted gas which eventually reaches a critical explosive limit.

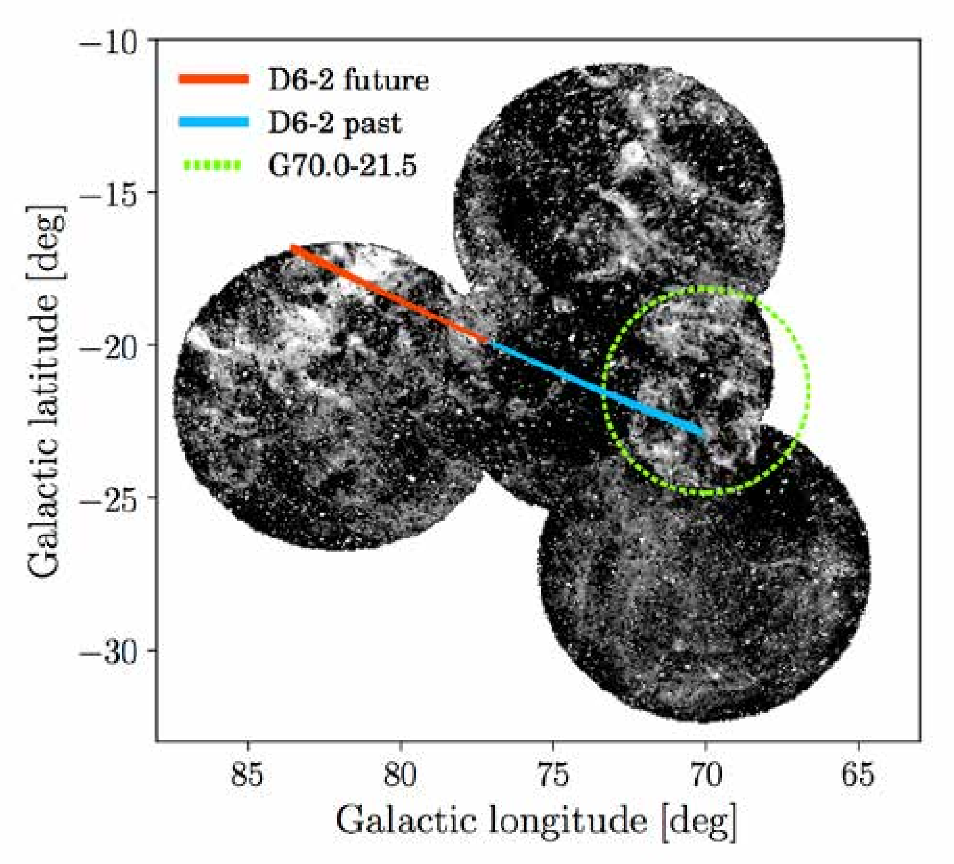
If nuclear fusion were the cause of the supersoft X-rays from ASASSN-16oh, it should have begun with a nova explosion and the emission should come from the entire surface of the white dwarf. However, the optical light did not increase quickly enough to be caused by such an explosion, and the Chandra X-ray data show that the emission is coming from a region smaller than the surface area of the white dwarf. The source is also a hundred times fainter in optical light than white dwarfs known to be undergoing fusion on their surface. These observations, plus the lack of evidence for gas expelled away from the white dwarf, provide strong arguments against fusion having taken place on this white dwarf.

The researchers propose instead an alternative scenario where the X-ray emission comes from the accretion of matter from the companion: the white dwarf pulls gas from its companion star, a red giant, and forms a large flattened rotating disc surrounding the white dwarf. The gas becomes hotter as it spirals inwards and finally falls onto the white dwarf, producing X-rays along an equatorial belt where the disc meets the star. The rate of inflow of matter through the disc varies by a large amount, and when the rate of mass loss from the companion increases, the X-ray and optical brightness of the system becomes higher. The transfer of mass in this case, however, is happening at a much higher rate than in any system known so far. All the SALT spectra show an intensely strong emission line from ionised helium changing in velocity from night to night. The white dwarf was also found to be unusually massive, so ASASSN-16oh may be relatively close – on astronomical timescales – to exploding as a supernova.

Image: An artist’s impression of the supersoft X-ray binary system, ASASSN-16oh, with a small white dwarf star (left) accreting hot gas from its Sun-like companion (right), through an accretion disc. The stream of gas from the companion forms a flattened accretion disc and the gas gradually spirals down to the white dwarf, getting hotter as it does so. Eventually the accreted gas impacts the equator of the white dwarf, heating it up to nearly a million degrees, emitting in soft X-rays.
– Credit: NASA/CXC/M.Weiss



SALT CHASES HYPERVELOCITY STARS



(Nov 2018) SALT has been involved in the identification of a hypervelocity star, flung across the galaxy by a supernova explosion that occurred 90 000 years ago. The discovery of this star and two other similar ones may help to solve a decades-old debate on how supernovae occur.

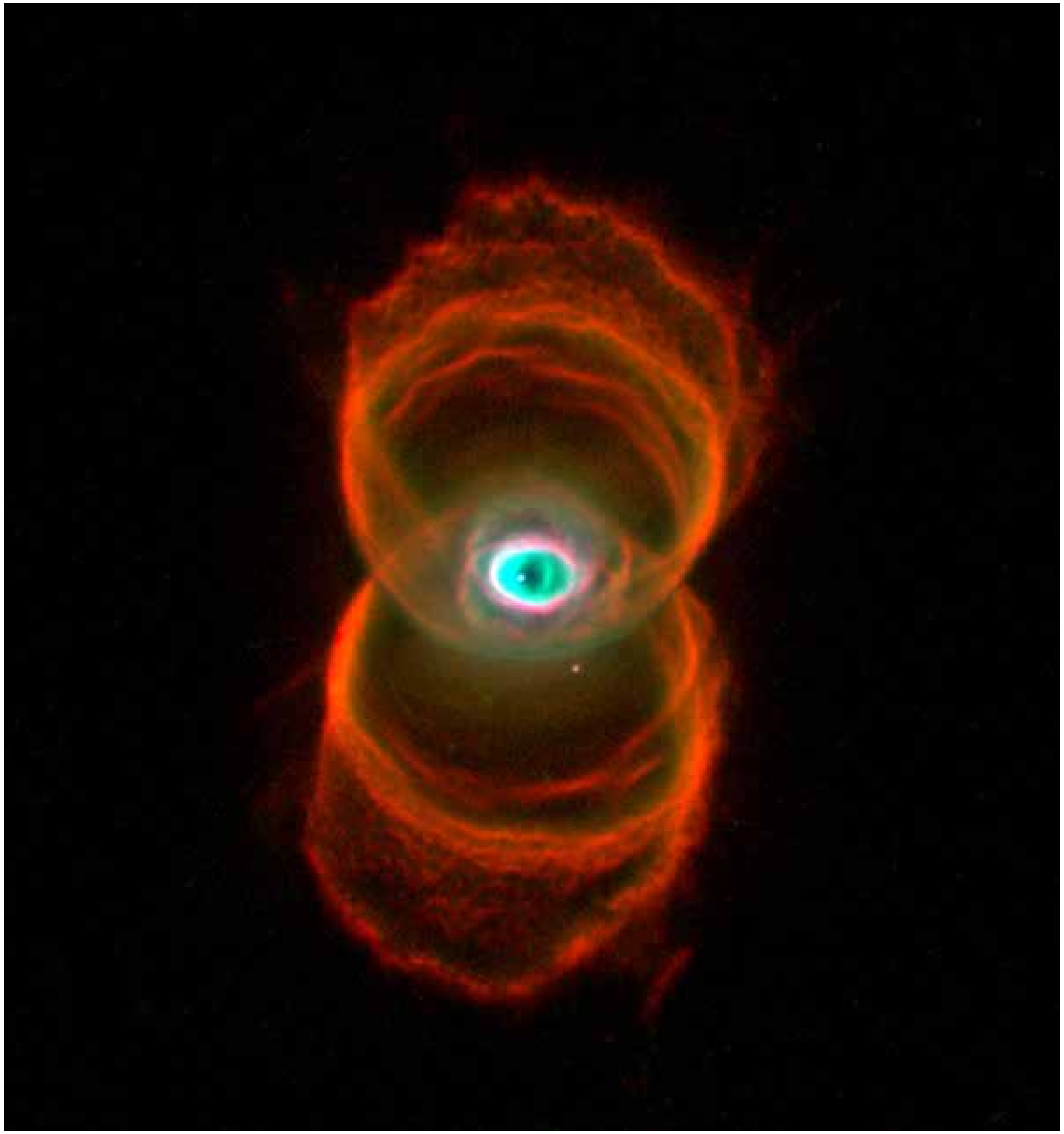
A Type Ia supernova is the thermonuclear explosion of a white dwarf in a binary star system. They are one of the most common types of supernovae, but the exact nature of the binary system involved and the details of such an explosion remain a mystery. Many theoretical models have arisen over the past few decades to explain how these stars explode, but there has been little direct evidence for any of these scenarios to actually occur in nature.

The model used in this research is dubbed the “dynamically driven double-degenerate double-detonation” (D6) scenario. It calculates the possibility that the companion star in the binary system is another white dwarf that can survive the explosion of its companion. Such a surviving star would be flung away from the system when the gravitational pull of its companion disappeared and would continue zipping away at a speed between 1000 and 2500 km/s.

The research team selected three likely candidates from the Gaia catalogue, and observed them with ground-based telescopes including SALT. All three candidates were found to possess many of the predicted features for survivors of a D6 Type Ia supernova: a lack of hydrogen and strong signatures of carbon, oxygen, and magnesium, as well as luminosities and temperatures unlike almost all other stars.

One of these stars was found to be close to a known supernova remnant, making it highly probable that it was ejected from a system that underwent a supernova.

Image: Orbital solution of the white dwarf near a supernova remnant, overlaid with H-alpha images from the Virginia Tech Spectral Line Survey. The blue trajectory extends 90,000 years into the past, the red trajectory extends the same amount of 90,000 years into the future. The green circle indicates the remnant of the supernova. – Credit: Shen et al. (2018)



SALT SEES DOUBLE IN THE HOURGLASS NEBULA

(May 2018) SALT has discovered a binary star system in the Hourglass Nebula, one of the most famous planetary nebulae captured by the Hubble Space Telescope. Astronomers have long suspected this peculiar nebula to be formed by interacting stars in a binary system. SALT's discovery of these two stars firmly settles the matter and gives new insights into how a wide variety of close binary stars and hourglass-shaped nebulae may form.

While previous authors have suggested that a nova explosion could explain many aspects of The Hourglass Nebula, this new study discovered that the stars were too far apart for this to have ever been possible. Instead, the orbital period of the binary system indicates that the Hourglass Nebula formed through an interaction that many close binary stars experience – a so-called common-envelope stage. In this scenario, the cooler star spirals into the atmosphere of its larger companion and ejects the shared atmosphere which we now see as the nebula. The Hourglass Nebula is one of very few such examples to show an orbital period above 10 days, which helps to improve our understanding of this brief phase that many types of binary stars experience during their lifetime.

Image: The Hourglass Nebula consists of two hourglass-shaped lobes of gas and what appears to be an eye staring back at us. Shells of gas form the eye surrounding the hot central star that illuminates the nebula like a neon sign. This HST image shows the nebula in the light of ionised nitrogen (represented by red), hydrogen (green), and doubly-ionised oxygen (blue). – Credit: Raghvendra Sahai and John Trauger (JPL), the WFPC2 science team, and NASA.

SALT & GRAVITATIONAL WAVES

(Oct 2017) SALT featured prominently in the first multi-messenger event: the merging of two neutron stars in a binary system. This violent episode was observed with gravitational wave detectors, as well as with conventional telescopes that detect electromagnetic waves, including the optical window in which SALT operates.

Neutron stars are the smallest, densest stars known. They are the remnants of massive stars that exploded previously as supernovae. In this particular event, dubbed GrW170817, two such neutron stars spiraled inwards and then collided, emitting gravitational waves that were detectable for about 100 seconds. The collision resulted in a kilonova explosion, initially in the form of gamma-rays that were detected by space-based telescopes. The gamma-rays were then followed by X-rays, ultraviolet, optical, infrared, and radio waves.

The significance of that event lies in the combination of the gravitational waves and electromagnetic radiation. The importance of getting early observations stems from the fact that the afterglow of the collision changes extremely rapidly. Piecing together the new science from the event requires combining observations spanning the first hours, days and weeks after the merger. The first SALT spectrum, being one of the earliest taken, has a very prestigious spot in the combined scientific paper that includes thousands of authors and hundreds of institutions.

Image: An artist's impression of the collision of two neutron stars. – Credit: Dana Berry, SkyWorks Digital, Inc.

LIFE CYCLE
OF A NOVA

(Aug 2017) On a cold March night in Seoul almost 600 years ago, Korean astronomers spotted a bright new star in the tail of the constellation Scorpius. It was seen for just 14 days before fading from visibility. From these ancient records, modern astronomers determined that what the Royal Imperial Astronomers saw was a nova explosion, but they have been unable to find the binary star system that had caused it. A new study finally pinpoints the location of the old nova, which now undergoes smaller-scale "dwarf nova" eruptions. The work supports the idea that novae go through a very long life cycle after erupting, fading to obscurity for thousands of years and then building back up to become full-fledged novae once more.

Finding the source of the nova that erupted in 1437 AD was painstaking detective work and involved several observatories. Only with a new interpretation of the ancient records, the nova remnant, which is the ejected nova shell with the cataclysmic binary near to its centre, was finally found. Its location was confirmed with another kind of historical record: a photographic plate from 1923 taken at the Harvard Observatory station in Peru: the difference between the 1923 position of the binary and the one measured today enabled the astronomers to calculate the velocity with which the star moves on the sky. Tracing back this motion to 1437 placed the binary right in the centre of the shell. Other photographic plates from the 1940s helped reveal that the system is now a dwarf nova, indicating that so-called "cataclysmic binaries" – novae, novae-like variables, and dwarf novae – are one and the same and not separate entities as has been previously suggested. After an eruption, a nova becomes "nova-like", then a dwarf nova, and then, after a possible hibernation, comes back to being nova-like, and then a nova, and does it over and over again, up to 100,000 times over billions of years.

SALT spectra of the binary and the shell allowed the researchers to identify the white dwarf companion and to determine its temperature and distance, to constrain the binary components' masses, as well as to estimate the temperature, density and mass of the shell.

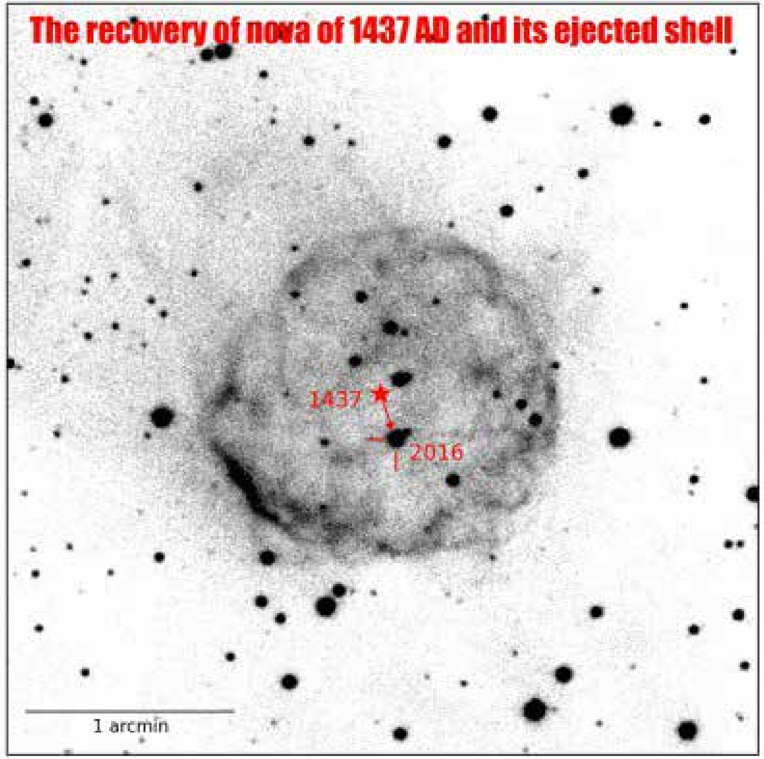
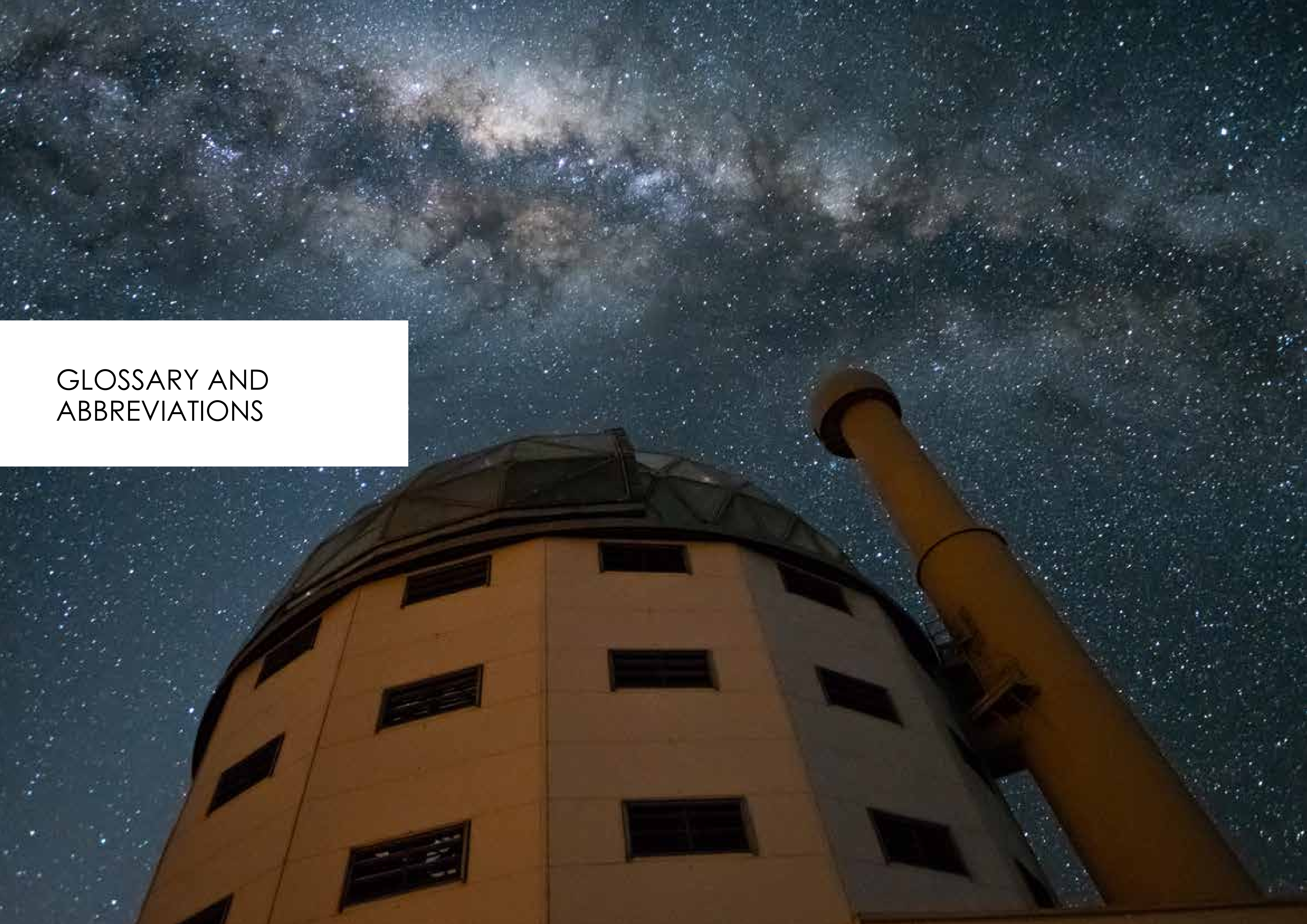


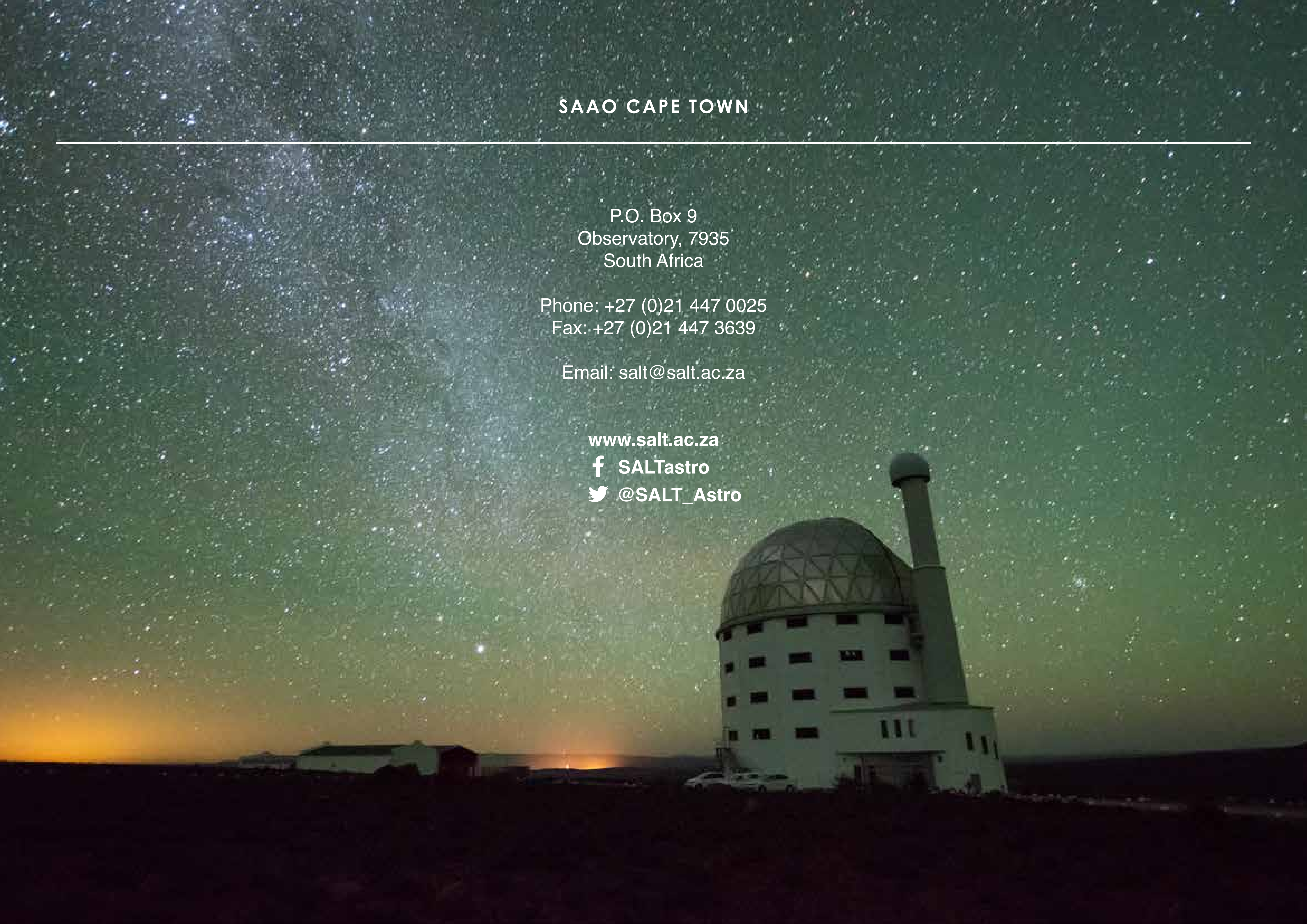
Image: The recovered nova of 1437 AD and its ejected shell. In this Hα image north is up and east is to the left. The location of the cataclysmic variable in 2016 is indicated with red tick marks and an arrow. Its motion places the 1437 AD cataclysmic variable 7.4″ east and 16.0″ north of its current position, at the red star symbol. The 1437 positions of the shell centre and of the cataclysmic variable agree very well. – Credit: Shara et al. (2017)

Novae are binary stars, where a white dwarf accretes material from a close companion star similar to the sun. The material transferred to the white dwarf builds up on its surface and eventually the pressure and density reach critical levels. This triggers a thermonuclear eruption on the surface of the white dwarf equivalent to a million hydrogen bombs. During the explosion, the brightness of the star increases dramatically, sometimes appearing as a new naked-eye star in the night sky, hence the name nova or "new star". The system survives the eruption and after a year or so the white dwarf resumes the accretion of material from the donor star. – Credit: David A. Hardy & PPARC

GLOSSARY AND ABBREVIATIONS



AM CVn Type of variable stars, based on AM Canum Venaticorum which is a cataclysmic variable binary star in the constellation of Canes Venatici
AMXP Accreting Millisecond X-ray Pulsar
ASASSN All-Sky Automated Survey for SuperNovae
BH Black Hole
CHEOPS CHaracterising ExOPlanets Satellite, a planned European space telescope for the study of the formation of extrasolar planets
CV Cataclysmic Variable stars
D6 dynamically driven double-degenerate double-detonation, model for supernova Type Ia eruptions
DES Dark Energy Survey
DN Dwarf Nova
FP Fabry-Pérot (RSS mode)
FRB Fast Radio Burst
GA Great Attractor
GRB Gamma-Ray Burst
GrW Gravitational Wave
HI neutral hydrogen
HII ionised hydrogen
HESS High Energy Stereoscopic System, a system of imaging atmospheric Cherenkov telescopes for the investigation of cosmic gamma-rays
HET Hobby-Eberly Telescope (McDonald Observatory in West Texas, USA)
HMXB High-Mass X-ray Binary
HRS High-Resolution Spectrograph
HST Hubble Space Telescope
IceCube name of the neutrino observatory constructed at the Amundsen-Scott South Pole Station in Antarctica
IFU Integral Field Unit
IR InfraRed
ISM InterStellar Medium
JWST James Webb Space Telescope
KM3Net cubic (3) KiloMetre Neutrino telescope, a future European research infrastructure that will be located at the bottom of the Mediterranean Sea
LADUMA Looking at the Distant Universe with the MeerKAT Array, a MeerKAT Large Survey Project
Λ-CDM Lambda Cold Dark Matter
LCO Las Cumbres Observatory is a network of astronomical observatories with offices in Goleta, California
LCOGT Las Cumbres Observatory Global Network
LIGO Laser Interferometer Gravitational-wave Observatory
LMC Large Magellanic Cloud
LMXB Low-Mass X-ray Binary
LSB Low Surface Brightness
LSST Large Synoptic Survey Telescope
MASTER Mobile Astronomical System of the TElescope-Robots Network (MASTER-Net) global transient alert system
MaxE Maximum Efficiency spectrograph
MeerKAT More Karoo Array Telescope
MeerLICHT "More Light" is an astronomical project which aims to provide a simultaneous, real-time optical view of the radio (transient) sky as observed by MeerKAT
MONET MOnitoring NEtwork of Telescopes, with two fully automatic robotic telescopes at the observatory sites in Texas (MONET-North) and South Africa (MONET-South)
MOS Multi-Object Spectrograph (RSS mode)
NIR Near-InfraRed
OGLE Optical Gravitational Lensing Experiment, a long-term variability sky survey based at the University of Warsaw
PLATO PLAnetary Transits and Oscillations of stars, a space observatory under development by the European Space Agency
QPO Quasi-Periodic Oscillation
RRAT Rotating RAdio Transients
RSS Robert Stobie Spectrograph
SAAO South African Astronomical Observatory
SALT Southern African Large Telescope
SALTICAM SALT Imaging CAMera
SAMS SALT Array Management System: active mirror alignment system
SKA Square Kilometre Array
SN SuperNova
SPIRITS SPitzer InfraRed Intensive Transients Survey
TAIPAN instrument consisting of a 150-fibre robot positioner operating over the 6 degree field of view of the UK Schmidt Telescope
TDE Tidal Disruption Event
TESS Transiting Exoplanet Survey Satellite
UV Ultra-Violet
WFIRST Wide Field Infrared Survey Telescope, a NASA infrared space observatory currently under development
XRB X-Ray Binary
XRT X-Ray Transient



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