NATIONAL STRATEGY FOR MULTI-WAVELENGTH ASTRONOMY

JULY 2015

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

TABLE OF CONTENTS

NOTE

This Strategy is based on reports produced by seven expert Panels set up by DST. The Panels solicited input from the broader research community and produced detailed reports on the advancement of Astronomy in South Africa. This Strategy distils the key principles, vision and recommendations of the Panel Reports. The implementation plan for this Strategy will be developed by the NRF and its Astronomy Sub-agency, drawing on the detailed Panel reports.

EXECUTIVE SUMMARY

Astronomy is a unique subject in which Africa has traditions stretching back thousands of years. Progress in Astronomy worldwide in the past decade has been phenomenal. We are now in a remarkable era for Astronomy, particularly in South Africa, where we are hosting the majority of the Square Kilometre Array (SKA) radio telescope, the world's biggest Astronomy project. This has changed the scientific landscape in South Africa forever and given us the potential to elevate our Astronomy research to truly international levels across the electromagnetic spectrum. Our advantages include geographic location with access to the southern skies, high-level government support and infrastructure investment and dark skies free of radio interference, that are protected by an Act of Parliament.

The time is ripe for a National Astronomy Strategy to ensure that we can exploit these advantages to the full – delivering world-class research, driving transformation, and adding major value to the knowledge economy of South Africa through human capital development and technological spin-offs.

PROMOTING RESEARCH EXCELLENCE AND INNOVATION

Strategic investment for the coming decade should focus on protecting, exploiting and expanding the world-class Astronomy facilities in South Africa, MeerKAT (the SKA Pathfinder telescope) and SALT (Southern African Large Telescope). MeerKAT will be the world's leading radio telescope before the SKA. The local Astronomy community has an unprecedented opportunity to produce world-leading science from MeerKAT – provided that the internet bandwidth and data infrastructure are urgently upgraded to world-class standards. These essential upgrades will in fact benefit all areas of a knowledge-based economy.

In addition to facilities and data infrastructure, we need an instrumentation programme to maintain and upgrade our capacity and to produce cutting-edge advances in telescope design and data processing – which in turn lead to innovative spin-offs for the economy.

Astronomy is based on observations – but we need the tools to find the information in vast datasets, to interpret it and to produce world-class science from it. These tools are theoretical – physical modelling, simulations and Big Data science – and they are as important as the facilities that deliver the 'raw material' of observations. Furthermore, advances in Astronomy theory, especially in simulations and Big Data, are highly transferable, leading to innovative spin-offs in many other areas.

The critical vehicle for research excellence is research groups that can focus and develop our research strengths and train the new generation of astronomers. Major progress has been made in the last few years, but a strategic effort is needed to consolidate and strengthen groups which can produce world-class research. The priority science areas are those that tackle the major questions in current Astronomy which are linked to MeeKAT/ SKA and SALT, and where we have existing or emerging excellence and critical mass.

Commitment to the two major South African facilities is core to our success in radio and optical Astronomy. In order to maintain excellence in optical Astronomy, new locally designed spectroscopic instruments must be built. In addition, we need to acquire access to a 4m class telescope that can host local spectroscopic instruments, thus enhancing our optical capabilities and at the same time delivering crucial follow-up spectroscopy for MeerKAT.

In addition, there are exciting international opportunities that will enhance the national research and training programme. Heading the list is the HESS (High-energy Stereoscopic System) facility in Namibia, giving us a superb multi-wavelength network in combination with MeerKAT/ SKA and SALT. This will receive a major boost if the planned CTA (Cherenkov Telescope Array) is sited in Namibia. International projects such as LSST (Large Synoptic Survey Telescope) and HERA (Hydrogen Epoch of Reionization Array, to be located on the South African SKA site) will also provide exceptional complements to the local facilities at relatively low cost. New projects that include world-leading science related to the priority areas, strong local leadership, and benefits for HCD and innovation, should be supported through a competitive process.

HUMAN CAPITAL DEVELOPMENT AND TRANSFORMATION

South Africa needs to take a huge leap forward in training a new generation in science, engineering and technology (SET), and Astronomy can make a significant contribution to this. Astronomy training gives students cutting-edge transferable skills, from engineering to data analysis – skills that are crucial to the knowledge economy of the 21st century. We must build on the SKA human captital development (HCD) programme and the National Astrophysics & Space Science Programme (NASSP), by developing a national HCD plan to increase the number of graduates and improve the relevance of their education to society.

The national HCD plan must extend beyond producing just the numbers, and commit to transforming the Astronomy community by developing a cohort of black and female astronomers. Progress has been made, but much remains to be done. A stronger commitment is needed from the community, and competitive bursary levels are essential to attract talented black students into Astronomy.

Science education initiatives at school level and engagement with the public are powerful instruments for recruitment of students to SET, for transformation and for the knowledge-based future. Astronomy offers huge opportunities for education and outreach, especially via the excitement surrounding the SKA, and these opportunities must be harnessed to draw young people into Astronomy and SET.

GOVERNANCE

South African Astronomy stands at the threshold of a new era. To exploit our potential and overcome our inherent weaknesses requires an improved and autonomous governance structure capable of delivering the value demanded by the investments in Astronomy. The establishment of the NRF Astronomy Sub-agency and its Astronomy Advisory Council has laid the foundation.

In particular, the management of funding should be overhauled to meet the needs of research excellence, training and transformation. The top priority is for the Sub-agency to form a standing Astronomy Grants Panel of local expert astronomers, with rotating chair and membership. This Panel will provide continuity of scientific peer review and will be able to monitor the performance of grant-holding groups against the requirements of the National Strategy.

1 INTRODUCTION: WHY ASTRONOMY IN SOUTH AFRICA?

Astronomy is a science that reaches from planets to stars to galaxies and the Universe as a whole, from the earliest moments up to the present, 14 billion years later. It embraces all of physics in an endeavour to understand the origin and evolution of the Universe and its constituents – including the emergence of life on Earth and its place in the vast Cosmos.

Some of the biggest questions in science are being tackled in Astronomy. These include:

- What was the nature of the Big Bang that formed our Universe?
- How did the first stars and then galaxies form and evolve to the present day, including our own Milky Way galaxy?
- What is the mysterious Dark Energy that is accelerating the expansion of the Universe?
- What is the invisible and yet-to-be-detected Dark Matter that holds galaxies together?
- What physics governs variable stars, binary stars, neutron stars and black holes, including the super-massive black holes at the centre of galaxies like the Milky Way?
- Can we detect gravitational waves, the ultra-weak ripples in the fabric of space and time predicted by Einstein, to open new vistas on the Universe?
- How did planets form, how many of them are habitable and is there extra-terrestrial life?

Astronomy has deep roots in human civilisation, linking us to our ancestors across all continents who have wondered at the beauty of the night sky. These ancestors, including the indigenous civilisations of South Africa, developed narratives and measurements in relation to the night sky, which form an important legacy for human civilisation today.

Astronomy has the broadest reach of all the sciences, uniting us in a common interest in the mystery of the Cosmos and our place within it. Astronomy is based on fundamental science and engineering, and it has powerful spin-offs in both areas, while also contributing to human understanding and culture. It is a strong pole of attraction into science, since it captures the imagination of the youth. Those trained in Astronomy have valuable transferable skills that can contribute to a knowledge-based economy of the future.

Over the last decade, South Africa has made major investments in Astronomy, based in part on a National Research and Development Strategy (2002), formulated by the Department of Science and Technology (DST) and accepted by government. The strategy emphasised the importance of areas of research in which the country has a competitive advantage and the need for innovation within the National System of Innovation (NSI). The unique opportunities in Astronomy were recognised in the forward-thinking Astronomy Geographic Advantage Act (2007), which protects a large area of the Northern Cape from light and radio pollution, thus securing a world-class site for astronomical observations. This has been further endorsed in the DST's Ten-Year Innovation Plan (2008-2018) that identifies space science and technology as one of the five grand challenges.

These initiatives have led to the outstanding success of South Africa in being chosen in May 2012 as the major host for the Square Kilometre Array (SKA), which will be the world's biggest Astronomy installation. Astronomy, through the SKA, is seen by government as a key infrastructure project. The SKA is one of seventeen Strategic Infrastructure Projects (SIPs) of the Presidential Infrastructure Coordinating Commission. Infrastructure investments, like the SKA, are a key priority of both the National Development Plan and the New Growth Path of government.

The development of Astronomy in South Africa will play a major role in South Africa's transition from a resource-based to a knowledge-based economy. It is only through technology and skills development and transfer that the national industrial sectors can become more globally competitive. A knowledge-based economy is characterised by products and services that are underpinned by knowledge flows.

One of the most important ingredients for a knowledge-based future is known as ‘Big Data’ – the capacity to generate, store, transport and interrogate huge volumes of data. Astronomy is at the forefront of Big Data, and the SKA in particular will generate the largest volumes of data ever – thus stimulating and contributing to major advances in scientific data methods and computational power. The skills, techniques and infrastructure developed in Astronomy are readily transferable to other areas, such bio-informatics. The SKA project in South Africa is already making significant contributions to Big Data science in South Africa. In order to maximise our advantages in Big Data, it is essential that South Africa develops a world-class internet backbone – not only for the success of the SKA, but for the economy as a whole.

Astronomy is a frontier science that operates on a global scale. It attracts to it some of the outstanding minds of the country, because of the challenge and the excitement of working in such an internationally-linked, intellectually-stimulating area of research that is tackling some of the big questions on the origin and evolution of the Universe and of life itself. The growing strength of South African Astronomy is raising the international science profile of the country.

Furthermore, Astronomy is a powerful lever for raising awareness of the excitement of science and technology amongst the new generation. For a knowledge-based future, we need above all to inspire young people across the country, and especially black and female youth, to enter a career in science, engineering and technology (SET). Astronomy can make a major contribution to this national effort. Already, the Human Capital Development (HCD) programme of the South African SKA project, together with the National Astrophysics & Space Science Programme, have made great strides in recruitment and training. Skills for modern Astronomy are also highly transferable – for example skills in Big Data, computing and engineering. Astronomy requires high-tech instrumentation and cutting-edge developments in the information, computing and technology sector (ICT). The interplay between scientific needs and the inputs by academia and industry can serve as a strong catalyst for research and innovation in developing these industrial sectors.

There are also more direct spin-offs from Astronomy. Investment in the Southern African Large Telescope (SALT) has stimulated the country's economy, with local industry manufacturing around 60 per cent of the telescope's components. It has also boosted tourism and created new jobs. Soon after opening, the annual number of visitors to the small town of Sutherland jumped from a few hundred to over 13,000. As a result, guesthouses, coffee shops and tourism-related businesses have sprung up. The SALT Collateral Benefits Programme, in partnership with local stakeholders, has developed 'astro-tourism' activities. A growing number of companies are also capitalising on the interest in Astronomy, using 'amateur' telescopes to attract foreign visitors and corporate companies.

Investment in the SKA project is generating even larger spin-offs. The construction of the 7-dish Karoo Array Telescope (KAT) proved that the country had the expertise and facilities to take on the SKA project. This is underlined by the successful construction of the first of 64 MeerKAT dishes in March 2014. MeerKAT holds significant opportunities for local South African industry. A number of cutting-edge technology developments are being driven by South Africa, especially in the area of high-performance computing. More than 75% of the value of the MeerKAT dishes will be spent on components procured in South Africa. South Africa is also involved in, and in some instances leading, work packages for the technological platforms of the international SKA. This provides significant opportunities for the country’s R&D and industrial sectors. In addition, the local communities in the Northern Cape Province have benefitted from the close proximity of the MeerKAT project through infrastructure jobs and social investment partnerships initiated by the SKA project.

South Africa has excellent radio and optical conditions to survey the southern skies, a key driver in Astronomy research. Targeted investments in high-level Astronomy infrastructure like the SALT, MeerKAT and SKA projects are delivering benefits that will grow as the projects develop. These include the development of skilled knowledge workers, increased business opportunities to local communities and the concomitant spin-offs within the industrial sector. These achievements are underpinned by government policies, which recognise the value of Astronomy and its potential contribution in the drive towards a knowledge-based economy.

2 BUILDING ON SOUTH AFRICA'S HERITAGE

Astronomy is one area in which South Africa truly has competitive advantages: access to the southern skies that are inaccessible from the northern hemisphere, dark, clear skies with low radio interference protected by a government act. There is also a further critical ingredient – access to advanced infrastructure networks of transport, power and communications. In addition, there is a strong knowledge base in Astronomy with a long history of success stretching over 150 years of high quality research, centred on what is now the South African Astronomical Observatory (SAAO) in Cape Town. Furthermore, the national industrial engineering base has shown the ability to build and maintain telescopes, and the infrastructure to support them is available locally.

Astronomy in South Africa has for many decades been based on a number of what are now termed small optical telescopes (in particular the 1.9m telescope), mainly at the Sutherland outstation of the SAAO, and a single dish 26m radio telescope at the Hartebeesthoek Radio Astronomical Observatory (HartRAO). The latter was used for both astrophysical observations and space geodetic work, based on international Very Long Baseline Interferometry (VLBI). The situation, however, has been changing dramatically in recent years.

The 10m Southern African Large Telescope (SALT) at Sutherland is the largest single optical telescope in the Southern Hemisphere, with an extremely cost-effective and innovative design. It is an international facility, with South Africa having a one-third share, and is operated by SAAO. With significantly improved optics achieved through the expertise of South African engineers and instrumentation experts, it now has improved capability and will play a major role in Astronomy for many years to come. Moreover, a number of robotic telescopes have been set up at Sutherland by international astronomers, and local astronomers have access to the gathered data.

Over the last decade there has been a small but effective South African participation in the High Energy Stereoscopic System (HESS), an international gamma-ray telescope in Namibia, to study high-energy astrophysics, including pulsars, supermassive black holes and supernovae. The facility was extended in 2012 when HESS-II was commissioned. The international Cherenkov Telescope Array (CTA) consortium is planning the next generation ground-based device. South Africa is supporting Namibia's bid to host the CTA as this will strengthen the participation of the South African Astronomy community in high-energy multi-wavelength Astrophysics.

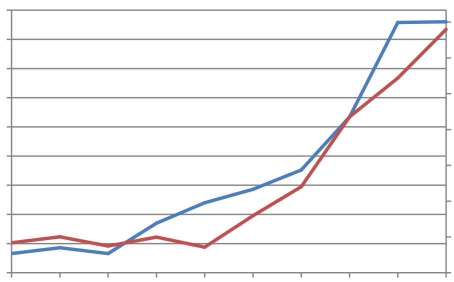
In the radio regime, construction of a world-class radio telescope has begun at an excellent radio-quiet site near Carnarvon in the Northern Cape Province. Called MeerKAT (KAT = Karoo Array Telescope), this array of 64 dishes will be the largest radio dish array in the Southern Hemisphere. The first MeerKAT dish was erected in March 2014, and the target completion date is 2016. MeerKAT is regarded internationally as one of the key Pathfinder telescopes leading to the construction of the proposed international Square Kilometre Array (SKA), and will be absorbed into Phase 1 of the SKA. The call for proposals for the use of the MeerKAT facility led to a large number of applications from a wide range of international teams involving also local astronomers. As a precursor and an engineering test-bed for MeerKAT, a 7-dish radio telescope, the Karoo Array Telescope (KAT-7), was constructed at the site, based on innovative technology, and has been commissioned. KAT-7 is presently in operation and is being used for scientific observations and in-depth interferometric activities.

Following sustained visionary strategic support from government, South Africa was selected in May 2012 as the major site for the SKA. The site proposal from South Africa is based on a core near Carnarvon, and includes further dishes in eight other African countries (Namibia, Botswana, Zambia, Mozambique, Mauritius, Madagascar, Kenya and Ghana). Having received explicit support from the African Union, it is officially called the SKA Africa bid. The SKA will be one of the world's largest scientific/ technological facilities and construction of Phase 1 is scheduled for 2018 – 2023. The total investment by the international consortium involved is expected to be several billion dollars over the first decade of operations.

Arising largely from SALT and SKA and the increased funding to Astronomy, there has been a dramatic growth in both postgraduate student numbers and researchers (postdoctoral, junior academic and Research Chairs) in Astronomy at South African universities including some with no previous Astronomy groups. Overall, the number of professional astronomers in South Africa has more than doubled in the past decade. This growth has been supported through very effective targeted Human Capital Development (HCD) programmes such as the SKA Bursary Programme and National Astrophysics and Space Science Programme (NASSP). One benefit of these interventions is that Astronomy is now the highest impact research field in South African science.

In recognition of these achievements, the International Astronomical Union awarded the hosting of the Office of Astronomy for Development (OAD) to South Africa, which provides a strong platform to use astronomy as a stimulus for connecting science research, education and outreach both locally and globally. This is being leveraged and exploited to inspire and educate the people of South Africa, contributing to the knowledge-based economy.

There has been a concurrent explosive growth in world-class engineering and instrument-building expertise in South Africa and a growth in strong collaborative/partnership links to universities and research centres in China, the European Union, Germany, India, Japan, the Netherlands, the USA and the United Kingdom. In the meanwhile, other international telescopes, such as PAPER and C-BASS, have been established or are being considered at the Carnarvon SKA site in collaboration with local teams. Plans are also under way to establish an African VLBI Network (AVN) in collaboration with a number of African partners, with the HartRAO team playing an important role. This will also enable other African countries to access practical applications of geodesy developed locally.



008 2009

Figure 1: Research performance in Astronomy and Astrophysics

South African Astronomy is thus increasingly involved in the international effort to tackle all of the key questions in Astronomy, making consistent contributions that are growing in significance with each passing year. The initial results of a scientometric analysis, shown in Figure 1(a) above, indicates that South Africa's research output in Astronomy and Astrophysics has grown in absolute numbers from 183 in 2004 to 580 in 2013 and that the comparative contribution to the share of world output, using the Web of Science classification, has grown from 0.73 in 2004 to 1.62 in 2014. This resulted in an increase in South Africa's global ranking in Astronomy and Astrophysics from 33rd in 2004 to 23rd in the world in 2013. In addition, the analysis also indicates that the overall citation impact, see Figure 1(b), moved from below the world average (where the world average is normalised to 1.0) in 2004 to above twice the world average in 2012. This implies that both the quantity and quality of publications in astronomy and astrophysics has increased significantly over the period 2004 to 2012. This marked growth in performance can be attributed to the significant investments made in SALT, KAT-7, MeerKAT and the SKA over the same period and that this commitment served as a natural attractor for international collaboration thus driving the increased research output.

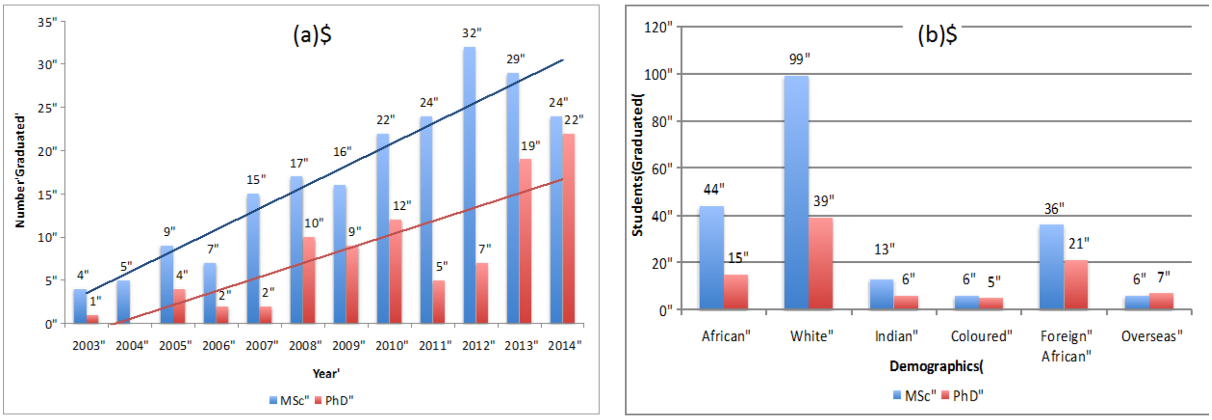


Figure 2: Human capacity development performance in Astronomy and Astrophysics

On the human capital development front there has also been significant growth in the number of students that have obtained Astronomy related degrees. Figure 2 (a) shows the number of student graduations per year, between 2003 and 2014, at the MSc and PhD levels, resepctively, together with its respective trendlines. The total number of graduations at the MSc and PhD levels are 204 (with 8 more MSc graduations already in 2015) and 93 (also with 8 more PhD graduations in 2015), respectively, over the period 2003 to 2014. However, it should be noted that there are still 78 students currently pursuing an MSc degree and 108 students pursuing a PhD degree in Astronomy related fields. Therefore, the rate of graduations at the MSc and PhD levels are set to increase even further in the years to come. However, the lack of transformation is clearly in evident Figure 2(b), where the majority share of graduating students are white. This underscores the need for urgent transformation within the Astronomy human capacity development pipeline.

In a recent review of the National Research Foundation (NRF) Astro-geosciences cluster (Report dated 01 June 2011) the 4-person review panel, which included 3 international experts in Astronomy, concluded:

> "We have great admiration for the achievements of South Africa and the NRF institutes in pursuing top-class research in Astronomy and geophysics during the last fifteen years. South Africa has shown exceptional foresight, determination and ambition in using its geographical advantage to build up a world-leading astronomical infrastructure that will include the largest single optical-infrared telescope in the southern hemisphere and the most sensitive telescope at centimetre wavelengths in the south. South Africa is also heavily involved in the development of the Square Kilometre Array (SKA), an international next-generation radio telescope of enormous capabilities. Not only is MeerKAT a pathfinder for SKA, but South Africa is one of two possible excellent sites where the international radio astronomical community has decided to locate SKA. We congratulate South Africa for becoming one of the two finalists for SKA during the period of this review."

The review panel further speaks of the combination of world class large research facilities and pioneering activities in outreach, capacity development and transformation as representing Astronomy as "a jewel in the crown of African science".

The recognition of unique opportunities in Astronomy has led to the enactment of the forward-thinking Astronomy Geographic Advantage Act of 2007, which protects a large area of the Northern Cape Province from light and radio pollution by humans, thereby safeguarding these areas for Astronomy. This initiative is yielding dividends, and the area is developing a reputation as a leading international site for Astronomy.

3 THE NEED FOR A NATIONAL ASTRONOMY STRATEGY

The massive infrastructure investment in Astronomy through SALT, KAT-7, MeerKAT and SKA requires a coordinated national strategy to maximise the return on this investment – both in terms of making South Africa a world-class player in Astronomy research and in terms of unleashing Astronomy as a force for socio-economic growth. To achieve this, it is critical that we further develop the current strengths but also address the current challenges in South African Astronomy, identified among others, by the NRF report, "A Decadal Strategy for Human Capital Development in Astronomy and Astrophysics". In many cases, the Astronomy community has made fantastic progress, but there are obstacles that threaten to limit the potential broader benefits for the scientific community and for South Africa as a whole, and hence it is crucial to address these in any strategic plan.

A major challenge arises from the fact that currently the internet capabilities available to most researchers in South Africa, even with recent improvements, are dramatically below international standards. The nature of Astronomy involves large data sets and hence demands excellent internet bandwidth. For example, participation in international Astronomy projects – e.g. the VLBI network and the transmission of the large volumes of data from SALT and MeerKAT to international collaborating scientists across the world – require multiple Gb/s connectivity, as does the unleashing of the full power of the Big Data training for the South African economy. Needless to say, all of these call for stable and ultra-high speed internet connectivity, which in the era of the SKA will have to be among the best in the world.

A further challenge identified by the report was that research in Astronomy is somewhat conducted in a silo fashion: isolated pockets focusing on areas of limited scope. The growing strength and quality of the Astronomy community has begun to overcome this problem. However, a clear national strategy is needed to identify a national framework of established or emerging research themes in which South Africa is, or could be, an international leader – and to help build our capacity to exploit the huge potential of SALT and the SKA. This strategy should also be based on a multi-wavelength view of Astronomy – a comprehensive understanding requires data from across the electromagnetic spectrum, as well as high energy particles, and melds together theoretical, observational and computational analyses to extract maximum scientific impact.

A related issue has been the lack of a coherent organization of Astronomy at the national level. The need for a new governance structure for Astronomy has been mooted consistently in reviews and studies during the past 5 to 10 years. Recently a major step forward has been taken with the formation of the Astronomy Sub-agency of the NRF, together with the Astronomy Advisory Council. Such an entity is required to oversee the development and management of all aspects of Astronomy activities within a single coherent framework, guided by a national strategy. In addition, there has been a concomitant realignment of astronomy programmes within the DST.

For historical reasons South African Astronomy, particularly outside Cape Town, has also suffered from a lack of critical mass of active researchers, together with limited international collaborations and partnerships. This has made it hard to have a vibrant, stimulating and active research community. Further, the number of postgraduate students in Astronomy at universities has been inadequate to provide the necessary pipeline to grow a strong cohort of researchers, as well as future generations of astronomers. This is particularly severe in the case of attracting and training black South African scholars both as students and researchers and is something that must be urgently addressed.

The Astronomy community is making concerted efforts towards reversing these trends and with support, it can massively increase the number of postgraduate students in Astronomy. However, there remains a severe shortage of permanent positions in universities and national facilities for these researchers, which threatens the capacity of the South African community to exploit the MeerKAT and the SKA.

Past activities to promote the discipline of Astronomy through science education and public outreach have been limited in extent and target areas. Astronomy outreach is a fantastic gateway to inspiring people and initiating them into scientific thinking. There is huge potential for expanding the positive impact of Astronomy across the entire social spectrum, as well as catalysing transformation of Astronomy.

While there are some important problems, Astronomy in South Africa also exhibits a wide range of significant strengths that give the community huge potential for impact and growth if an appropriate national strategy is created and executed. These strengths include the visionary and steadfast support of Astronomy by the South African government through the DST and NRF that led to the building of SALT and KAT-7, the funding of MeerKAT and the Astronomy Geographic Advantage Act (2007) which protects South Africa's astronomical advantages through an act of parliament. These initiatives culminated in the choice of South Africa as the main host of the SKA, a fact that has revolutionised the Astronomy landscape of South Africa and will continue to shape it for decades to come.

South Africa's radio and optical facilities, together with the presence of the high-energy telescopes HESS and HESS-II in Namibia, provide South African astronomers with world-class access to multi-wavelength facilities. Internet bandwidth in South Africa currently cannot yet deliver on the promise of Big Data Astronomy, although some progress has been made. For example, the South African National Research Network (SANREN) has addressed the need to improve the broadband capacity between South African research institutions.

In terms of human capacity development the Astronomy community has come together to develop the National Astrophysics and Space Science Programme, which has significantly increased cooperation between Astronomy groups in South Africa and trained African and South African students to a high level. The SKA HCD programme has also been exceptionally successful in building a dynamic young multi-wavelength community. The number of SKA HCD grants has grown dramatically, with over 600 bursaries and other grants awarded in total, from the undergraduate level to senior fellowships, since 2005.

This human capacity development has been supplemented by a remarkable influx of world-class researchers who have taken up SARChI and other positions in South Africa. They have significantly increased top-class supervisory capability in the community, while simultaneously bringing strong international links and involvement in cutting-edge projects all over the world. South Africa has also demonstrated significant capacity for world-class instrumentation development in both the optical and radio. This is critical to research success in Astronomy and provides an exceptional way to train engineers and technicians with high-level transferable skills that are highly valued in industry.

The importance of high-performance computing and simulations has also been recognised with the creation of the Centre for High Performance Computing (CHPC) which provides South African researchers, for the first time, with access to globally-competitive computational resources.

In order to leverage these powerful advantages and overcome our weaknesses to grow the South African Astronomy community to world-class strength, we need a step-change in the strategic support and management of Astronomy. In particular, Astronomy must attract a new generation of South Africans, especially black and women, to build a new community for the future, and this community must also provide major spin-offs for the economy – skilled scientists and engineers who can work in a range of fields outside of Astronomy in the knowledge economy of the 21st century.

4 STRATEGIC CONTEXT AND FRAMEWORK

4.1 Vision

South Africa as a global centre of research excellence for multi-wavelength Astronomy

4.2 Mission

Develop Astronomy as a means to stimulate frontier science, cutting-edge technology and human capacity development within South Africa and throughout the African continent

4.3 Strategic Objectives

Strategic Objective 1: To promote South African Astronomy research and development to be globally competitive.

The research agenda shall be driven within a national strategic framework, building on existing research excellence, promoting the development of emerging research excellence, and linking to national facilities, in areas where South Africa is or could be internationally competitive.

Strategic Objective 2: To support human capital development that is representative of the national demographics and that develops world-class scientific, engineering and technical skills.

The research, technical and engineering capacity essential for South Africa to be at the cutting edge of Astronomy research, to host appropriate infrastructure and to be capable of extending the boundaries of current research shall be developed in line with the transformation agenda.

Strategic Objective 3: To support the strengthening and expansion of appropriate Astronomy infrastructure that is both world-class and scientifically productive.

A new generation of telescopes and data infrastructure which exploit the latest technological advancements shall be developed, maintained and operated with resources and technical support drawn from national and international collaborative partnerships.

Strategic Objective 4: To establish a governance framework to coordinate and integrate astronomy activities.

New governance structures for Astronomy that will ensure the effective management and development of all aspects of Astronomy activities shall be established and integrated within a single coherent framework.

Strategic Objective 5: To ensure that the advantages of Astronomy, such as Big Data and the transfer of skills, are translated into socio-economic benefits for South Africa.

The transferable technical skills and benefits emanating from Astronomy, such as Big Data platforms, high-end scientific and engineering skills, and the various innovative technology spin-offs and the localisation thereof, shall be supported within the NSI to ensure optimal contribution to the knowledge-based economy and to address the social challenges of the country.

Strategic Objective 6: To promote outreach activities in support of public awareness and education

Recognising the potential of Astronomy for capturing the public interest and thereby the attraction of students to science and mathematics education, national Astronomy outreach activities shall be strengthened and used to support the development of a more skilled workforce.

5 PRIORITY SCIENCE AREAS

Excellence in research is driven by the big unsolved science questions. The ambition for world-class Astronomy in South Africa requires that we be part of the major international efforts to tackle the open questions. A small community with limited resources cannot cover all topics. Instead we must build on existing critical mass and must develop leadership and innovation in specialised areas where South Africa can make a significant contribution to these big questions. We must also support areas that will make a real impact on transformation, human capital development and innovation, which can contribute to the broader knowledge economy.

The SKA project has forever transformed Astronomy in South Africa. The huge national investment in MeerKAT gives us the capacity to punch well above our weight and develop South African leadership. The wonderful opportunities provided by MeerKAT/SKA, SALT and HESS/CTA will drive the science priorities in South African Astronomy in the coming decade. Science related to these facilities will naturally have the highest priority.

To maximize the science outputs from these facilities, we need to build on the strong theoretical expertise in South Africa to complement observational Astronomy. Theory – including simulations and Big Data science – is essential to optimize the science returns from the major instruments we are investing in. Theory allows us to forecast, interpret and exploit data – and it requires only relatively modest investment, with very high returns.

The dramatic growth in data volumes that will arise from MeerKAT, SKA and other surveys make Big Data capacity a priority science area for Astronomy. Simulations and data science will continue to revolutionise the way Astronomy is done both locally and internationally – thus presenting an excellent opportunity for South Africa to build world-class leadership. Simulations and Big Data science also provide a natural route for South Africa Astronomy to make an economic impact through innovations that are widely applicable in other fields.

Based on the above considerations, priority areas for South African Astronomy have been identified within the following three fields (in order of the very large to the small):

1. ***Cosmology***
2. ***Galaxy formation and evolution***
3. ***Stellar and compact object astrophysics***

However, groups with excellent research in other areas, such as planetary and solar system science and asteroseismology, should also have access to adequate funding for research and training, via applications to the proposed Astronomy Grants Panel. In general, it is very difficult to predict the outcomes of new research – and there should be flexibility of planning and management to allow for unexpected opportunities. These can arise from innovative ideas, new observations or new developments in technology and modeling.

We now discuss in turn these priority fields and the focus areas within them.

5.1 COSMOLOGY

Cosmology – the study of our Universe – has made enormous strides over the past two decades, with two Nobel prizes being awarded in this period: for the discovery that the Universe is expanding faster and faster, and for the high-precision measurement of the cosmic microwave background radiation (CMB), which is the after-glow of the Big Bang. These exciting advances will continue into the next decade with a variety of cutting-edge projects currently being executed, built or planned – including the SKA. South African researchers are well positioned to play a leading role in some of these projects and to be involved at the forefront of new cosmological discoveries.

The current model of our Universe has reached a level of theoretical sophistication and precision, underpinned by observational data, that was unthinkable a few decades ago. This model describes an unimaginably large (possibly infinite) Universe, initiated by a Big Bang about 14 billion years ago. Quantum fluctuations in the primordial Universe created tiny irregularities in the Universe. These were the seeds for the formation of the first generation of stars a few hundred million years later – the epoch of the 'Cosmic Dawn', bringing to an end the 'Dark Ages', when giant clouds of hydrogen were still giving birth to those stars. High-energy radiation from these stars ionized the surrounding hydrogen – the 'Epoch of Reionisation'. The inexorable force of gravity gathered the stars into galaxies, leaving behind giant 'void' regions from which much of the matter had been sucked into galaxies. Thus began the growth of the beautiful and complex 'Cosmic Web', with galaxies grouped into clusters in filamentary and wall-like structures surrounding the voids. In order to reproduce the observed properties of galaxies and the cosmic web, we need 'Dark Matter'.

The emergence and growth of large-scale structure in the cosmic web takes place in the framework of an expanding Universe, where space is continually stretched as explained by Einstein's theory of General Relativity. Against intuition, observations showed that the expansion has been accelerating for the last few billion years, instead of slowing down under the mutual attractive pull between galaxies. This acceleration is attributed to the anti-gravity effect of the energy in the vacuum – known as 'Dark Energy'.

Tremendous progress has been made in pinning down the features of the cosmological model, but much remains to be done to achieve the higher levels of precision that can distinguish between alternatives that are still accommodated by the data. There are many open questions about the nature of key constituents of the Universe and their origin. We can summarise the key big questions where South Africa can make competitive contributions:

- *What was the primordial mechanism that generated the seeds for galaxy formation?*
- *What are the details of the Dark Ages, the Cosmic Dawn and the Epoch of Reionisation, which up to now have been inaccessible to observations?*
- *What is the mysterious dark energy that is accelerating our Universe today?*
- *Is it possible that there is no dark energy, but instead Einstein's theory breaks down on the largest scales?*
- *What is the nature of the dark matter that holds together cosmic structures?*
- *What are the properties of the elusive cosmic neutrinos that pervade the Universe?*
- *Is the Universe flat, isotropic and smooth on the largest scales?*

In order to answer these questions, we require massive surveys of the cosmic web and of the after-glow from the Big Bang, the CMB radiation.

Surveys of the cosmic web come in two forms – galaxy surveys and surveys of the pre-galactic era, i.e. from the Dark Ages to the Epoch of Reionisation (EoR). Pre-galactic surveys have not yet been achieved. Galaxy surveys up to now have nearly all been done with optical and infrared telescopes. The SKA is bringing a revolution in cosmology – it will survey the EoR and Cosmic Dawn, and it will deliver the biggest ever galaxy surveys. The SKA is potentially the most powerful cosmology 'machine' ever planned – and its other great strength is that it simultaneously covers the other two priority science areas (discussed below).

South African priorities

South Africa has an unprecedented advantage in cosmology – direct access to massive galaxy surveys that can be done with MeerKAT and then the SKA. This represents the forefront of galaxy surveys in the radio – and the SKA is predicted to perform at a similar level to the biggest optical galaxy surveys being planned, Euclid and the Large Synoptic Survey Telescope (LSST). SKA will deliver the largest ever galaxy surveys, covering three-quarters of the sky and reaching back further in time than ever before. With such surveys, we will be able to probe the primordial Universe, the dark energy and the dark matter to unprecedented accuracy, placing our cosmological model and Einstein's theory under the sharpest scrutiny. Moreover, South Africa has the expertise to start exploiting this tremendous opportunity.

South African astronomers will have access to the SKA survey instrument for Epoch of Reionisation/ Cosmic Dawn (located in Australia). In addition, the South African SKA site hosts a precursor EoR instrument called PAPER, and there are plans to host and participate in a next-generation EoR instrument called HERA. This means that we also have major opportunities for direct involvement in EoR cosmology, before the SKA is operating.

Galaxy surveys with MeerKAT/ SKA and EoR surveys on SKA and its precursors require the theoretical skills to understand the cosmological model at the deepest levels and then to design observational tests of the model. These surveys are both also at the frontiers of Big Data and of simulations. South African cosmology has the expertise that can deliver on all three fronts – theoretical modeling, simulations and Big Data science – given the necessary strategic support. Opportunities to participate in world-class optical galaxy surveys, such as the SDSS and DES, have been exploited on an individual basis, leading to excellent research and training outputs. Opportunities for future national involvement in such surveys include the LSST, which promises to deliver major returns for small investment, especially for Big Data science. LSST will also find large numbers of supernovae, which are key probes of dark energy, where we have strong expertise.

Studies of the structure and evolution of our own and nearby galaxies will probe "fossil" evidence of the Big Bang that is complementary to studies of very distant sources. This near-field cosmology offers a particularly attractive opportunity as it draws together the three priority science areas of this strategy. Major advances will be possible with SALT and MeerKAT follow-up on the Gaia and Euclid space missions.

The South African community has also developed a highly productive involvement in some of the leading CMB experiments, such as ACTPol. Critical mass in this science has recently been built and will allow us to contribute competitively in probing the primordial Universe. In particular, the CMB contains possible signatures of primordial gravitational waves, which can rule out large classes of primordial models. The CMB also allows us to estimate the mass of the neutrinos. Combining CMB and galaxy data gives higher precision on the neutrino masses than laboratory experiments. In general this combination of datasets is a very powerful method.

5.2 GALAXY FORMATION AND EVOLUTION

Tracing how galaxies evolve over the history of the Universe, from the Epoch of Reionisation (EoR) through to the assembly of the Hubble Sequence and the large clusters that we see in the Universe today, is a key goal of modern Astronomy, because galaxies are central to all aspects of astrophysics and cosmology. Key questions in galaxy evolution that are the central focus of many of current and upcoming forefront telescope facilities, and where South Africa can make significant contributions, include:

- *When did galaxies assemble most of their stars and where in the galaxy does this occur?*
- *What is responsible for the remarkable dichotomy in properties between 'blue' and 'red' galaxies?*
- *What were the objects responsible for reionizing the Universe, and how did reionization proceed?*
- *How do galaxies trace the underlying dark matter distribution, and what do galaxies tell us about the nature of dark matter?*
- *How do supermassive black holes form in the centres of galaxies, and what role does feedback from these black holes play in the evolution of galaxies?*

To make progress on these key astrophysical questions, one needs large observational surveys spanning the whole of the electromagnetic spectrum. Stars and therefore galaxies emit the bulk of their radiation at ultra-violet to near-infrared wavelengths. While the radio is essential for measuring the neutral hydrogen content of galaxies, the molecular gas from which stars form is best measured in the infrared and sub-millimetre bands. Black hole accretion is most easily probed in radio and X-rays. For gamma-rays, upcoming facilities such as CTA can overcome the current main limitation of positional accuracy. Finally, perhaps the greatest uncertainty in galaxy evolution studies today is "feedback", describing all the energetic processes (from stars, black holes, and supernovae) that are responsible for self-regulating the growth of stars, gas, black holes, and heavy elements in galaxies, and that make galaxies the truly complex and beautiful objects that they are.

Galaxy evolution science is currently being driven observationally by multi-wavelength data in the optical and near-infrared wavelengths. Leading facilities around the world include those available to ESO-member countries, who have access to four 8m class telescopes with probably the best instrumentation programme in the world. Various parts of the US community have access to several 8 to 10m and 4 to 6m class telescopes, and Australia, in collaboration with the UK, has conducted leading spectroscopic surveys on the AAT. Such facilities provide both the deepest observations of relatively small areas of sky to study galaxies in detail, coupled with large-area imaging and spectroscopic surveys to gain the necessary statistical measurements of galaxy properties from the local volume through to the EoR.

South Africa is well positioned to lead breakthrough science at radio wavelengths with the commissioning of MeerKAT, followed by the SKA, and potentially at gamma-ray wavelengths with the CTA. This will enable South Africa to probe galaxies in an unprecedented range of wavelengths. However, to maximize the value of these facilities for galaxy evolution studies, it is crucial that we also have access to world-leading facilities (in addition to SALT) in the wavelengths *between* radio and gamma-rays.

In the radio, MeerKAT already has several approved surveys whose key goals are to address the formation and evolution of galaxies. These surveys will provide revolutionary, cutting-edge science by 2019, when they will far outstrip similar surveys. Furthermore, given the South African leadership and involvement in these surveys, they will help to ensure that South Africa is well positioned to lead the science in similar areas with the full SKA.

South African priorities

In order to fully exploit the scientific content of this data, a number of ancillary data is minimally required: (1) Spectroscopic redshifts for objects in the HI and continuum deep fields; (2) Access to ground- and space-based survey data to complement the deep fields; (3) Access to multi-wavelength data on MeerKAT galaxies. Note that it is not only important to have access to data from ongoing surveys, but ideally South Africa needs to have significant access to multi-wavelength facilities to *lead* the cream of the science that will come from MeerKAT and SKA, rather than simply participate and contribute to it.

Access to leading observations at optical and near-infrared wavelengths is therefore crucial for numerous reasons, including

- The bulk of work in South Africa comes historically from the optical and so near-infrared is essential as one moves to higher redshift.
- To measure the redshift of galaxies, yielding distance information to convert from observed flux density to physical quantities.
- To measure the stellar mass in galaxies that is dominated by the massive old stars which mainly emit at near-infrared wavelengths.
- To provide additional information on the physical processes occurring in galaxies, such as black-hole accretion activity and star-formation activity.
- To provide an estimate of the dust content of galaxies, and thus provide an estimate of the preponderance of obscured galaxy formation.

South Africa must explore access to such facilities or provide a competitive South African-led telescope/instrument combination, and ensure that the galaxy evolution science from MeerKAT and the SKA is led from South Africa. South Africa should also explore building a 4m class competitive facility, or a new instrument on either SALT itself or a 4m class telescope, where a massive integral-field unit and inexpensive mass-produced spectrograph would reduce the cost whilst retaining a high scientific impact.

In the millimeter to infrared wavelengths there is no obvious path for South African leadership although there may be a niche for a 20-30m mm-wave telescope in the southern hemisphere, comparable to the productive IRAM and the upcoming LMT, provided that a good site can be found in Southern Africa.

It is clear in the field of galaxy formation and evolution that MeerKAT and the SKA will make a major, world-leading impact. However, the highest-profile science will be enabled by combining this radio data with multi-wavelength observations from other facilities. On the imaging side South Africa does not need to make a large investment in a new facility although exploring strong connections with LSST for future synergies with the SKA is crucial. On the large-scale spectroscopic survey side, as well as investigating the possibility of a South African built facility, a fruitful avenue to explore is to contribute to European or US-led multi-object spectroscopic facilities. This contribution should be predominantly in-kind, i.e. trading time on local facilities and local instrument-building and software contributions. The aim is to provide strong human capacity development and skills training, with a “proudly South African” aspect for these projects.

5.3 STELLAR AND COMPACT OBJECT ASTROPHYSICS

Stars are fundamental constituents of the Universe. All the chemical elements except hydrogen and helium have mainly been produced in the interiors of stars and sprayed all over the Universe through supernova explosions. Galaxies are populated with stars and many of these stars are almost as old as the Universe itself. Their impact on our understanding of the Universe has been profound. A fundamental driver of astronomical research is the question: “Are we alone in the Universe?” Life as we know it needs a planet to host it, and a star nearby to provide the heat on which it depends.

The overall aspects of stars and stellar evolution are reasonably well understood, but there are many uncertainties in our understanding of the relevant physical processes. This has serious effects on the determination of stellar ages, crucial for the study of the evolution of the Milky Way Galaxy and the characterization of planetary systems, and on the studies of the latest phases of stellar evolution and the resulting production of all elements beyond hydrogen and helium.

The lives of most stars, especially those in binary systems, end as compact objects: white dwarfs, neutron stars, black holes. Amongst these some of the most energetic physical processes in the Universe are found, news of which is conveyed to us through high energy radiation such as gamma-rays and X-rays, as well as ultraviolet, optical, infrared and radio waves. Beyond black holes of mass similar to the Sun, it is now clear that there are supermassive black holes in the centres of most galaxies and these have a profound influence on the evolution of the galaxy. Compact object astrophysics is multi-wavelength Astronomy in its broadest scope.

Extreme astrophysical events such as cataclysmic explosions, gas flowing at speeds close to that of light, and black hole accretion are a key area for astrophysics in the 21st century. The extremes of physics (density, temperature, pressure, velocity, gravitational and magnetic fields) experienced in these environments provide a unique glimpse at the laws of physics operating in extraordinary regimes. Nearly all these events call attention to themselves as transient changes in brightness somewhere in the electromagnetic spectrum. Much deeper surveys for transients are in development, including a MeerKAT key survey for radio transients.

South African scientists have for decades made world-class contributions in pulsating stars (giving vital information about distances in the Universe and detailed physics of stellar interiors) and stellar population studies (revealing the ages, chemical compositions, and star formation histories of the galaxies in which they live). This has been done with telescopes at the traditional optical observatories in South Africa.

Studies of compact objects in close binary systems have been a particular strength of South African Astronomy, also for decades. These studies began in the optical, but have been extended to the highest energies with South African participation in HESS, along with international access to the best X-ray observatories in space.

The key questions in stellar and compact object astrophysics, where South Africa can be competitive, include:

- *What can stars in nearby galaxies tell us about the origin and evolution of galaxies?*
- *What are the final stages in the lives of Asymptotic Giant Branch stars, which recycle key chemical elements previously locked up in their interiors.*
- *Which stars harbour planets, especially Earth-sized planets with potentially habitable environments?*

- *What physical processes govern mass accretion onto compact objects?*
- *What is the nature of thermonuclear burning on the surfaces of compact objects?*
- *What are the parents of Type Ia supernovae, the objects which showed us the existence of Dark Energy?*
- *What is the origin and mode of acceleration of the highest-energy cosmic rays?*
- *What is the nature of space-time under the extreme conditions in the vicinity of black holes and neutron stars?*
- *Is there evidence for new physics beyond the Standard Model of particle physics, potentially found in such extreme environments?*
- *How are the relativistic jets from compact objects launched, accelerated, and collimated, in some cases over many thousands of light years?*

Beyond these specific questions, possibly the most exciting prospects come from unexpected discoveries made in future radio and gamma-ray surveys for transient objects.

South African priorities

Solving these problems requires the closest co-ordination and interactions between observational astronomers and theoretical and computational astrophysicists. New telescopes and instrumentation, critical-mass theoretical groups, better and faster computers are the key ingredients which will unlock progress in these areas.

A multi-wavelength approach in observational facilities and overall approach is critical to success. South Africa has a unique opportunity to exploit the remarkable span of wavelengths, which will soon be at its disposal. At the longest wavelengths, dazzling facilities under construction in the radio regime; visible and near-infrared light with SALT, the largest optical telescope in the southern hemisphere, along with other optical telescopes; reaching all the way to gamma-rays detected by HESS and ultimately CTA. These facilities will elevate southern Africa to the position of the world's leading multi-wavelength Astronomy centre. Furthermore, supplementary observations on open-platform space observatories at infrared, X-ray, and gamma-ray frequencies will often complement these facilities.

The upcoming generation of astronomical survey facilities at optical, radio, X-ray and gamma-ray wavelengths will probe the transient Universe at unprecedented cadence and sensitivity. MeerKAT will be the prime radio transient survey machine in the coming decade through round-the-clock commensal searches and dedicated follow-up. This will be combined with a linked optical facility (MeerLICHT) as well as follow-up by SALT (and potentially a 4m class telescope) to continuously monitor and instantaneously characterize the optical-radio transient sky.

It is hard to overstate the importance of the LSST, a real-time survey of the Universe on a large telescope. Not only will it become the prime source of optical transient discoveries, its output will touch almost every area of astrophysics. South Africa involvement in LSST will reap huge rewards with modest funding requirements.

Many neutron stars manifest themselves as “pulsars”, magnetized neutron stars that rotate about their axis as fast as several hundred times a second. The use of pulsars to probe fundamental physics is a key science area of the SKA. MeerKAT itself will deliver world-leading observations of pulsars through one of its key surveys. This offers a unique opportunity to develop local, world-class expertise in pulsar science, culminating in science exploitation of the SKA.

6 PROGRAMMES TO SUPPORT ASTRONOMY AND ITS SPIN-OFFS

Astronomy holds huge potential for the development of world-class research and training and for spin-offs that promote a knowledge-based economy. This Strategy guides us via the strategic objectives and key priorities that are identified as necessary for success. In order to achieve this success, we need a set of inter-locking programmes.

6.1 HUMAN CAPITAL DEVELOPMENT AND TRANSFORMATION

Through recent large-scale investments in Astronomy facilities and people, the community has grown significantly over the past decade. A strategic human capital development (HCD) and transformation programme is necessary to organise the future growth in a coherent way. This programme will train talented astronomers who will exploit world-class South African and international facilities to produce excellent science. Many skilled scientists trained through this programme will feed into the national system of innovation and thereby contribute to the South African knowledge economy. A strong embedded focus on transformation in this programme, with additional key strategic interventions, will address the existing demographic imbalances in the Astronomy community, particularly relating to black and women scientists.

Key success factors for this programme include:

- Astronomy research groups at universities and national facilities that are funded to deliver excellence in research and training. A crucial component in developing such groups is an increase in the number of permanent academic/research positions to achieve critical mass and continuity.
- An integrated national HCD programme that builds on the SKA Bursary Programme and the NASSP.
- Undergraduate and postgraduate training programmes that deliver a world-class research and teaching experience. This requires national partnerships so that better established groups can assist emerging groups, especially at historically disadvantaged institutions, to develop their core training programmes. At postgraduate level this means building on the existing NASSP structure.
- Strategic bursary and fellowship funding of Astronomy students, postdoctoral researchers and academic/research staff at universities and national facilities. Bursary funding levels must follow the example of the SKA HCD programme and be competitive enough to attract talented black students into Astronomy.
- Strategic interventions to normalise transformation, which should include: the focused recruitment and training of black students in undergraduate Astronomy programmes; strong support for growing existing Astronomy programmes at historically disadvantaged institutions; support for an Astronomy bridging programme until the main student pipeline is established; and an Astronomy leadership transformation programme.

6.2 BIG DATA SCIENCE

Astronomical instrument development changes at a rapid rate due to the exponential growth of computing power, storage, bandwidth and data volumes. Current-generation experiments produce hundreds of gigabytes of data per day. Facilities like MeerKAT, HERA and eventually LSST will take of the order of 10 terabytes of data per day while the SKA will be capable of vastly larger data rates. The South African Astroinformatics Alliance (SA3) is a joint initiative of SAAO, SKA, HartRAO and NRF which has made a start in facilitating access to international Big Data by providing mirror sites of key astronomy data-bases at CHPC. SA3 is providing training via NASSP and the IAU OAD in the tools used to access, manipulate and visualise Big Data.

The ground-breaking discoveries will increasingly be made by those groups that can work effectively with petabytes of data. South African Astronomy will need to develop cutting-edge Big Data skills, including new statistical and computational techniques, as well as Big Data infrastructure, including high-end storage, computing and networking. This will allow us to take advantage of the future massive datasets to produce new science results. The resulting leadership in Big Data science will provide a platform for Astronomy to make major contributions to Big Data in the broader context of the South African knowledge-based economy.

Key success factors for this programme include:

- The formation of an SKA Data Centre that effectively serves the Astronomy community and maximises the science output from MeerKAT/ SKA.
- Support for SA3 and training in Big Data Astronomy through targeted courses and workshops. This will allow the local Astronomy community to maximize scientific output from SKA data.
- Sufficient computing power to enable analysis of large datasets and the development of new data analysis techniques.
- High enough internet bandwidth to allow access to astronomical data stored on large local and international data archives. These archives are a crucial resource for competitive research in multi-wavelength Astronomy.
- Appropriate trans-disciplinary skills training for Astronomy postgraduates. This will facilitate the application and transfer of Astronomy-related expertise to industry and business.
- Increased research productivity and enhanced quality and impact of publications in Big Data, following from increased funding for research groups.

6.3 THEORETICAL MODELLING AND SIMULATION

Internationally competitive science requires world-class theoretical capacity to exploit world-class data. Theoretical modelling and simulation are essential for optimising the science returns from the major instruments we are investing in, and there is a strong theoretical base for us to build on. Massive numerical simulations that model the behaviour of astrophysical systems are needed in order to predict and interpret observations – and this requires only relatively modest investment, with very high returns.

Key success factors for this programme include:

- Sufficient high-performance computing power and ICT expertise for computational research at universities and facilities. For nearly all cutting-edge international projects, high-performance computing is a critical resource for achieving excellent science.
- Significant South African involvement in the MeerKAT Large Survey Projects and the SKA Science Working Groups. We need to capitalise on investment in MeerKAT to ensure that we play a leading role in SKA science.
- Key involvement in LSST science collaborations. This will also deliver added value to MeerKAT/ SKA science.
- Strengthening international science collaborations in theory that are relevant to the key priority areas – a critical resource for building further theoretical capacity.
- Increased research productivity and enhanced quality and impact of publications in theoretical modeling and simulation, following on greater funding for research groups.

6.4 INSTRUMENTATION

Building a coherent instrumentation programme in South Africa will help us to remain competitive in the priority science areas. Nearly all progress in Astronomy involves the development of new instrumentation. Instrument-building capacity will allow us to leverage participation in world-leading international projects through in-kind contributions. The development of specialised instrumentation to tackle specific Astronomy questions usually leads to significant scientific advances, and by developing this capacity we can add to our scientific repertoire in leading high-impact Astronomy projects of the future.

Key success factors for this programme include:

- Funding for the development of small, medium and large instruments. Developing our own instrumentation in focused areas will contribute to producing internationally competitive science from South Africa.
- Instrumentation development that is internationally competitive, scientifically relevant and implementable. Large- and small-scale instrumentation development allows us to lead our own science projects and to buy into international projects – while at the same time growing our instrumentation skills development and training.
- Development of high-quality instrumentation with applications relevant to the science, engineering and industrial sectors. We should showcase industry applications of innovations in Astronomy technology.

6.5 INFRASTRUCTURE AND NEW INVESTMENTS

The baseline of Astronomy infrastructure funding is the maintenance and operation of existing facilities. The next essential requirement is that the internet bandwidth and data infrastructure available to the facilities and the research community must be upgraded to world-class standards.

In order to further enhance excellence in research and training, we need to consider possible innovative extensions to the existing facilities. A peer-review panel should consider proposals for new projects. Such proposals should show that they build on our existing advantages to strengthen our science at an international level, and that they will produce high returns in research and training.

Key success factors for this programme include:

- Support for MeerKAT operations and maintenance, in order to maximise the high-impact science return from MeerKAT and then the SKA.
- Support for SALT operations and maintenance, which is core to our success in optical Astronomy and to exploiting the multi-wavelength opportunities in each of the priority science areas.
- Upgrading of the internet bandwidth and data infrastructure to world-class levels. This is indispensable if we are to realise our potential to produce world-leading science from MeerKAT.
- Funding to maintain the South African participation in HESS/ CTA, delivering high-impact science for a small investment.
- Funding to support South African participation in the LSST project, which promises to deliver major returns from a small investment, especially for Big Data science, and will provide high-impact science in each of the priority areas.
- Funding to participate in the African VLBI Network (AVN), an important strategic initiative that is closely aligned to the SKA and will build scientific ties with the European and Australian VLBI networks.
- Funding to participate in the HERA project. HERA will deliver high-impact science and provide an exceptional complement to local facilities at relatively low cost.
- Funding to acquire a 4m-class telescope with a wide field of view and locally designed and built kilo-fibre spectroscopy. This is key to enhancing our optical capabilities and delivering crucial follow-up spectroscopy for MeerKAT and LSST.
- Support for innovative South African based projects, which will deliver new excellent science and complement our existing local facilities.

6.6 INTERNATIONAL COLLABORATION

International collaboration in observation, instrumentation and theory has been essential for the development of South African Astronomy to international levels. It will be even more important in future, given the growing role of large international projects that perform the full chain of science, from instrumentation and engineering, to observations and data analysis, to modelling and simulation. By participating in high-impact international projects and building strong collaborative partnerships we will extend our competitiveness in research and innovation. In-kind contributions from South Africa to international projects can leverage access to international facilities.

Key success factors for this programme include:

- Ongoing support for participation in HESS/ CTA and the African and European VLBI networks (AVN and EVN). These projects are strategically important to deliver excellent science and training in priority science areas.
- Support for a nationally organized participation in the major new LSST project, giving access to world-class data and training.
- New bilateral linkages with key partners. Strategic links with international partners yield numerous benefits ranging from science and training to instrumentation and innovation.
- Skills training and human capacity development through international partnerships. We must take advantage of international expertise to advance Astronomy research, innovation and training in South Africa.
- Support on a smaller scale for continued participation in world-leading international experiments, including CMB and galaxy surveys. These projects will have excellent return in terms of high-impact science and extensive training opportunities.
- Access to international Astronomy data archives, which will provide numerous opportunities for Big Data and other science and training.

6.7 INNOVATION

The plethora of developments in Astronomy, from instrumentation to Big Data, create the basis for technology development and spin-offs to advance activities in other sectors, and technology transfer to promote socio-economic development. The success of corporate social investments in communities near astronomy facilities has already been demonstrated, but the potential to do more must be exploited for improving the quality of life and the creation of wealth. Public-private partnerships and partnerships with other entities within the NSI will be needed to translate opportunities arising out of Astronomy into other productive sectors and into socio-economic benefits.

Key success factors for this programme include:

- Business training for astronomy postgraduates to promote the transfer of skills to other sectors of the economy – equipping them to be more effective in applying their skills in other sectors.
- Public-private partnerships to capitalise on spin-off opportunities, with great potential for economic growth and job creation.
- Corporate social responsibility investments by high-value technology companies that are contracted to undertake technical work for Astronomy.

6.8 EDUCATION AND OUTREACH

Critical to this Strategy is education and outreach – using Astronomy in schools and taking the message of Astronomy and SET to the public. Astronomy has the ability to inspire the youth and attract them into SET careers. An increased number of SET graduates will have an impact on the knowledge economy. It is also important to increase public awareness of and pride in Astronomy, taking into consideration the cultural diversity and indigenous knowledge systems within South Africa.

Key success factors for this programme include:

- Implementation of key projects that develop resources for Astronomy education and outreach, drive engagement activities for schools and the public, and support training of science communicators and educators. These projects should balance short-term inspirational activities with long-term systemic interventions.
- Education and public engagement activities in Astronomy-related institutions, especially historically disadvantaged institutions, coupled to their research and training programmes, and in collaboration with education and outreach communities. We need to develop a closer connection between scientists and the public, especially the youth.
- A coordinated and well-resourced national education and public outreach programme, building on existing national and international SET education and outreach infrastructure.

6.9 GOVERNANCE

A key requirement for the development of Astronomy in South Africa is a coherent governance structure at the national level that strategically manages Astronomy facilities and funding. The establishment of the Astronomy Sub-agency and its Astronomy Advisory Council has laid the foundation. Due consideration should be given to the effectiveness of the current institutional arrangement and the possible need for any further structural reforms to strengthen the governance of astronomy.

In order to consolidate this progress, astronomers must play a key role within the governance structure. This requires first and foremost a standing Astronomy Grants Panel of expert local astronomers, with a rotating chair and membership, to provide high-level scientific peer review with continuity. Through the Astronomy Grants Panel, the Astronomy Sub-agency can ensure that available funding for research and training is directed according to this Strategy. Additional peer-review panels, including international experts where appropriate, should be set up to consider proposals for major new projects.

Finally, this Strategy itself should be reviewed at mid-term.

Key success factors for this programme include:

- An overhaul in the management of funding by the Astronomy Sub-Agency to improve efficiency and focus and to meet the needs articulated in this Strategy.
- Establishment of the standing Astronomy Grants Panel by the Astronomy Sub-agency. This Panel will provide stability and continuity of scientific peer review and will be able to monitor the performance of grant-holding groups.
- Establishment of a framework for peer review of proposed new instruments and other projects. This will include a national committee of expert astronomers, with a small number of international advisors, to consider project proposals on a fixed timetable and report to the Astronomy sub-Agency.
- A mid-term Review of the National Astronomy Strategy and its implementation, conducted by the Astronomy sub-Agency with co-opted national and international astronomers. New developments will inevitably require reconsideration and adjustments of the strategic focus.

7 CONCLUSION

This Strategy expresses the national intent of developing and advancing Astronomy in South Africa, and within the region, as a global hub for multi-wavelength research and development. This effort is based on historical investments made in optical, radio and gamma-ray astronomy, which already provide a geographic advantage for multi-wavelength Astronomy.

In addition to the scientific advancement, there are many co-lateral benefits that will accrue from the committed investments, especially in the area of human capital development and technological advancements, which should be harnessed for socio-economic development and growth. If optimally captured, these benefits could assist in advancing South Africa's drive to a knowledge-based economy.

The Strategy reflects the strategic positioning and orientation of Astronomy within the country, for which oversight responsibility lies with the Department of Science and Technology. The implementation plan for this strategy will be developed and implemented by the Astronomy Sub-agency of the National Research Foundation and will be periodically reviewed to assess alignment with the Strategy. The Strategy will also be periodically reviewed to take into account new developments in the field that hold significant benefits for the country.