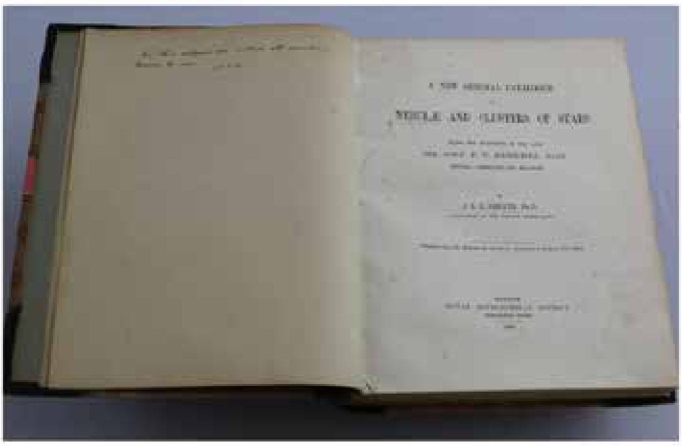
The Cosmic Journeys of Galaxies, Stars, Planets and People

A Research Programme for the
Armagh Observatory and Planetarium






This document was produced by the staff of the Armagh Observatory and Planetarium, in particular through discussions and contributions from the tenured astronomers, together with input from the Governors and the Management Committee. The document was edited by the Director, Michael Burton and designed by Aileen McKee.

Produced in March 2017

Front Cover Images

The Four Pillars of the Armagh Observatory and Planetarium

Research

The Armagh Observatory was founded in 1790 as part of Archbishop Richard Robinson's vision to see the creation of a University in the City of Armagh. It is the oldest scientific institution in Northern Ireland and the longest continuously operating astronomical research institution in the UK and Ireland.

Outreach

The Armagh Planetarium was founded by Dr Eric Lindsay, the seventh director of the Observatory, as part of his vision to communicate the excitement of astronomy and science to the public. It opened on the 1st of May, 1968 and is the oldest operating planetarium in the UK and Ireland.

History

Dreyer's NGC – the New General Catalogue – was published in 1888 by JLE Dreyer, fourth Director of the Observatory. It has been used extensively by astronomers ever since. This is his annotated copy, complete with all known corrections at the time. Galaxies and nebulae are still often cited by their NGC number, e.g. NGC 1952 (Crab Nebula), NGC 5194 (Whirlpool Galaxy) and NGC 2359 (Thor's Helmet).

Heritage

The Observatory has been measuring the weather conditions at 9am every day since 1794, a meteorological record covering more than 200 years, believed to be longest standing in the British Isles. This image shows the sunshine recorder and anemometer. On the Observatory building behind lies the original Robinson Cup Anemometer, designed by third Director Romney Robinson, the basis for anemometer designs the world over.

Table of Contents

Foreword

My predecessor, Archbishop Richard Robinson, founded Armagh Observatory in 1790 with the aim of pursuing research in astronomy and it remains the oldest scientific research establishment in the United Kingdom and Ireland still operating from its original site. It is important that any organisation engaged in scientific research undertakes regular reviews of its work and makes plans and proposals for future work, including an assessment of the infrastructure and staffing it needs to undertake this work. The present document provides an overview of the proposed research plans for Armagh Observatory for the next few years.

In the 1960s, the then Director of the Observatory, Dr Eric Lindsay, saw the need for the developments in astronomy, both in Armagh and in other institutions throughout the world, to be disseminated to a wider audience and particularly to the local community. To this end, the Armagh Planetarium was opened in 1968 to provide the general public with an insight into the latest developments in astronomy, and at the same time inspire them and perhaps motivate in them an inquisitiveness to learn more about astronomy and other areas of science.

Astronomy is arguably the area of science most readily appreciated by a wide audience, a source of inspiration for human curiosity. One only has to stand outside on a clear night to see a myriad of stars, and to allow one's mind to reflect on questions such as how this came into being and where we fit into the universe. The motto of the institution "the Heavens declare the glory of God" remains as apt today as when inscribed on the fabric of the Observatory during its foundation. The Planetarium now seeks to offer answers based on science to these questions in a manner accessible to the non-specialist. The present document points to the ways in which the research being undertaken by the astronomers in Armagh Observatory can further our understanding of such fundamental issues.

Over the past three years, the Board of Governors and the Management Committee of Armagh Observatory and Planetarium have been working, first with the Department of Culture, Arts and Leisure and now with the Department for Communities, to bring together the expertise both of the research astronomers in the Observatory and of the educational staff in the Planetarium, to exploit the synergies between the two 'wings' of the organisation. We have appointed Professor Michael Burton as Director of the entire organisation and he is now leading the development of Armagh Observatory and Planetarium as it moves forward as a single, coordinated scientific establishment.

I welcome the direction outlined in the very positive analysis provided in this document, and I look forward to seeing the progress that is made in the coming years.

Archbishop Richard Clarke
Chairman
Board of Governors of Armagh Observatory and Planetarium

The Cosmic Journeys of Galaxies, Stars, Planets and People

A Research Programme for the Armagh Observatory and Planetarium

Executive Summary

Armagh contains an historic observatory and a renowned planetarium. There is a proud record of achievement in astronomical research that extends across four centuries. This recognition as a centre for research and as a centre for outreach, together with its history on the international stage of science, and the heritage of its building, telescopes and instrumentation, provides four substantial pillars upon which the Armagh Observatory and Planetarium stands.

Armagh is the oldest scientific research institution in the UK and Ireland still retaining this activity on its original site, much of it within its original building. The four pillars of Armagh – research, outreach, history and heritage – make it a unique and special place, visible on the world stage despite its modest size. In the modern age of advanced communications systems, our location and often cloudy skies are no longer impediments to astronomical observation. From Armagh we can directly access and use some of the largest and most powerful telescopes – on Earth and in space – for our research.

The pillars of Armagh support an institution that is exploring the cosmos. They parallel four seminal questions that have long challenged humanity whenever and wherever they gazed up to the night sky. Is there life elsewhere? How did the universe begin? What is the nature of space and time? How does outer space affect us here on Earth? These enduring questions can be directly related to corresponding themes for the research programme at Armagh. These are on the existence of extra-terrestrial life, on the fate of the universe, on the nature of black holes and on cosmic impacts to life on Earth.

In turn, each of these themes provides focus to specific research topics at Armagh where questions are investigated and understanding advanced. These centre on the active Sun and its relation to flares seen in other stars, on planetary systems both near and far, and on the lives of stars, from their formation to their death. At Armagh this last topic links to research on the effects and influences of massive stars, where stellar death – often a cataclysmic event of unimaginable violence – has profound impacts on galaxies, as well as providing a laboratory for studying extreme physics, such as the formation of black holes and the acceleration of the most energetic particles in nature, some of which strike the Earth as cosmic rays.

These topics form the core of the research programme at Armagh. Carrying it out requires access to a range of facilities and capabilities. Some are modest and locally housed. Others are substantive and require international efforts to build next generation facilities, where Armagh would be a participant in large collaborative projects.

High calibre and motivated staff, adroit in the use of these facilities, is the key to maintaining the vibrancy of the research programme at Armagh. We need to ensure we can access a range of facilities as players on the world stage, with special expertise to apply them to our areas of speciality, able to tackle key scientific problems. The introduction of a senior fellowship programme, as well as restoring investment in the PhD student programme, would ensure the vitality and the continual renewal of the research effort. Refurbishing the on-site housing would also enable AOP to position itself as an attractive destination for leading academics through sabbatical visits. The Planetarium Dome may be used to aid in the visualisation and interpretation of the 3D data sets that are now being increasingly obtained with frontline research facilities.

The document here describes how Armagh can remain a leader on the international stage of science through conducting and facilitating world-leading astronomical research.

Seminal Questions for our Age

The 21st century has embraced a golden age of scientific discovery and technological advance across the whole spectrum of human activity. Amongst this vastness, astronomy and space science have enabled us to explore the universe, from our nearest neighbours in space to the beginning of time itself.

This exploration raises seminal questions that have challenged humanity across history and invoke wonder amongst young and old alike, such as:

- What is that bright new star in the sky?
- Is there life elsewhere?
- How did it all begin?

In modern day society, familiar with the stunning photographs obtained from telescopes like the Hubble Space Telescope and the pictorial language of modern astronomy, new questions have arisen, such as:

- What are black holes?
- How does outer space affect life here on Earth?

Now, when a new star appears in the sky, we can usually explain what it is. The other four questions remain, however, substantially unanswered. In setting its research goals for the next decade, the Armagh Observatory and Planetarium is driven by such enduring themes. They continue to represent the big science questions for our generation. In pursuing their answers and then communicating the discoveries we make, we can help to ignite a sense of wonder about our place in the cosmos. In turn, this can inspire the next generation about science and the methodology we use to understand the world around us.

The fundamentals of science, the basic premises behind our understanding of physics and chemistry, are the same across the universe. The knowledge we gain as we pursue the unknown drives the development of new technologies. The tools astronomers use to pursue their research, for instance the spectrometers attached to their telescopes which disperse light into its colours, so allowing them to identify the constituents of the cosmos and measure their motions through space, apply the same principles we use on spacecraft when remote sensing the Earth to monitor the health of crops or map the distribution of minerals in the rocks. The techniques are common across science. New understanding and developments in one field can be applied elsewhere to improve the quality of human lives and for building a better society. Following our natural curiosity to seek answers to big questions about the cosmos, by pursuing research into the unknown, can have profound consequences. It can lead to the betterment of civilisation. Astronomy, as the queen of the sciences, serves to ignite passion about science and technology. Armagh can play a pivotal role in this endeavour.

Armagh Observatory, with the 1790 and 1827 Domes in the background and the Robinson Dome in the foreground. Inside the latter can be seen the 10-inch refracting telescope built for the Observatory by Howard Grubb of Dublin in 1885. The firm of Grubb Parsons later went on to construct optical components for many of the great telescopes around the world, including the Anglo Australian Telescope, the UK Infrared Telescope, the Isaac Newton Telescope and the William Herschel Telescope.

Pivotal Challenges for the Armagh Observatory and Planetarium

Frontline scientific research and public outreach can be intertwined through the agency of education. The unique setting of Armagh, combining the Observatory and Planetarium in one institution, within an environment that is rich in astronomical history, enables these complementary facets to converge. This special combination underpins the scientific programme upon which Armagh has embarked.

The research at Armagh is centred on four themes, encapsulating the enduring questions we have posed above. In turn, these themes each provide focus to four topics where they can be addressed. They form the base underpinning the research programme at Armagh. The themes and their research topics are as follows:

Themes	Research Topics
Is there life elsewhere in the Universe?	• the Solar System • exoplanets around other stars • star formation and the interstellar medium connection • the stellar life cycle
What is the fate of the Universe?	• the first stars • calibration of the distance scale for the universe • supernovae and their progenitors • the physics of supernovae
What are Black Holes?	• the lives of massive stars • the physics of extreme processes • stars in the early Universe • gravitational waves
What external factors affect life on Earth?	• variability of the Sun • asteroid and comet impacts on the Earth • flare activity in the Sun and other nearby stars • nearby novae and supernovae

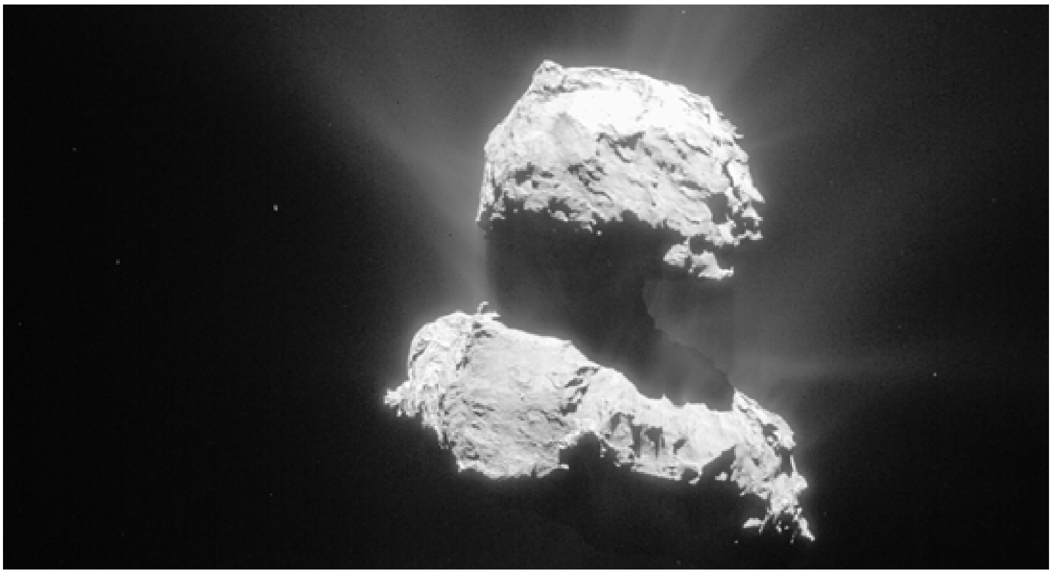
Themes Underlying the Research Programme of Armagh

Theme 1: Is there life elsewhere in the Universe?

Four hundred years ago, Galileo Galilei began the telescopic exploration of our Solar System. His observations eventually helped to place the Sun, rather than the Earth, at the centre of the Universe in the collective consciousness of humanity. Today, we know that our Sun and the Solar System are not unique, but a minuscule component of only one among countless galaxies, each populated by billions of stars and stellar systems. We are now exploring the Universe with much larger telescopes than Galileo's, yet one basic question remains unanswered: are we alone? An answer to this question is a primary goal of Astronomy and would represent the most important discovery in the history of humankind.

By studying our own Sun and its planetary system, and by devising new techniques to look for exoplanetary systems around other stars, we seek to understand the recipe for life, and how and where it might flourish in the Universe. We need to comprehend how the chemical elements necessary for life are created inside stars and recycled into interstellar space, from where new stars are formed, with associated planets, asteroids and comets. Thus, we need to explore the life stories of stars, their internal physics and their interactions with companions. We need to explore the rocky debris in the Solar System that represents not only actual planetary building-block material, but also the reservoirs of water and carbon-bearing compounds necessary for organic life to exist. Studying the changes to the orbits of these bodies, their collisional history, and how their surfaces change when affected by space weathering, can reveal how key materials may be delivered to planetary surfaces, to then participate in the chemical reactions that may eventually lead to life.

The other two key requirements for life are stability and good timing. Planetary systems must be cleared of debris so that life has the chance to evolve. If the planets can indeed remain there over long timescales, how do their host stars evolve during this time? Living organisms may be destroyed by extreme stellar flares. Life bearing planets must be protected from these. Can life survive or develop during and after the late stages of stars, for instance while the host star is dying as a white dwarf? Some planetary systems, including our own, have undergone extended periods of upheaval that act both as a catalyst and as an impediment for the development of life. Orbits must lie within a star's habitable zone to allow, for instance, liquid water to exist. Do planets exist and survive within these zones around other stars? To successfully predict where life might emerge and proliferate, we must develop a deep understanding of the birth and aging of star and planetary systems.



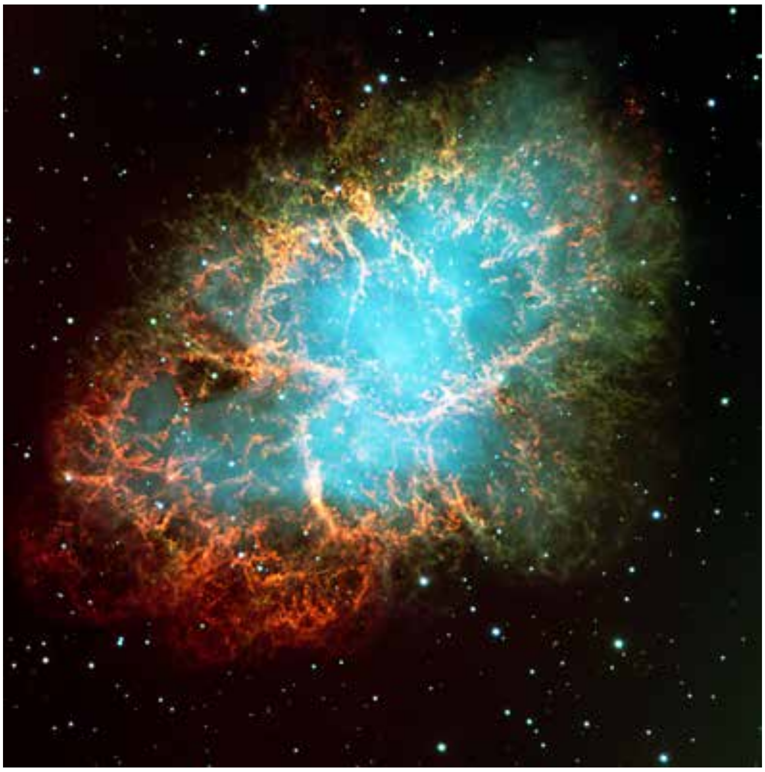
Comet 67 P/Churyumov-Gerasimenko, visited by the Rosetta spacecraft from 2014-16. Such kilometre-sized bodies were the building blocks from which the planets originally formed.

Theme 2: What is the fate of the Universe?

Nearly one hundred years ago, Edwin Hubble made the remarkable discovery that the redshift of galaxies increased with distance. This result was interpreted as being due to an expanding universe and led to the development of the "Big Bang" model. The detection of the cosmic microwave background in 1965 gave direct evidence for a relic signal from the Big Bang that took place around 13.8 billion years ago. Although the standard model of the universe is now widely accepted, there are a number of serious gaps in our understanding. For instance, how and when did the first stars form? What is the universe actually made of, for we can only detect 5% of its mass? The rest appears to be accounted for by mysterious "dark matter" and "dark energy".

One way to probe the distant universe is through studies of supernovae. These mark the explosive end of stars and can be seen to great distances. A particular kind of supernova called a type Ia has been used to show that the universe is expanding at an increasing rate, a discovery that led to the Nobel Prize for physics in 2011. However, we do not yet know what kinds of objects produce these outbursts. The currently most favoured options involve binary stars, in one case where a star is gaining material from its companion, in another where two compact stars orbiting each other merge. Given our failure to detect dark matter and dark energy, determining what kinds of objects produce type Ia supernovae is essential to our understanding of the Universe.

Progress may be made by identifying binary stars that are rotating around each other on short timescales and then determining if they are likely to undergo a supernova explosion. Several examples have been found where two compact stars orbit one another in less than ten minutes. As their orbits are shrinking over time they might well end up as supernovae. These binary stars are also predicted to be emitting intense amounts of gravitational waves and so could be detectable by a future gravitational wave experiment.



The supernova remnant known as the Crab Nebula (NGC 1952). The parent star's dramatic brightening due to a supernova explosion was observed by the Chinese in AD1054. The expanding debris from the explosion, known as a supernova remnant, is one of the most studied astronomical objects in the cosmos. It provides a foundation upon which much astrophysical understanding is based.

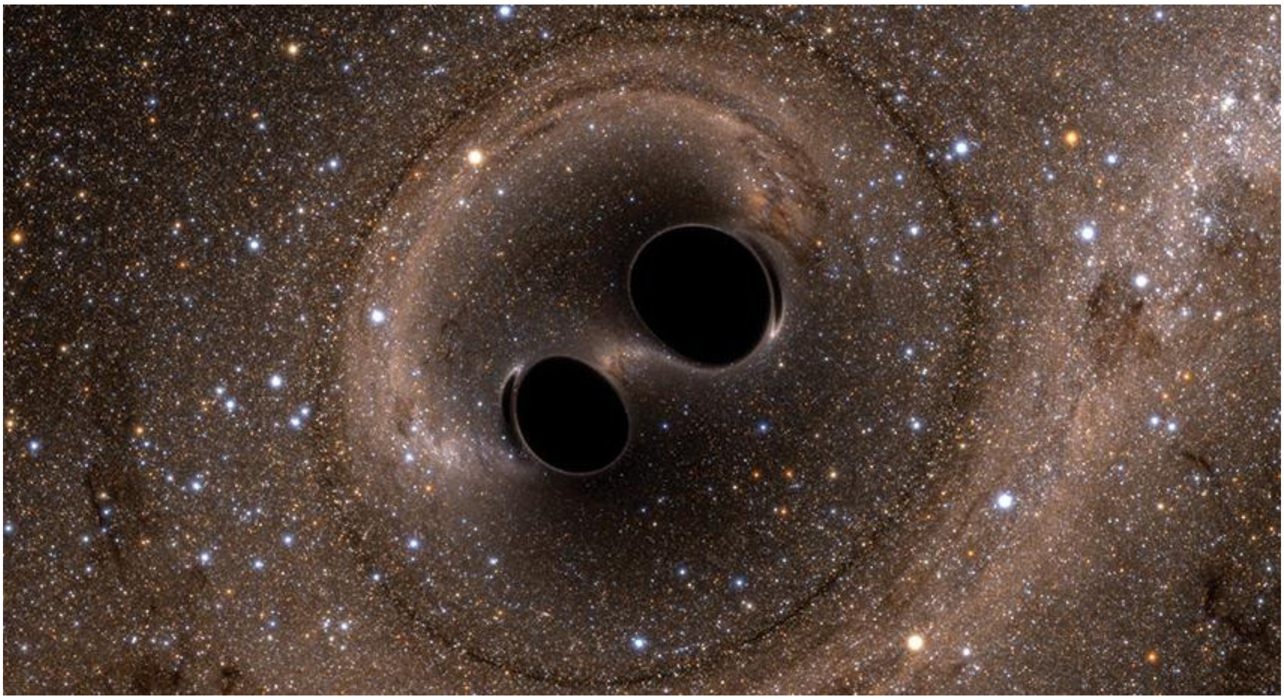
Theme 3: What are Black Holes?

Recently the first gravitational wave signal was detected, not only proving the general relativity theory of Einstein to be correct, but also securely demonstrating that black holes do indeed exist.

Black holes can be produced at the end of the life of a massive star. Such stars may be up to 300 times heavier than the Sun, as well as up to 10 million times brighter. They undergo ferocious nuclear burning. When their fuel is used up, their cores collapse to become a black hole. "Black" because the force of gravity is so enormously strong that absolutely nothing can escape it, not even light. Their formation produces copious amounts of gravitational waves.

The largest surprise to come from the very first gravitational waves to be detected was the sizes deduced for the black holes involved. They were about 30 times more massive than the Sun, implying that they had evolved from very massive stars with an almost pristine chemical composition, characteristic of that expected for the first stars to be born in the early Universe.

The reason we know that the chemical composition was pristine is that massive stars in our own Milky Way galaxy evaporate as the result of strong outflows that depend on their chemical composition. Such outflows could not therefore have existed for the progenitor stars of these black holes, as otherwise they would be less massive than they were found to be. This raises important questions about how black hole masses vary throughout cosmic time, starting from the very early universe just after the Big Bang, till the birth of stars like our Sun in the Milky Way today. The creation of black holes is associated with other extreme processes in physics, such as the acceleration of the most energetic particles in nature. These may be produced in the remnants of the exploding stars that produce black holes. The energies of such particles may be more than a million, million times that associated with light coming from the Sun. How have these particles gained such prodigious amounts of energy?



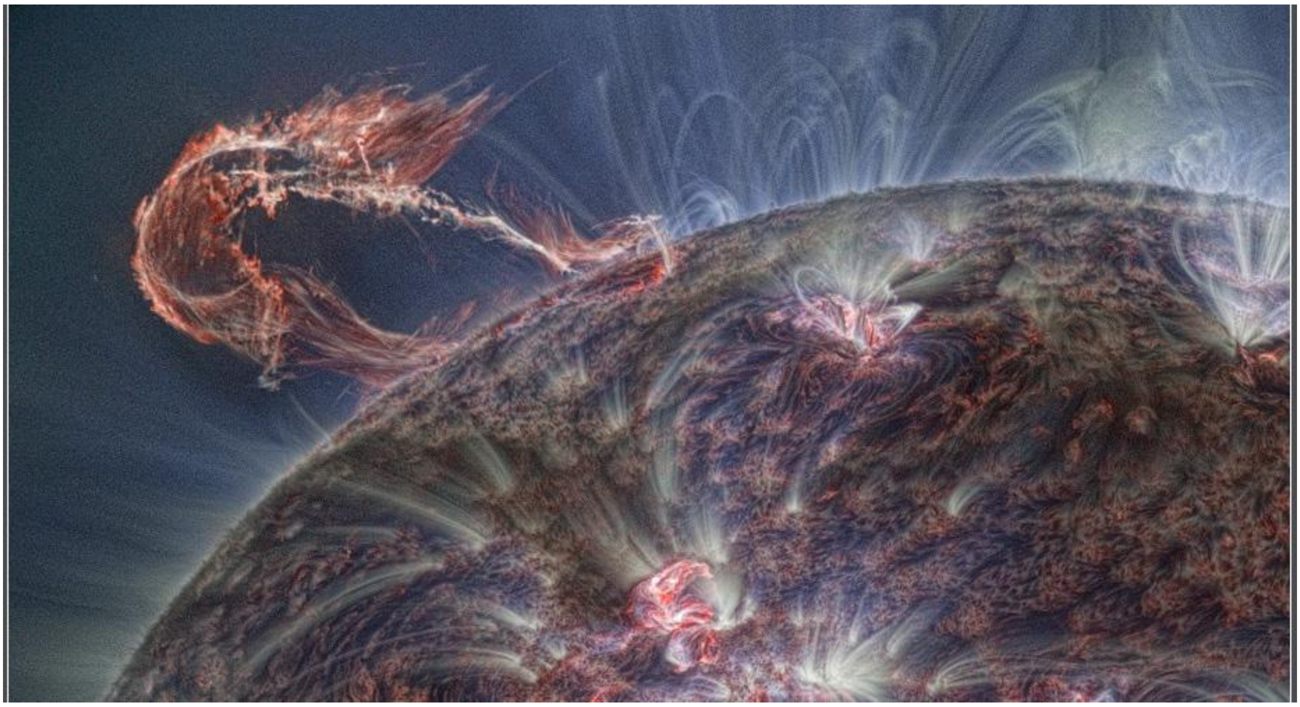
An artist's representation of two "heavy" black holes, just before their merger. Such an event led in 2016 to the first successful detection of gravitational waves by the LIGO interferometer, as predicted by Einstein's theory of General Relativity. These were produced by the merger of two black holes, weighing around 36 and 29 times the Sun's mass.

Theme 4: What external factors affect life on Earth?

Solar variability has profound consequences for the Earth and the modern space-based technological systems upon which we now depend. Two centuries ago William Herschel introduced the idea of the Earth–Sun climate connection. After all, since the Sun is itself a star, it is natural to ask whether its brightness might vary, so bringing cooler or warmer periods on Earth? The jury is still out with regards to the degree of such influences on our climate. Key questions we still need to answer are how is energy transferred within and from the Sun, and how does it power the phenomena we observe on the Sun's surface and atmosphere? What triggers solar eruptions and can we predict them? What is the contribution of the Sun to the Earth's climate?

At first glance, studying flare activity on other stars might not seem to tell us about such activity on the Sun. However, this is far from the truth. Flares from many of these stars can be far more powerful than the largest solar flare, thus challenging us to develop models explaining their enormous energy releases. This leads to the question of whether a super-flare from the Sun could one day send us back to a pre-industrial era?

During the Earth's 4.6 billion year existence it is likely that several nearby stars have exploded, as novae or supernovae, blasting our planet with X-rays or gamma rays. The ultimate environmental catastrophe, however, may be caused much nearer to home through the impact of a large asteroid or comet with the Earth, perhaps disturbed in its orbit by a passing star, or even collected from an interstellar gas cloud on our Sun's 250 million year orbital journey around the Galaxy. We need a thorough knowledge and inventory of the contents of both the Solar System and the Galaxy to understand the likelihood and consequences of such events.



An image of a Coronal Mass Ejection (CME) from the Sun, as seen by the Solar Dynamics Observatory. These eruptions can cause geomagnetic storms when they are directed towards the Earth, resulting in aurorae.
(Image courtesy of Prof. Miloslav Druckmuller, Brno University.)

Capability Needs – how do we get there?

We must use the entire electromagnetic spectrum to address the questions that arise when these themes are considered. Radio waves – the longest wavelengths and lowest energies of light – are used to track the motions of cold, dark gas and study the coolest stars and exoplanets, in addition to outbursts from the Sun. Infrared telescopes excel at finding cool, dim stars, slicing through interstellar dust bands, and even measuring the temperatures of planets in exoplanet systems. However, the majority of stars emit most of their electromagnetic energy as visible light, the tiny portion of the spectrum to which our eyes are sensitive. At wavelengths shorter than violet, we find ultraviolet and X-rays; at these wavelengths we must use telescopes placed on board satellites above the Earth's atmosphere. Gamma rays, which trace the highest energy processes, on the other hand, can be imaged with arrays of telescopes spread across the ground that are sensitive to the particle and photon showers that the incident radiation produces in the atmosphere.

Furthermore, we need astrometric (i.e. accurate information on the positions and motions of astronomical sources such as stars), spectral (i.e. detailed information on individual spectral lines), polarimetric (i.e. information on the orientation of the radiation as it traverses through space) and broadband photometric (i.e. information on its overall intensity) data in order to gain a full picture of the astronomical sources that we study.

Many of the instruments that we will use produce several terabytes[1] of data per day. This requires us to have access to high performance computer facilities to process the data. In addition, we need to be able to apply a range of theoretical and modelling codes to interpret, and so understand, the data. For instance, in order to predict the amount of mass that is lost from the stars that make black holes, we need to be able to construct detailed stellar atmosphere models that include the many elements in the periodic table that have been observed in stellar atmospheres or in their ejecta.

These models are highly complex. Furthermore, to then compare this theory to observation, we also need to predict the resulting stellar spectra and compare them to those measured. Computers capable of making these calculations require large memory capacities, as well as large number of processors to enable the parallel calculations needed to examine the extensive parameter set ranges that the models encompass. Armagh astronomers have abundant expertise in calculating models for stellar atmospheres, evolution and pulsation. We are well placed for the next decade to exploit the next generation of observational tools and the most advanced theoretical models.

The ALMA (Atacama Large Millimeter Array) telescope, 5,000m high in the Andes. Data from 66 antennas are combined to provide remarkable resolution at millimetre radio wavelengths. Armagh has access through the UK membership of ESO.

The ESO VLT (Very Large Telescope) in Chile, comprising four individual telescopes with 8-metre primary mirrors. These are among the world's largest optical telescopes today. A new generation of extremely large telescopes (ELTs) is now under construction.

[1] One terabyte is equivalent to the storage capacity of one million old floppy disks!

The Research Opportunities for Armagh

The Sun

There are several key questions that we need to answer about how the outer regions of the Sun – its photosphere, chromosphere and corona – work. How much energy is transferred between these different regions? What is the relative significance of the two main energy release mechanisms; magnetic reconnection versus waves? How do solar magnetic fields dissipate energy at all length and time scales?

Over the next decade, Armagh astronomers will be able to use a range of facilities to address these questions about the Sun. They include the present suite of US, European and Japanese satellites such as the Solar Dynamics Observatory (SDO), Hinode and the Interface Region Imaging Spectrograph (IRIS), together with the ground-based LOw Frequency Array (LOFAR) radio telescope and the optical Swedish Solar Telescope. Future facilities include the Solar Orbiter, the Daniel K. Inouye Solar Telescope (with Armagh as a partner) and the Square Kilometer Array (SKA) radio telescope.

At present, Armagh uses the Kepler/K2 satellite to investigate flare activity on other stars. This, in turn, feeds into our research on solar flare activity as it provides an insight into the range of flare activity that may occur on a solar-type star. Other opportunities to study the solar-stellar connection will include the Gravitational wave Optical Transient Observatory (GOTO; again Armagh are partners in this project), the TESS (Transiting Exoplanet Survey Satellite) and the PLAnetary Transits and Oscillations (PLATO) observatories.

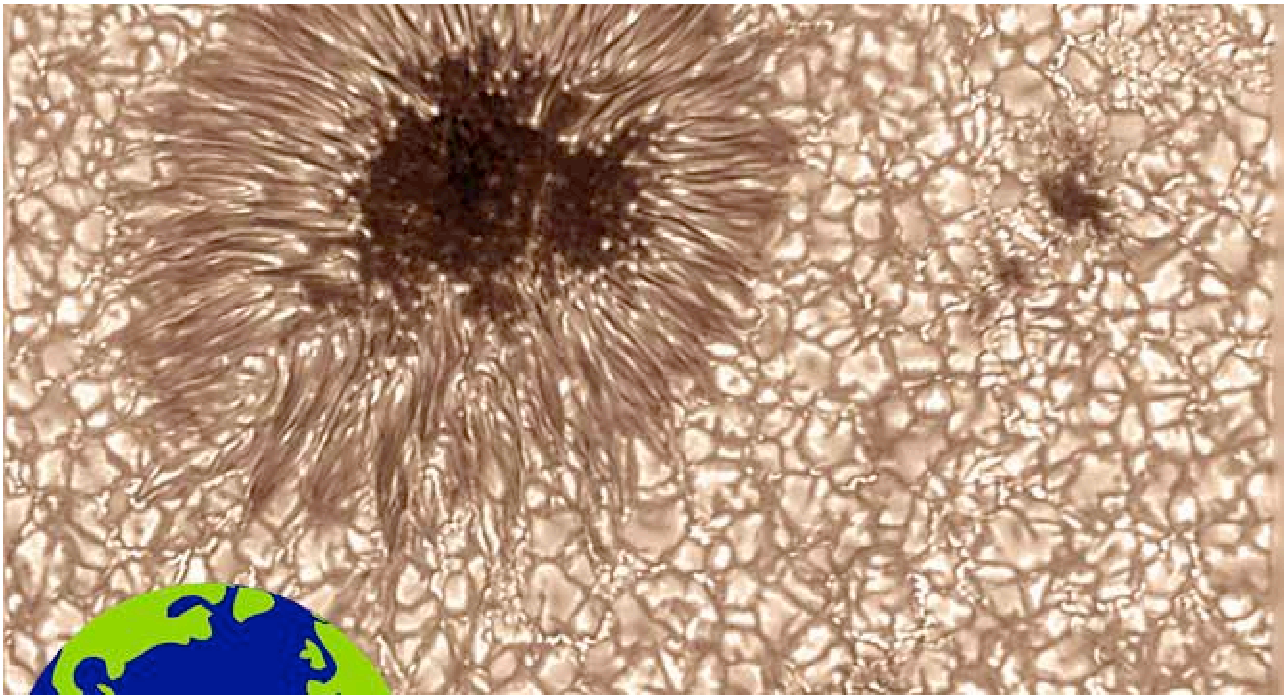


Image of a sunspot (with the Earth shown for size), taken in June 2014 with the Swedish Solar Telescope. Sunspots are transient, cooler regions in the Sun's photosphere that are closely linked to magnetic activity. (Image courtesy of Dr. Eamon Scullion, obtained using the CRisp Imaging Spectro-Polarimeter on the Swedish 1-m Solar Telescope.)

Planetary Systems near and far

Central questions that need to be answered here are what are the main processes that operate in the Solar System and in other planetary systems, both now as well as in the past, how do stars and the bodies orbiting around them form and evolve over time, where are the stable safe-havens where material can accumulate, and how is material transported across different small body reservoirs and to/from planets?

To address these questions we need to run intensive computer models. These have first to be developed on in-house workstations. Then they need to executed on high-end computing facilities, such as the Fionn computer cluster at the Irish Centre for High-End Computing in Dublin, to undertake the prodigious number of calculations needed to obtain the model results.

The observational data to test these models will come from large ground-based facilities such as those operated by the European Southern Observatory (ESO) in Chile, the Large Synoptic Survey Telescope (LSST), and the Isaac Newton Group (ING) of telescopes in the Canary Islands. We will also make frequent use of smaller telescopes, for instance the imager / spectrometer equipped with polarimetric optics attached to the 2m telescope of the Bulgarian National Astronomical Observatory in Rozhen. Armagh astronomers have guaranteed access to this telescope.

Access to such smaller facilities will be of crucial importance for testing new ideas that require a special flexibility in observing techniques that may not be possible at the largest observatories, as well as for projects that need guaranteed telescope time over long periods. In addition, they are crucial for the training of students, who otherwise would have difficulty in gaining any hands-on experience of using professional instrumentation. For, when using large international facilities, the instruments are invariably operated by observatory staff. The user only provides scripts that define the observation sequences. It is important that we are able to train our students beforehand so that they properly understand and appreciate how the international facilities work.

The planet Neptune's large satellite Triton, as seen by the Voyager 2 spacecraft. Triton does not orbit Neptune in the normal direction, indicating its origin elsewhere and capture by Neptune early in the history of the Solar System.

To maintain leadership in certain fields of astronomy (e.g., studies of cosmic magnetic fields and the surface structures of small bodies of the solar system), as well for testing ideas about exo-planet characterisation, Armagh also needs access to special instruments with polarimetric optics, both on small and large telescopes, such as the FORS instrument of the ESO Very Large Telescope (VLT). We also aim to increase our involvement with current and future space missions, in particular those funded by the European Space Agency that have strong UK contributions (i.e. Exomars, GAIA astrometry mission, JUICE Jupiter orbiter), in order to use the high-quality datasets these missions will deliver.

The Lives of Stars

The transformation of a star from birth to death takes it through many metamorphoses. To study each phase of evolution requires a range of different techniques. Observationally, we require instruments operating across several wavebands, for example to look at infrared light from very cool stars and ultraviolet light from very hot stars. The armoury of world-class telescopes now available provides opportunities for significant advances here.

Astrometry, or the measurement of positions, is used to determine distances and motion and hence deduce the absolute properties of stars. It also allows us to establish the scales by which we can measure the size of the Universe. ESA's flagship GAIA spacecraft has just released data with the distances to 2 million stars. Over the next 5 years this will increase to over one billion stars, enabling us to trace out the evolution of stars much more precisely and so completely transform our understanding of the Milky Way.

The Whirlpool Galaxy (NGC 5194). The dusty spiral arms trace the formation sites of massive stars. The spiral structure was first seen using the Earl of Rosse's "Leviathan" telescope in Birr in 1845, and studied there by Armagh Director Romney Robinson. Understanding the nature of such spiral nebulae led to realisation of the existence of galaxies and their role as fundamental building blocks in the Universe.

The precise measurement of a star's flux (photometry) allows astronomers to determine a star's properties through its varying brightness. The technique can be used for the detection of planets, the study of binary interactions, stellar surface activity, and to probe the internal structure of stars. Modest advances can be achieved using ground-based observatories, for instance Armagh is a partner in GOTO that will similarly characterise the brightness changes of millions of stars in the northern hemisphere. The most precise measurements, however, require facilities in space. Currently, the Kepler/K2 space mission is revolutionizing our view of exoplanets, stellar pulsations and stellar structure. It will be followed by first TESS and then PLATO. These spacecraft will monitor the light from millions of stars over long periods of time, without the noise inherent when viewing through the Earth's atmosphere, or the daily interruptions to the data record caused by night and day. Together, all these facilities will provide new opportunities to study the near neighbourhoods, active environments and the interiors of stars in much greater detail than is currently possible.

Spectroscopy allows astronomers to determine the surface properties, chemistry and dynamics of stars, as well as to study their interactions with planets, binary companions and other star systems. Spectroscopy requires large telescopes to gather the faint light and high-quality spectrometers to measure it across wide spectral ranges. Current access to international facilities via the UK membership of ESO assures the use of crucial instruments operating in the optical and near-infrared, such as the Very Large Telescope (VLT). In addition, Armagh's own investment in the Southern African Large Telescope (SALT) guarantees a small amount time on this 11m diameter telescope each year, in addition to opportunities for hands-on student training. Ad hoc access to other 8m-class telescopes (e.g. Japan's Subaru Telescope on Mauna Kea) also maintains research momentum. At ultraviolet wavelengths, the Hubble Space Telescope remains the only operational instrument, while in X-rays XMM-newton and Swift provide the backbone for such observations, until the launch of the Athena spacecraft.

The study of polarized light enables astronomers to explore magnetic fields and the structure of disks, winds and flaring material around stars. To do so requires a substantial light collecting area to achieve sufficient sensitivity for the precise measurements that are required. This capability has only recently been realised with 8m class telescopes. Armagh astronomy is well prepared to exploit the construction of the European Extremely Large Telescope (E-ELT), whose diameter will be more than five times larger than the VLT and so greatly improve capabilities in this arena. In particular, it will further our investigation of the circularly polarized radio emission unexpectedly discovered from cool brown dwarf stars, and attributed to aurorae.

The stars themselves form within giant clouds of molecular gas, the cauldrons of a galactic ecosystem involving the cycling of material expelled in winds and explosion from stars. Driven by the flows of energy from these stars, this material is eventually converted into new stars, enriched by the products of nucleosynthesis from the previous generation.

Radio telescopes, with capabilities ranging from the millimetre to the metre wavebands, are able to probe the gas processes that occur. On the finest scales, the exquisite resolution of the Atacama Large Millimeter Array (ALMA), whose construction in Chile is now almost finished, will allow the structure of the dense gas cores, where new stars are born, to be unveiled.

On larger scales, the collection of gas into the clouds themselves may be followed by a new generation of low frequency radio telescopes, such as LOFAR and eventually the SKA. These facilities will permit, for instance, the key element carbon to be followed as it transitions from ionized, through neutral and into molecular form. This is a process that lies at the heart of cloud cooling that allows them to grow in mass and in density, leading to the birth of new stars in their cores.

Armagh has access to these radio facilities, in particular through the UK membership of ESO for ALMA, the I-LOFAR consortium across Ireland, and UK leadership in the still-forming SKA consortium.

None of these techniques generates scientific discoveries in isolation; all require significant efforts in data processing and interpretation, involving large-scale computations. Given access to the best observing facilities as well as sufficient computing resources, Armagh astronomers will be able to measure the surface chemistry of many new and interesting stars, to probe the structure of their atmospheres, winds and magnetic fields, to explore extreme physics encountered in very hot plasmas, and to explain the evolution cycle for many different types of star. Thus Armagh can play a central role in furthering our understanding of the lives of stars.

An Armagh PhD student on an observing trip to the European Southern Observatory's VLT (Very Large Telescope). The VLT is used by Armagh astronomers to study stellar atmospheres and planetary systems.

The Deaths of Stars

The life cycle of a star ends as it exhausts its nuclear fuel. The end depends on how heavy the star is and what nuclear fuel is available. This varies dramatically between different types of stars. Massive stars burn carbon through to iron and end their lives in supernova explosions, producing neutron stars or black holes. Low-mass stars don't burn carbon and fade away as white dwarfs, but not before some of them eject spectacular planetary nebulae. Stars in binary systems can evolve in very different ways, depending on their masses.

For low-mass stars, we have a reasonable idea of how single stars evolve, first to become red giants and then to turn into white dwarfs. However, there are surprises, particularly in multiple systems. Very rarely a white dwarf is reborn to become a supergiant in a matter of months. Another white dwarf, on the other hand, might accrete enough matter to explode as a Type Ia supernova. Or possibly a pair of white dwarfs can merge, but will the resulting object explode or become another type of star? The new armoury of survey telescopes coming online, including GOTO and the Large Synoptic Survey Telescope (LSST), which Armagh and the UK are partners in, will allow us to discover "new" stars quickly, at an early stage of their development, and so address such questions about stellar death.

Thor's Helmet Nebula (NGC 2359). The bright star near the centre is WR7, a massive star on the way to collapsing into a black hole. Intense radiation and powerful winds from the star leads to the glow of the surrounding emission nebula.

For massive stars, we now have a good understanding about how their death occurs for stars up to 20 times the mass of the Sun. However, we know little about the fate of the most massive stars in the Universe, those up to 300 times the Sun's mass. Do these objects collapse directly to black holes? Or do they explode, as either faint or bright core-collapse supernovae?

The evolution of massive stars up to their death is dominated by the mass loss from their surfaces through the agency of strong stellar winds. The nature of these winds depends on the chemical composition of the host galaxy. Massive star evolution in the Milky Way today looks very different to that which occurred for the very first stars in the Universe, which formed just a few hundred million years after the Big Bang, as the latter lacked the heavy elements that exist in stars today. The detection of two merging black holes by the LIGO gravitational wave observatory showed that black holes do exist with masses 20–30 times the mass of the Sun. However, the initial masses of their parent stars must have been very much greater since much of their material would have been lost via a strong stellar wind. How massive might they have been?

A key ingredient needed to make progress in this area is a deeper theoretical understanding of their stellar mass loss. This has now become feasible due to the increase in computing power over the last decade. In addition, it is important to test our theoretical computations against large samples of observations. Thanks to multi-object facilities on the Very Large Telescope (such as the FLAMES instrument) and the coming generation of extremely large telescopes (such as the E–ELT), there is a path towards understanding the phenomena involved. The calculation of the forward evolution of massive stars, until their deaths, can also be tested against observations of (super-) luminous supernovae with facilities such as the LSST, shortly to be commissioned.

Extreme winds and supernova explosions may also be responsible for the generation of some of the most energetic particles found in nature – cosmic rays in the TeV to PeV energy range; i.e. particles that are 10^{12} to 10^{15} times more energetic than typical phenomena observed with optical telescopes. When such cosmic rays interact with ordinary nuclei in space, the ensuing reaction may result in a gamma ray which carries away much of the incident energy. These photons can travel directly to the Earth from their origin, unlike their parent cosmic rays, which are deflected by Galactic magnetic fields.

The gamma rays may be detected by TeV-energy telescopes on the Earth – air Cherenkov arrays that are sensitive to faint pulses of blue light. These are generated by particle cascades, initiated by gamma rays when they strike the atmosphere. In the coming decade, with the construction of the Cherenkov Telescope Array (CTA), in Chile on the ESO site nearby to the VLT and E-ELT, the clarity of gamma ray images will be improved by an order of magnitude, transforming our view of the high energy Galaxy.

The sources for the gamma rays are typically expected to be molecular clouds, since these provide the greatest columns of nuclei in space that the cosmic rays can interact with. A close correspondence between molecular clouds and nearby sources of cosmic rays – cosmic accelerators – is anticipated. Coincidentally, the resolution of the gamma-ray sky produced by the CTA will be comparable to that of a new view of molecular gas being obtained by the Mopra telescope in Australia. This database is now a part of the Armagh collection. It will provide a crucial tool for interpreting the CTA's gamma ray images. Hence, there is an exciting opportunity for Armagh to play a key role in this new scientific endeavour.

Supernovae may be used to constrain the distance ladder of the universe. The furthest distances that can be probed, stretching back to the earliest stages of the universe, use superluminous supernovae from very massive stars. Can some of these be pair-instability supernovae, where the entire star is disrupted and its elements all returned to interstellar space? Or are these supernovae so bright because they are interacting with strong stellar winds from the progenitor, so generating additional luminosity? These questions need to be answered before we can use these luminous supernovae as cosmological distance indicators.

The recent detection of two merging black holes by the LIGO gravitational wave detector team will surely rank as one of the great scientific discoveries of our age. However, their location on the sky is not yet well constrained. If a visible counterpart of the merging black holes could be identified, the distance, and hence luminosity, of the merging event could be determined from the redshift of the host galaxy. By then monitoring how the optical light fades after the merger, its environment could be modelled to provide information about the black holes themselves.

To reliably detect these visible counterparts we need to survey the whole sky every few days, to build a continuous digital picture (or database) of it so that new events can be found quickly. When gravitational waves are detected this database is then searched for new or varying objects, near to where triangulation of the gravitational wave signal has placed it. The uncertain nature of this process means that the search area on the sky is large. This is a key goal of the forthcoming GOTO telescope, to find where the newly created black holes lie in the cosmos.

Realising the Opportunity

Armagh needs to be able to participate on the international astronomical stage through access to a range of instrumentation, from small, in-house telescopes to the next generation international facilities involving many of the most developed nations.

The Armagh Robotic Telescope provides use with a training tool that gives students their first experience of using a telescope for research.

Small facilities such as the Rozhen optical telescope, the GOTO transient observatory and the I-LOFAR radio telescope, allow Armagh astronomers to gather data in extensive programs that require large allocations of observing time, at the same time providing hands-on, advanced training tools for our students to use and learn from.

The extensive range of facilities provided by the European Southern Observatory provides the backbone to Armagh's stellar research, particularly the Very Large Telescope (VLT). Space telescopes underpin our current solar research. For the future, the large ground-based international facilities of the coming decade, such as the European Extremely Large Telescope (E-ELT) and Large Synoptic Survey Telescope (LSST) in the optical and infrared, with the Daniel K. Inouye Telescope (DKIST) for solar astronomy, the Cherenkov Telescope Array (CTA) at high energy (gamma rays) and the Square Kilometre Array (SKA) at low energy (i.e. radio waves), will provide transformative capabilities and open up new research vistas.

To ensure Armagh astronomers can be active participants in these new facilities requires us to contribute to and lead support programmes for the science they will tackle. We can do this by using smaller facilities to provide complementary datasets. However, and more importantly, we can provide scientific leadership by having the ability to model the systems being studied and calculating the resulting spectral or imaging properties that could be observed with a new telescope or facility.

Armagh needs to retain the ability to produce computational models in-house. However, the complexity and scale of the calculations means that national or international scale computer facilities are needed, e.g. cloud computing. Connections to high-speed networks (i.e. > Gbps speeds) are essential, both for upload and download of data and simulations, in order to be able to utilise the remotely hosted capabilities. In addition, cloud computing also mitigates against the risk of failure from the increasing complexity involved in supporting high-end computing capability on site, when there are only limited human resources available to maintain it.

The Robinson Dome at dusk with Armagh Robotic Telescope Dome in background. The constellations Orion and Taurus are prominent in the star field.

Central to Armagh's ability to remain as a productive and thriving research institution are the quality of the people we employ. We have to continue to provide an attractive and stimulating environment for them to work in. We also need to ensure that regular renewal in our research team occurs so that new ideas will constantly flow through the institution. This could be achieved by establishing a fixed term senior research fellowship at Armagh, of five years duration. This could be a named fellowship, perhaps drawing on the prestige of a former Director's contributions to astronomy. Such a fellowship would provide an opportunity to regularly attract leading international scientists to Armagh, so ensuring that our research remains current and vital.

A vibrant postgraduate student community is another key element in ensuring the health of the research programme. In particular, this provides a catalyst to keep Armagh as an active participant in collaborative programmes using major facilities. The modelling of systems that is needed in astronomical research, blending theory with data to provide new insights about a cosmic source, is well suited to the learning needs of a PhD and the writing of theses. Such modelling also provides the primary motivation around which the science case for a facility time request can be made, in turn ensuring Armagh's active role in the facility's utilisation and the resulting science.

With Armagh's relatively isolated location, away from major population centres, an active visitor programme is also necessary to bring leading scientists to the institution to ensure that new ideas are heard. Armagh is also an attractive location for sabbatical visitors, university academics taking short breaks from their teaching duties to rejuvenate research programmes and explore new ideas. The brightest such academics often have young families, making it difficult for them to get away from their home base. Armagh has a particular opportunity here given the housing on our site. While Bailey House is quite suitable for student visitors, it cannot readily accommodate families. Refurbishment of AOP's other houses, in particular Lindsay House and de Groot House, would, however, provide suitable family accommodation and could be done for modest cost. Armagh could position itself as a prime destination for sabbatical visitors, and benefit from the steady stream of new ideas that would then continually flow through the organisation.

Observing the Pleiades star cluster with the Grubb 10" Telescope at Armagh.

Communicating our Research

Astronomy has a special place in the sciences due to its accessibility to the public. People of all ages have a wonder about the heavens and are open to learning how the universe works. They do ask questions about astronomy and space, and our place in the cosmos.

There is a special opportunity to link the results of research with outreach at Armagh given the close proximity of the Planetarium and the Observatory. Increasingly, telescopes are producing three-dimensional data sets, as are the numerical calculations applied to the modelling of systems. These may be suitable for immersive visualisation provided by the Fulldome experience of a planetarium. This can allows a researcher to gain new insights into a data set. It also provides an opportunity for the public to gain a better comprehension of the results of research, and to understand and appreciate what the public investment in science is yielding for the nation. Armagh has the opportunity to take the lead in such interactivity, for instance hosting workshops to bring researchers together to explore their rich data sets.

It is the special relationship of our Observatory and Planetarium together in Armagh that brings an opportunity that virtually nowhere else in the world has available. The Planetarium provides an infrastructure to communicate astronomy to all, and a staff that excel at inspiring both children and adults to appreciate the excitement of galaxies and stars, of planets and the human exploration of space.

Modern research is a worldwide effort, scientists individually and collectively building on each other's work. A part of this international activity happens in Armagh. By engaging in it we are active participants in the voyage of discovery. Exploring the unknown and making new discoveries about how the universe works invokes curiosity and wonder in people. At Armagh we can explain the story, we can show that part of it happens right here, that work in Northern Ireland is seen and heard on the world stage.

Science and society, culture and history. These are all brought together in the Armagh Observatory and Planetarium. The research and the outreach programmes at Armagh both follow the cosmic journeys of galaxies and stars, of planets and people. While the researcher and the visitor may see these from very different perspectives, at Armagh they both can experience the same voyage of discovery.

The dark dot, small but clearly visible near the bottom of the solar disc, is the planet Mercury passing between the Sun and observers on the Earth. In the foreground is the weather vane atop the Grubb 10" telescope at Armagh.

Armagh's successful public viewing event of the Mercury transit on May 9, 2016. The historic 10" Grubb refracting telescope was used to project the image of the Sun on to a white card, for safe viewing as the planet crossed the solar disc.

Table: Overview of Facilities utilised by Armagh

	Armagh Partners	General Access Facilities	Survey Resources
Current Facilities	Optical: SALT - South African Large Telescope (11m) Rozhen - 2m Telescope Bulgaria (polarimetry) ART - Armagh (training) Radio: LOFAR - low frequency radio array (European sites inc. I-LOFAR @ Birr) ICHEC - Irish Centre for High End Computing (Fionn; Dublin)	Optical: ESO facilities (esp. VLT; Chile) WHT, INT, LT (La Palma) HST - Hubble Space Telescope (Space) Kepler/K2 (Space) Radio: Mopra, ATCA (Australia) JVLA (USA) ALMA (Chile) Solar: SDO - Solar Dynamics Observatory (Space), Hinode (Space), IRIS (Space), Swedish Solar Telescope (La Palma) X-ray/UV: XMM-Newton, Swift	Gaia (ESA) Sloan Digital Sky Survey (SDSS) Laser Interferometer Gravitational-Wave Observatory (LIGO)
Near Future (~2017+)	Optical: GOTO - Gravitational wave Optical Transient Observatory (on La Palma, Canary Islands). Solar: DKIST - Daniel K Inouye Solar Telescope (Hawaii)	TESS - Transiting Exoplanet Survey Satellite (Space) Gamma-ray: CTA - Cherenkov Telescope Array (La Palma, Chile; UK partner)	Gaia (ESA) Future releases EXoMARS (ESA) VIRGO (GW observatory) LIGO upgrades
Medium Future (~2021+)	Optical: LSST - Large Synoptic Survey Telescope (2 LSST:UK Affiliate PIs)	Optical: E-ELT - European Extremely Large Telescope (ESO, Chile) PLATO - PLAnetary Transits and Oscillations of stars (ESA) Radio: SKA - Square Kilometre Array (South Africa, Australia; UK partner) X-ray: Athena (ESA) Solar: Solar Orbiter (ESA)	JUICE - Jupiter Moon Mission (ESA)

Armagh Observatory and Planetarium Staff and Students
1 September 2016

First staff photo from the newly merged Armagh Observatory and Planetarium.

Front row, left to right: Gavin Ramsay, Nick Parke, Samantha Steed, Sinead Mackle, Heather Taylor, Colin Johnston, Kerry Scullion, Simon Jeffery.

Middle row, left to right: Ruxandra Toma, Stefano Bagnulo, Kathleen McLoughlin, Pamela Martin, Alison Neve, Yanina Metodieva, Conor Byrne, James Finnegan, Galin Borisov, Giovanni Paolini, Michael Burton (Director), Diane Neill, Aileen McKee, Gerry Doyle, Tolis Christou, David Asher, Aidan Grant, Shane Kelly.

Back row, left to right : Rok Nezic, Will McLean, Alastair Hughes, John Butler, Eamon Rafferty, Daohai Li, Philip Hall, Alex Martin, Jorick Vink.

Missing from the main photograph, and shown at bottom (left to right): Mark Bailey, Martina Glass, Erin Higgins, Greg Milligan, Holly Preece, Eliceth Rojas Montes and Juie Shetye.

A panorama of Armagh Observatory. From left to right we see the Robinson Dome housing the Grubb 10 inch refractor, the main Observatory building with the 1790 Dome housing the Troughton telescope, the library with the 1827 Dome to rear, and the archive building. In the foreground is the human orrery.

Armagh Observatory at Night.

Image Credits

	Image	Image Credit
Cover (top left)	Armagh Observatory	Armagh Observatory and Planetarium
Cover (top right)	Armagh Planetarium	Armagh Observatory and Planetarium
Cover (bottom left)	Dreyer's New General Catalogue	Armagh Observatory and Planetarium
Cover (bottom right)	Armagh Observatory Weather Station	Armagh Observatory and Planetarium
Page 4	Archbishop Richard Clarke	Church of Ireland
Page 6	Armagh Observatory with the Robinson Dome in the foreground	Armagh Observatory and Planetarium
Page 8	Comet 67P/Churyumov-Gerasimenko	ESA - European Space Agency (copyright ESA/Rosetta/NavCam - CC BY-SA IGO 3.0: http://creativecommons.org/licenses/by-sa/3.0/igo).
Page 9	The Crab Nebula, NGC 1952	ESO – European Southern Observatory
Page 10	Heavy Black Holes	SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)
Page 11	Coronal Mass Ejection	Prof. Miloslav Druckmuller, Brno University
Page 12	The ALMA (Atacama Large Millimeter) Telescope	ESO/C. Malin
Page 12	The VLT (Very Large Telescope)	ESO/B. Tafreshi (twanight.org).
Page 13	Sunspot	Dr Eamon Scullion
Page 14	Triton	NASA/JPL/USGS.
Page 15	The Whirlpool Galaxy, NGC 5194	NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA)
Page 16	Armagh PhD Student at the VLT	Armagh Observatory and Planetarium
Page 17	Thor's Helmet Nebula, NGC 2359	ESO/B. Bailleul.
Page 19	Robinson Dome with the Armagh Robotic Telescope in the Background	Armagh Observatory and Planetarium
Page 20	Observing with the Grubb 10 inch telescope	Armagh Observatory and Planetarium
Page 21	Transit of Mercury	Armagh Observatory and Planetarium
Page 21	Public viewing event of the Mercury transit	Armagh Observatory and Planetarium
Page 23	Armagh Observatory and Planetarium Staff and Students on 1 September 2016	Armagh Observatory and Planetarium
Page 24	Armagh Observatory Panorama View	Armagh Observatory and Planetarium
Page 24	Armagh Observatory at Night	Armagh Observatory and Planetarium