Institution: Liverpool John Moores University

Unit of Assessment: 9 (Physics)

1. Unit context and structure, research and impact strategy

Unit Context and Structure

Research in Physics at LJMU is carried out solely within the Astrophysics Research Institute (ARI). The ARI resides within the Faculty of Engineering and Technology. Unlike most astronomy groups in the UK, the ARI does not sit within a larger physics department. Presently, the Institute has 25 permanent academic staff, 25 postdoctoral and technical staff, 35 postgraduate students, and 10 outreach and administrative staff (95 members in total), making it one of the largest UK astronomy groups. During the present REF period, the ARI has generated over £12M in external grant income and has successfully graduated 38 PhD students, both representing an approximate **doubling** of our tallies compared with REF2014.

The Institute is represented on the Faculty Management Team and all Faculty strategy and operational committees. Oversight is provided through the Institute's Advisory Board, which provides strategic advice on all activities, including feedback on the allocation of staffing and financial resources between activities and ensuring that the Institute stays focused on delivering outstanding research. The Advisory Board comprises three external members and a representative of University senior management. Day-to-day management is through the ARI Management Board, chaired by the current Director (P. James), and involving representatives for all core activities: Research, Teaching, Technology, Public Engagement, ED&I, and representatives for admin staff, postdocs, and PhD students. Each of the core activities also have their own committees and governance structures.

In 2018, the ARI underwent a quinquennial review of our research, teaching, and outreach plans for the period 2019-2024. The review is standard practice at LJMU for all departments and, whilst predominantly an internal evaluation of strategy, performance and governance, there is a strong external input aspect to the evaluation as well. The review highlighted the significant contribution ARI makes through its internationally outstanding research. An important part of the process was the implementation of a transparent succession plan that covers all aspects of the ARI's core activities. The succession plan calls for the continuous rolling of all ARI leadership positions (including directorship, heads of teaching and research, ED&I committee membership) on typically a three-year timescale. The aim is to ensure all staff are able to engage in the running of the Institute and that a high level of motivation for leading our activities is maintained.

The research environment of the ARI benefits significantly from enthusiastic support from the Faculty and the wider University. For example, over the current REF period a large fraction of grant overheads from UKRI- and EU-based grants has been devolved to the ARI to support its research activities, including enabling participation in national and international projects. In addition, for the past five years the Faculty has matched STFC-funded studentships and we have also benefited from a new programme of LJMU Scholarships. Furthermore, the Faculty and University have provided strong support for a number of ARI strategic projects, including supporting the development of the New Robotic Telescope (NRT) and a new ARI-managed high-performance computing (HPC) facility.

The ARI strongly supports a culture of research integrity. For example, all staff are required to complete yearly online training modules in Research Ethics and Data Protection. Our research outputs are subjected to rigorous independent peer review at top international journals (e.g., MNRAS, ApJ, Nature, Science). ARI researchers make their publications available to the community through open access websites (including **arxiv.org** and **LJMU Research Online**) and our datasets and codes publicly available on open repositories, such as **github** and the **LJMU Data Repository**.

Research Strategy

Progress since 2014

In the REF2014 submission, our objectives focused on fundamental questions in the field: the origin of the stellar initial mass function; physics in extreme environments; the structure and formation history of the Milky Way; and the evolution of galaxies and clusters, aligning with key questions in the STFC Roadmap. We defined a number of specific goals, virtually all of which have been achieved, including:

➔ Our Technology group built and delivered the mosaiced **WEAVE** detector system to NOVA (Netherlands), where it is being integrated into the spectrograph. The combined unit will be integrated with the 1000-fibre system before first light on the William Herschel Telescope (**WHT**), in early 2021. On the exploitation side, we have leadership roles in the WEAVE Galactic Archaeology science team (Schiavon, Font), the **MOONS** analysis pipeline and spectral library working groups, the WEAVE survey strategy panel (Schiavon), the **4-MOST** cluster survey steering committee (Schiavon), and a WEAVE science verification PI (Davies).

➔We were awarded 200+ hours of **ALMA** time since Cycle 2 as part of two international projects, of which 90 hours are led by LJMU PIs (Longmore, Smit). We are now leading an international consortium of 60 Galactic centre astrophysicists in the ACES Large Program (submitted in Cycle 7).

➔As a strategic investment using devolved grant overheads, two staff members joined the **SDSS-IV** collaboration, participating heavily in the **APOGEE-2** (Schiavon is a core member) and **SPIDERS** (Collins) surveys, resulting in 3 PhD completions (4 ongoing) at LJMU, over 10 completed MPhys/MSc projects, and >25 refereed publications**,** accruing over 3,400 citations (not including SDSS data release papers).

➔ Members of the Time Domain Astrophysics group (Perley and students) have been closely engaged with Zwicky Transient Facility (**ZTF**) since first light in 2017. We have written software filters to search for SNe automatically and contribute personnel effort to confirm and respond to them, and have contributed data from PI programmes at the Liverpool Telescope (**LT**), Very Large Array (**VLA**) and other international facilities, resulting in a dozen papers.

➔STFC have funded participation of UK scientists in **LSST**, allowing up to 100 affiliate PIs to join the project. The ARI currently has four LSST:UK affiliate PIs (Baldry, Collins, Perley, McCarthy). STFC also funds a PDRA to develop LSST pipeline infrastructure for low-surface brightness science as part of the LSST:UK Phase B project.

➔ Our involvement in the ESA **Euclid** satellite is focused on the low-luminosity dwarf galaxy population (Baldry, a Euclid Independent Legacy Scientist) and modelling large-scale structure (McCarthy, in the lensing and simulations working groups).

➔Since 2015, LJMU have invested a further £1m in the LT2 project (now named **NRT**) to establish a project office with 6 staff to provide scientific and technical leadership of the consortium, which consists of the IAC, Spain, University of Oviedo and the National Astronomical Observatory of China. A joint design study prepared by LJMU and IAC passed its review in April 2019, enabling work to begin on design of key components (enclosure, telescope structure, mirror topology and mirror support).

➔ Using the rapid response capability of LT we have played an active role in the follow-up of electromagnetic (EM) candidates potentially associated with gravitational wave (GW) signals detected by the **Advanced LIGO/VIRGO** experiments (e.g. for the first confirmed event the LT was one of only 5 telescopes worldwide which provided spectroscopic follow-up). ARI took a leading role in the observation and interpretation of the GW170817 event. In 2016 we joined the

Caltech-led **GROWTH** network, giving immediate access to transients from the ZTF and other facilities. In 2020 an online STFC-supported GROWTH summer school was held in Liverpool.

➔A new research group, Computational Galaxy Formation, was established by McCarthy, Font and Crain. The group played a central role in the successful EAGLE simulations project and has successfully bid for highly-competitive grants and fellowships (including two Royal Society fellowships, two Ernest Rutherford fellowships, and an ERC Consolidator grant), which are helping to grow the group and to fund a new HPC facility within the Faculty. The group currently has 4 permanent members, two permanent-track fellows, 4 ERC-funded postdocs, and 10 PhD students.

Research Strategy for 2021-2026

The ARI plans an ambitious programme of research for the coming REF period which exploits observational and theoretical data from a wide variety of UKRI/STFC-funded facilities in order to address some of the most pressing and fundamental questions in astrophysics. These map well onto the **three science challenges** identified by UKRI/STFC: "**A**: *How did the Universe begin and how is it evolving?*"; "**B**: *How do stars and planetary systems develop and how do they support the existence of life?*"; and "**C**: *What are the basic constituents of matter and how do they interact?*", and also align extremely well with the science goals outlined in the **ASTRONET Roadmap**. In addition, we have a burgeoning programme that links astronomical techniques and ecology in order to address key issues identified as part of the UKRI's Global Challenge Research Fund (GCRF).

There are currently six main research themes (or "groups", up from three in REF2014) within the submission:

➔Computational Galaxy Formation
➔Technology and Instrumentation
➔Galaxy Formation and Evolution
➔Star formation and Stellar Populations
➔Time Domain Astrophysics
➔Astro-Ecology

While the titles provide a good representation of the mix of research in which ARI staff are involved, in reality there is significant cross-talk and staff and students can participate in multiple groups. Consequently, there is a high degree of synergy between the groups that fosters a strongly collaborative environment. All groups are represented on the ARI's Research Committee (10 academic staff members; chaired by McCarthy), which reports to the ARI Management Board and coordinates the overall research aims of the Institute.

Below, we describe the main aims of the groups for the coming REF period and how these align with the UKRI/STFC science challenges, highlighting the techniques and facilities employed and the synergies between the groups.

1) The **Computational Galaxy Formation group** works on aspects of galaxy formation and computational cosmology, seeking to address STFC science challenges A:2, A:3, A:4, A:5, and C:4. The group uses state-of-the-art cosmological hydrodynamical simulations, typically carried out on national and international supercomputing facilities, such as **DiRAC** and **PRACE**. The group now represents the second largest node of the **Virgo Consortium** in the UK. Over the next five years, the group will lead the development of LJMU's first HPC facility. Using this new facility, the principal scientific aims include the development of simulations in preparation for forthcoming large-scale structure surveys, including **LSST**, **Euclid**, **CMB-S4**, and **eROSITA** (A:2, A:3, C:4) and simulating the Milky Way at extremely high resolution in a widely-varying cosmological landscape (A:5, C:4) for comparison with state-of-the-art data from **Gaia**, **WEAVE, 4-MOST**, and **MOONS**, as well exploiting the Virgo Consortium's flagship EAGLE-XL and COLIBRE simulations (A:3-A:5).

2) The **Technology and Instrumentation group** activity primarily centres on research and development into new instrumentation and software technologies in support of the scientific

exploitation of the **LT**. Its activities are strongly tied to STFC science challenges A:4, A:7, A:8, and B:1. Over the next five years, the group's focus will shift from LT to the development of the 4.0 meter **NRT**, with 4x greater sensitivity and 10x faster reaction time than the LT, for first light in 2025. This will enable ultra-rapid (<30s) spectroscopic and polarimetric follow-up of EM counterparts of gravitational waves (GW, A:7) and neutrino (**IceCUBE, ANTARES**) sources and new radio (e.g. **LOFAR, SUPERB**) and high energy (e.g. **SVOM, Fermi, CTA**) transients (A:8). It will also provide rapid simultaneous spectroscopy and polarimetry of (e.g. **LSST, ZTF**) supernovae (SNe) to explore the shock-breakout phase and find spectral signatures of the progenitor, and of recurrent novae and galactic transients, such as outbursting binary X-ray transients and eruptive Young Stellar Objects (B:1) detected by **VISTA, Pan-STARRS**, and **LSST**.

3) The **Galaxy Formation and Evolution group** works on topics over a range of scales including the dynamics of bars, star formation in disks, and clusters of galaxies; and on studies of galaxy demographics at low and high redshift, primarily from an observational perspective. The group seeks to address STFC science challenges A:4 and A:5. Over the next five years, the group aims to progress in the study of the frontiers at low galaxy masses, high redshifts, central components of disc galaxies, and large-scale structure distributions (A:4, A:5). This will test galaxy formation and evolution models for the lowest mass haloes, for the epoch of reionization, and for bars and inner discs in spirals; and test cosmological models using non-standard dark matter or gravity. Group members are involved with science programmes using **LSST**, **eROSITA**, **Euclid**, **4MOST**, and **JWST** guaranteed time; and will aim to continue exploitation of **ALMA**, **HST**, and **MUSE**.

4) The **Star formation and Stellar Populations group** works on a diverse range of topics from the formation of individual stars to the full stellar populations of globular clusters, and to the history of star formation of the Milky Way and Local Group galaxies, addressing STFC science challenges A:4-A:6 and B:1-B:2. The group combines state-of-the-art observations and simulations (in collaboration with the Computational Galaxy Formation group). Over the next five years the group aims to retain its leading role in the design and scientific exploitation of large surveys (**APOGEE-2, WEAVE, MOONS, MUSE**) of Milky Way stars (A:5, A:6, B:1) and of multiple populations in massive star clusters (A:6, B:2), using **HST** and **JWST**. The group's expertise in theoretical modelling of stellar populations will be invaluable to exploit data gathered from these observations. The group will also continue to exploit the ERC-funded E-MOSAICS simulations to use globular clusters as tracers of galaxy evolution. They will also lead international consortia proposing Large Programs on the **JCMT** and **ALMA** to understand the evolution of gas clouds in the Galactic Center (A:5).

5) The **Time Domain Astrophysics group** works on a large variety of topics, addressing STFC science challenges A:5, A:6, A:8, and B:1. The group has access to the best astronomical surveys: **ZTF** and **ASAS-SN**, and has memberships in international collaboration projects such as PESSTO/ePESSTO+ (spectroscopic transient survey), ENGRAVE (GW-EM counterpart collaboration) and GROWTH (international transient follow-up collaboration). The group is also internationally leading in transient theory and interpretation of data. Over the next REF period the group will continue to be involved with cutting-edge observations and interpretation of data of astronomical transients, taking advantage of privileged access to the **LT** and **NRT**. The focus will be study of supernovae, novae, GW counterparts and exotic transients (B:1, A:6, A:8). The group will also improve radiation transport codes to deal with the heavy elements produced in kilonovae, in order to make estimates of the composition of these ejecta more quantitative (A:6, A:8) and will further develop numerical models of relativistic outflow to understand the structure and energy content of GW merger outflow and hypernova jets (A:5, A:8), in preparation for the forthcoming facilities such as **SVOM**, **LSST**, and **CTA**.

6) The **Astro-Ecology group** uses techniques developed in astronomy and ecology to tackle global challenges facing the planet such as biodiversity loss and climate change. This strongly interdisciplinary research is underpinned by £1.5M in funding from the GCRF to support cutting-edge research addressing challenges faced by developing countries. Working with leading conservation agencies around the world (e.g. World Wildlife Fund for Nature), the group has developed a drone plus thermal camera system with a highly specialised machine learning back-

end that improves the efficiency of animal surveys and fire detection by up to 100x over existing methods. This saves conservation agencies thousands of pounds per project per year and is having a transformative effect on their ability to tackle biodiversity loss and climate change. In turn, this is affecting change in national governmental policy on the uptake of drones. The group has been awarded GCRF funding to begin systematically implementing the system in global biodiversity hot spots around the world to significantly counteract current biodiversity loss and CO_2 emission from fires (a leading cause of climate change) in these areas.

Impact Strategy

Progress since 2014

As indicators of the planned increase in research impact, the impact strategy for REF2014 set targets in four areas:

➔ Reach and impact of the **National Schools Observatory** (NSO): The targets for teacher registrations (8,000) and total registered users (20,000) have been met or exceeded with 8,100 teachers (mainly UK, but some international) and 37,000 users in total.

➔ Spaceport: A new exhibit was developed with **Spaceport** which improved the offer for older students. The Spaceport site is now being taken over by *Eureka! Mersey*, with an ongoing relationship with LJMU both through ARI and extended to our Sports Science colleagues.

➔New robotic telescope: Substantial industrial engagement with local and national SME and larger industry partners was undertaken, with initial contracts being awarded for collaborative development of the telescope enclosure.

➔Commercialisation of engagement activities: In response to national changes to student fees, our short-course Distance Learning provision has been fully commercialised, and a Masters DL course created.

Approach to impact

Building on the success of our strategic plan from 2014, we have expanded our range of impact to currently cover three key areas:

1) **Public Engagement:** using research to stimulate interest in, and uptake of, STEM subjects among the general population, particularly school-age children;

2) **Astro-Ecology:** using research to deliver environmental and ecological outcomes that can exploit the specific research skills and experience of astrophysics researchers and is aligned with global challenges.

3) **Industrial Engagement:** using research to drive knowledge-transfer to, and up-skilling of, local SMEs and larger national engineering companies as well as those working in the New Space and established space industries.

The first area, **public engagement** (PE), centres on the NSO as an educational resource and collaboration with non-scientists (see Impact Case Study 1, **ICS 1**). The NSO grew from a Research Council-funded feasibility study in 1996, through a regional (EU ESF-funded) project to the national and international project (with funding from RCUK and now UKRI, as well as University and benefactor funding). Similarly, collaborative projects are developed with groups and organisations that work with particular demographics that are under-represented in STEM subjects.

ARI has embedded PE alongside our other main activities by establishing a dedicated unit of 5 staff (3.2FTE), led by A. Newsam. This is focused upon the NSO but maintains a wider outreach responsibility. Funding for the unit comes partly from grant income, but largely from the University, via LJMU's Widening Participation and civic engagement strategies. We are guided by the NSO

Advisory Board, including teachers, industrial experts and other external stakeholders, and by an open-membership departmental PE committee, which reports to the Management Board.

Updates on engagement activities are given at regular open meetings. Research members work with the NSO on research-led educational projects (e.g. in **ICS 1**) with appropriate allowance made through the workload allocation process. Achievement in the area of impact is also recognised within the University through the Appraisal process, and in the criteria for promotion (e.g. Newsam has a Chair in Astronomy Education and Engagement - one of only two in the UK primarily for outreach in astronomy).

The ARI encourages (through funding, training, mentoring and administrative support) all staff and students to engage with diverse audiences, through the media, community organisations, visitors to cultural attractions, business, and schools. Examples range from our annual Work Experience Week for schools to a residency at Tate Liverpool (June/July 2017).

We work to reach non-traditional audiences with activities from shopping-centre science demonstrations to award-winning theatre productions. For example, in June 2018 we were approached to develop an exhibit for the London Design Biennale. The exhibit showcased the innovative robotic design of the LT to around 40,000 people. Similarly, we collaborated with an architect, garden designer and landscape management company to create a show garden for the **2015 Chelsea International RHS Show** to coincide with the International Year of Light. Based on Dark Matter, the garden won a Gold Medal and the Best Garden award in its category. The garden was staffed by ARI researchers and featured on international media (RHS official figures put the global TV audience at 211 million).

Assessment of the impact of our work occurs in several ways with regular reporting to management and advisory boards. As well as statistical data gathered about all PE activities, specific initiatives are individually evaluated, including by independent external evaluators, using an Evaluation Framework which defines a set of Generic Learning Outcomes. From August 2014 through to July 2019, for example, supported in part by STFC funding (PIs Newsam and Leigh), ARI staff and students gave more than 600 presentations to over 50,000 people. In that period, an additional 250,000 people experienced an ARI-led exhibit at an exhibition or show.

The **Astro-Ecology** group's research has demonstrated that astrophysically optimised thermal-drone systems are extremely efficient at finding and identifying animals (**ICS 2**) and pinpointing the location of wildfires (**ICS 3**). The approach to impact has been to apply for external grant income (>£1.5M generated) to (i) develop and implement an automated monitoring system that is very low cost, robust, simple to operate, that can automatically detect, identify and geo-tag animals and fires in thermal infrared footage over large and inhospitable areas, and (ii) begin systematically taking this to key global biodiversity and fire hotspots. We are now working with 14 leading conservation agencies on 5 continents around the world in real-life conservation and fire-fighting situations. The 100-fold improvement in survey efficiency our system offers over existing methods has had a direct impact on halting biodiversity loss and reducing the size and duration of fires which comprise a significant fraction of annual anthropogenic CO_2 emissions – a main driver of climate change. Our interaction with government agencies is shaping conservation/land use policy, and legislation at a national level, e.g. working with the Madagascan Government's Civil Aviation Authority to help implement a National Drone Policy document.

In the area of **industrial engagement**, the research-driven needs of the LT project provided a natural "hub" for organizing, coordinating and initiating new activities (networking, knowledge transfer, exposure to new markets, etc.) between both local and national academic and industrial partners (e.g. Senar Precision Engineering, a case study presented in REF2014) in high-value engineering activities across a wide range of disciplines. The development of NRT provides an opportunity to expand this activity. Project Scientist Helen Jermak and Lead Engineer David Copley have been specifically tasked to lead the technology impact activity. In April 2020 we were awarded an STFC Innovation Account (£50k/year) to support pump-priming activity in this area as a first step to larger programmes of support.

Impact Strategy for 2021-2026

Our impact strategy is guided by our external Advisory Board and ARI committees (involving external members where appropriate). Impact is discussed at all Management and Advisory Board agendas, is a major part of our published strategic plans, and receives significant investment of staff time and resources.

The ARI Management Board has formalised a specific Impact Strategy to enhance our work in the areas of Engagement, Industry and Policy. Its main strands involve: (i) spreading the impact culture and good practice via measures including training in evaluation techniques, introducing engagement activity into staff appraisals, requiring submitted papers to be discussed with outreach staff (see Section 2 - People); (ii) building stronger links with our partners, beneficiaries and audiences; and (iii) enhancing the economic/industrial impact of our technology initiatives through supplier days and enhanced links with local trade bodies.

To support these strategic strands, significant planned developments over the next 5 years include:

a) **Greatly enhancing the reach and impact of the NSO.** The University endorsed the **NSO's 5-year plan in 2017**, providing central funding at the level of £265k p.a. Core aims include further developing engagement with under-represented groups in STEM, enhanced support for those with disabilities, and enhancing school engagement with ongoing research.

b) **Further developing collaborations** with other groups, both within LJMU (the Widening Participation team, Art and Design, Research Institute for Literature and Cultural History school, etc.) and externally (Tate Liverpool, World Museum Liverpool, Shakespeare North, Knowsley Safari, National Astronomical Institute of Thailand, etc.). Each collaboration will develop engagement with specific target audiences with known under-engagement with STEM or under-representation in STEM careers.

c) **Further development of astro-ecology projects.** The project will build upon our current successes to (i) facilitate the automated monitoring of animal species and wildfires around the world; (ii) create a secure online environment accessible to world-wide conservationists and researchers for uploading aerial data and providing near real time geo-locations of objects (e.g. animals, poachers, wildfires); and (iii) support our partner organisations to work with government bodies to maximise the benefits of the ecological data during meetings with policy makers, helping to shape conservation/land use policy, showcasing the results to local stakeholders (e.g. farmers) to highlight conservation issues and economic gains by communicating the benefits of long-term healthy ecosystems.

d) **New engagements with the Liverpool Local Enterprise Partnership (LEP) and Knowledge Quarter (KQ):** At the regional level, priorities for investment are defined by the **LEP**, who have established the KQ to attract investment and drive forward new projects. LEP have identified the Knowledge Economy (specifically Advanced Manufacturing) as a key sector driver and have highlighted ARI technology projects on their Innovation Ecosystem Map. The advanced controls and materials solutions necessary for the NRT are an excellent fit to this priority and LEP see the ARI as a beacon for attracting related industry and as a source of high-calibre graduates and researchers. We will work with these bodies to ensure the opportunities and resources associated with our activity are captured in their roadmapping, which identify local specializations and drive investment decisions.

e) **Moving beyond the local and national picture**. We plan greater engagement with the Newton and GCRF funding opportunities, enabling us to deliver UN sustainable development goals (SDG) in developing countries. We will target this opportunity by (i) developing projects based around topics such as telescope control systems and big data management, as well as education and training; and (ii) expanding our activity in the wider SE Asia region (see Section 4). Based on pilot programmes with Thailand, Kenya and Indonesia, we aim to develop approaches to education and PE that can be easily adapted

to the needs of low/middle income countries. For example, we will develop a modular in-school data analysis feature for the NSO software that allows for new configurations and tools to be easily added; and to allow teachers to customise their teaching interfaces. This meets UN SDG 4 through enabling quality technical, vocational and tertiary education. The experience and training of students overseas in STEM will equip them with skills that can be exploited in other sectors leading to increased economic development (UN SDG 8, 9).

2. People

Staffing strategy

The ARI's staffing strategy centres on the aim to be a destination of choice for world-leading astrophysicists in each of the discipline's three pillars: observations, theory, and technology. In addition to research excellence, the Institute seeks staff with a demonstrated commitment to teaching, outreach and building equity and inclusivity, primarily by proactively identifying leading early-career researchers (ECRs) that will strengthen and diversify the Institute, and closely supporting their bids for high-profile research fellowships. In recognition of the calibre of candidates that the ARI is now regularly able to nominate for these fellowships, LJMU have provided (4+ year) fellowship winners with a structured path to a permanent academic position.

Since REF2014, the ARI's academic staff has grown by 7 (4 male/3 female), now comprising 11 Professors, 7 Readers and 8 Senior Lecturers (of which 4 are proleptic). Two senior lecturers were recruited in 2016 to replace departing staff, via an open call that attracted over 100 applicants (70 male/30 female), of which 10 were shortlisted (5m/5f). Marie Martig and Dan Perley were appointed. The remaining 5 hires are senior research fellowship holders with proleptic appointments: Rob Crain (RS URF, 2014); Renske Smit (STFC ERF, 2019); Joachim Harnois-Deraps (STFC ERF, 2019); Sebastian Kamann (UKRI FLF, 2020); Azadeh Fattahi (UKRI FLF, 2021).

Recruitment has tangibly strengthened ARI research, enabled expansion into crucial areas of future activities, and has rebalanced the ARI's seniority demographics. The latter has enabled the implementation of a succession plan covering all core aspects of the ARI's activities, and an appropriate balance of seniorities on the ARI's key committees. Examination of publication outputs by seniority highlights a balanced contribution, attesting to the calibre of recently recruited staff: Professors delivered 65 papers per staff member, Readers 55 and Senior Lecturers (including proleptic staff) 47. This simple measure does not account for the fact that four of the proleptic staff were still completing their doctorates at the start of this REF period.

LJMU is a signatory to the **Researcher Development Concordat**, which places responsibilities on the Institution to improve the research environment and employment support for researchers. As one of the largest research institutes within LJMU, the ARI has over 25 postdoctoral researchers and technical staff and is acutely aware of its responsibility to represent the interests of its fixed-term staff (e.g. career progression). To this end, ARI staff (Steele, Jermak) are members of the LJMU Researcher Concordat Working Group.

Staff development

Staff at ARI benefit from a wide range of staff development activities available within the Faculty and the wider Institution.

At the institutional level (see institutional environment template), LJMU has a programme of researcher development (ACTivator) workshops addressing a variety of topics (Impact Development, Researcher Wellbeing, Funding, etc.). LJMU also organises researcher development schemes, for example the **TRANSPEER** programme is an ERASMUS+ project delivered by a consortium of EU-based institutions. ARI staff have participated in the ACTivator and TRANSPEER schemes both as guest lecturers (senior staff) and attendees (ECRs).

The Faculty organises a programme of biannual grant writing workshops targeting specific themes (e.g. ERC, ERDF, UKRI) where successful applicants share advice with colleagues, particularly ECRs for whom grant writing is particularly crucial. ARI staff (Bastian, Longmore, McCarthy, Smit) provided talks on obtaining funding from the ERC and UK funding councils.

Within the ARI, weekly research group meetings and seminars from external speakers create a strong research culture. ECRs are assigned a mentor to advise them on career development. The ARI Research Committee provides research support, guiding staff in the preparation of grant applications. During the annual appraisal process, line managers engage with all staff to discuss issues, achievements and career progression. Staff, particularly ECRs, are encouraged to engage in development activities such as training (e.g. Project Management, ACTivator workshops, Leadership Programmes, STEM ambassador workshops), grant applications and teaching opportunities to facilitate internal promotions and external employability. Following feedback from the ED&I committee, the Director regularly meets with ECRs and postdoctoral researchers to discuss departmental news, career progression and general wellbeing.

The ARI recognises the importance of good mental health and wellbeing. The department arranges annual Mental Health First Aid workshops, lunchtime meditation sessions and promotes relevant activities provided by the University (e.g., free gym memberships and yoga sessions). The ARI also recognises the difficulty that can be felt by staff and students in reporting and dealing with harassment, bullying or victimisation. The best way to prevent bullying and harassment is to intervene early, and tackle problems when they are hopefully more manageable. As such, we have developed an informal and internal programme called the "listeners". This consists of several staff volunteering (often undergoing training in mental health oversight, harassment and bullying, unconscious bias, etc.) to be available to listen to anyone in ARI that is having a problem. The role of the listeners is complementary with existing support structures within LJMU and the ARI. Listeners do not decide on the validity of a complaint, nor encourage a particular course of action. They act as a sounding board, helping to resolve problems before they grow.

Training, supervision, and support mechanisms for PGR students

We receive applications from students worldwide and all shortlisted candidates are interviewed. Funding sources include: STFC quota awards, Faculty-funded studentships, LJMU Scholarships and other ad hoc funding streams. During the REF period, 38 full-time students successfully completed their PhD. Our completion rate of on-time **92%** (STFC) is the highest in LJMU. A quarter of completing students were from overseas and three were mature students. Three PGR students have been accepted to the prestigious ESO studentship programme, to spend 1-2 years of their PhDs at ESO in Garching, Germany. Two other students have undertaken internships in Science Communication and Outreach at ESO-Garching. We have also had two PGR students spend 1-2 years at the Center for Astrophysics at Harvard University over the past 5 years. Of our students graduating in the REF period, **>80**% remain in astronomy. Destinations are worldwide and include: two NASA Hubble Fellows (Ivan Cabrera-Ziri → Harvard; Emma Beasor → Arizona), a UKRI Future Leaders Fellow (Joe Lyman → Warwick), and a Banting and CITA Fellow (Ted Mackereth → Toronto).

PGR student induction is compulsory and provided by LJMU's **Doctoral Academy**. All supervisors are required to complete the University's Research Supervisors Workshop. ARI runs compulsory courses on a range of topics designed to introduce PhD students to the wider research environment and help develop research and engagement skills. Up-to-date information and advice on "careers in astronomy" is provided each autumn to final year PhD students in a tutorial given by a staff member.

Each PGR student chooses a supervisory team responsible for the student's project and progression throughout the PhD. All students have access to programmes and assistance from the LJMU Doctoral Academy and they follow the University procedure regarding the progression of PhD students from their first year into the full PhD programme.

In 2014, based on feedback from the students, we instituted an ARI PhD oversight committee. Each cohort of students are assigned two independent staff members (i.e. not their supervisors) who follow their progress throughout their PhD project and troubleshoot any problems as they arise. Every six months, the two staff members meet with each student in the cohort to discuss progress. This system has been extremely successful, receiving praise from the students (e.g., "the PhD oversight committee gave me confidence, due to them being external to my project, that the progress that I had made on my PhD was adequate, in fact, above average, allowing me to expand my studies and tackle harder problems") and staff alike, as well as from the STFC as an exemplar of good practice.

All PGR students are required to attend the weekly colloquia at ARI and are encouraged to attend seminars at other institutes within LJMU. We also have weekly talks by ARI staff/students on their own research to the whole Institute. All research groups have weekly meetings to discuss recent papers in the field and present new findings as well. Students also organise their own monthly research series in which presentations of their recent work are made to the other PhD students. This encourages students to support each other via feedback, to identify areas of common activity, and sharing best practice. Finally, PhD students are represented on all appropriate committees within ARI.

Support for, and promotion of, Equality, Diversity, and Inclusivity (EDI)

The ARI was awarded the Institute of Physics Juno Practitioner Award in 2018 (lead: Habergham-Mawson), having held Juno Supporter status since 2014. In April 2021, the ARI will submit an application to AdvanceHE for conferral of an Athena SWAN Bronze Award (lead: Darnley). The ARI's **ED&I** committee (chair: Bastian) reports directly to the Management Board. ED&I membership also includes the Director, Head of Teaching, and representatives from all areas in the department; academic staff, technical staff, support staff, NSO, PRDA and fellows, PhD students, and undergraduates. The primary aim is to build the necessary diversity structures to make a positive long-term impact on the culture. Notable recent successes include: embedding a core hours policy within scheduled activities, implementation of the "listeners"; and organising biannual ED&I-focused seminars and training (e.g., unconscious bias and mental health awareness), on top of LJMU-wide staff development sessions. The committee also successfully lobbied the University for compulsory unconscious bias training for all members of interview panels and continues to push for additional University-wide initiatives.

The ARI ensured that the 1400 delegate **European Week of Astronomy and Space Science (EWASS) 2018 conference**, held in Liverpool, promoted diversity and inclusion. The organising committee actively sought women speakers, organised free childcare and chaired a day-long ED&I session, which directly resulted in publications in Science and Nature. Topics discussed included imposter syndrome and mental health within academia. We worked to ensure both these initiatives became embedded for future EWASS and National Astronomy meetings.

In order to make significant, long-term improvements to diversity there is a crucial need for visibility and role models, particularly those from lower socio-economic backgrounds, with protected characteristics and intersections in-between. Long-term, the lack of diversity in candidate pools can only be improved by increasing the number of students who study physics and engineering subjects at school and university, which we are actively tackling through our Impact activities (particularly PE). Our first strategy is to make engagement an essential component of all new positions (including fellows), with staff appointed based on their research, teaching, and outreach excellence. Our second strategy is to add an independent panel member (from LJMU or ARI professional services) to challenge unconscious bias within interviews for all positions within ARI.

Developing proactive recruitment processes is key to addressing low numbers of under-represented applicants. We plan to continue increasing our engagement with diversity networks and disability charities to promote jobs and studentships via wider recruitment portals. For engineering and technical posts, we advertise to wider engineering communities, making clear that appropriate training and support will be provided for these roles.

These ARI strategies align well with the University's dedication to ED&I. We will continue to actively promote diversity and inclusivity in all activities. This includes making shortlists for all positions as gender-balanced as possible. Additionally, we will continue to 'head-hunt' the best candidates for all positions, paying particular attention to fellowship applicants and academic staff open positions. Our recruitment goal is to increase the diversity of applicant pools and resulting shortlists, both in terms of ethnicity and gender. As part of this, we aim to increase the representation of permanent women academic staff in the ARI from ~13% to at least 25% over the next decade. Of particular note is the issue of "lag time", i.e. that for an equal representation in senior staff roles change must be enacted at earlier career stages. Over the past 5 years, at least 50% of our offers of PhD positions to prospective students have been given to women. At present, 33% of our PhD students and 41% of our postdoctoral researchers are female. Additionally, ARI maintains an active equality focus in our weekly seminars: 40% of our speakers over the period 2016-2019 have been women. All committees within ARI have at least one female representative and all hiring committees require at least one female.

3. Income, infrastructure and facilities

Income

The ARI is funded by a diverse range of sources including domestic research councils and charities (UKRI, STFC, EPSRC, Royal Society); international councils such as the ERC; UK central government; and industrial partners. The generation of research income is a key focus of the ARI's research strategy, and opportunities are continually monitored by the Research Committee.

The ARI's research income throughout this reporting period amounts to £12.2M, representing a **115% increase** with respect to REF2014. The growth was primarily from research council income. The ARI's Research Committee has made a concerted effort to identify ECRs whose profile will strengthen and diversify the Institute, and supported their bids for high-profile research fellowships. During the current REF period, this effort has led to senior fellowships from STFC (AF - McCarthy; ERF - Harnois-Deraps, Smit), UKRI (FLF - Kamann, Fattahi), and the Royal Society (URF - Crain, Bastian; DHF - Font, Parker). The ARI also secured its first ERC awards (Consolidator Grants - Bastian, McCarthy). The Astro-Ecology initiative (Longmore) has also spearheaded our diversification into UKRI GCRF areas.

In-kind funding through PI access to observing facilities, such as HST, ALMA, WHT and ESO, and HPC facilities (DiRAC) equates to £6.67M over the reporting period.

Infrastructure & facilities

Major investments in ARI infrastructure and facilities for the period 2014-2020 supported by the Faculty and University include:

Liverpool Telescope. ARI is unique among UK universities in owning and operating an overseas national astronomical research facility, and has received ~£7m LJMU investment in construction and operation over the past 20 years. Sited on the Canary island of La Palma, LT is currently the world's largest robotic telescope and it has unique AI capabilities that enable rapid response (<3 minutes) time-domain astrophysics. It is a national facility operated on behalf of STFC and has supported observation requests by 564 unique PI and CoI's in the past 3 years. The high impact of the telescope's science is evidenced via citation rates: refereed publications over three years old that include LT data average 39 citations/paper (NASA ADS), which is triple the average rate for all astronomy papers selected with the same criteria. 27 papers have appeared in the high-profile journals Nature or Science and ARI staff are authors on 50% of LT papers. In 2019, a telescope optical beam simulator for instrument testing was built using matched STFC and LJMU capital allocations.

HPC facility. Following a proposal from the Computational Galaxy Formation group, in 2020 the Faculty commissioned LJMU's first HPC facility, which will be a centrepiece of ARI research in the coming 5 years. This is a "Tier-3" facility that enables diverse research computing applications

within the Faculty, and acts as a development bridge from desktop workstations to the national and international HPC research facilities (e.g. Archer, DiRAC & PRACE). The facility (which consists of 1600 AMD Rome cores, 12TB of memory, and 2Pbytes storage), can be used both as a "work farm" that runs many independent computing tasks simultaneously, and as a massively-parallel cluster capable of running individual jobs that require many computer cores and/or a large memory footprint. The facility was realised with a £450k investment contributed by the Faculty and the ARI, and was designed in collaboration with systems architects from Hewlett Packard Enterprise (HPE), with a focus on ensuring a cost-effective path to modular expansion of the facility as future funding is unlocked. The facility is hosted by LJMU's IT Services division in a modular HP Performance-Optimised Datacentre. IT Services manage the hardware, whilst the software level administration is performed by the ARI's computing officers, both of whom are PhD-level technicians with a background in research.

ARI office expansion. In 2018 LJMU approved a business case from ARI to acquire additional floor space, creating two dedicated astrophysics floors within the IC2 Building on the Liverpool Science Park site. The expansion is in response to an increase in PhD students and postdoctoral researchers funded by growing external income. The new space combines a tailored-design of individual offices and open-plan areas that foster interaction between researchers at all levels, enhancing the academic environment and melding with LJMU's Strategic Plan to support high-quality activity. The new accommodation contains offices for four research groups, an office for PhD students, meeting and skype rooms, and a communal breakout area (4600 sq. feet in total). The Faculty invested £38k in refurbishing the new office space and LJMU invests approximately £100k p.a. in increased rental costs.

Drone lab. LJMU has two world-class drone labs that are used for both teaching and research. The labs feature six drone flight simulators that can be used for training on multirotor and fixed-wing drones. There are many workbenches on which to construct drones, and a wide variety of the tools needed for construction. To design and build various parts of drones the lab has computers with the required software (e.g. CAD software) as well as a computer-controlled cutting machine and two 3D printers with which various parts of drones can be custom-made. The lab also houses computers that can be used to plan drone missions (e.g. MissionPlanner) and analyse data (e.g. Pix4Dmapper). LJMU also has a closed netted area on campus for test flights (10x3x3m) and two flying fields (75x150m, 50x50m). Over the current REF period, the University has contributed in excess of £100k in funding and two support staff positions to the drone lab initiative.

The NSO, which is an integral feature of the ARI's research culture, is an online educational resource, targeted at UK and Irish primary and secondary schools, but with significant additional international impact as well. Supporting the LT as its educational arm, it allows teachers and pupils to request their own observations. In recent years investment in upgraded servers and a doubling of LT time (from the LJMU allocation) has allowed free registration to be opened to all, leading to a total of around 16,000 active users at any time. The dedicated servers also provide the capacity for significant access without registration, serving over 2 million web pages per year, making it a major international educational resource. These investments have been crucial to the delivery of our impact strategic plan, particularly as regards to PE (see Section 1).

4. Collaboration and contribution to the research base, economy and society

Collaboration and contributions to the research base

High-impact research: Over the period 2014-2019, ARI staff published 1100+ peer-reviewed articles (one every two days) that have attracted 40,000+ citations. The mean number of citations per ARI paper (34) is roughly triple the field average over the same period. As a specific highlight, in 2015 our Computational Galaxy Formation group published the most highly-cited paper (the EAGLE simulations) in the whole of space science, out of more than 23,000 publications. ARI staff have also led, as first author, 10 (35) publications with at least 100 (50) citations since 2014.

A recent assessment of our research impact is provided by **a study ranking over 6.9 million researchers worldwide** according to standardised citation indicators. Four ARI staff (Bastian, Mazzali, Salaris, Schiavon) ranked among the top 2% most impactful researchers across all disciplines when considering career-long citations. When considering data from 2019 only, seven staff members (Baldry, Bastian, Crain, Mazzali, McCarthy, Perley, Schiavon) are included, demonstrating the strength of recent hires.

National leadership: ARI staff are helping to steer the national science agenda through strong participation in key panels and reviews, including membership on (during this REF period):

- ➔STFC Projects Peer Review Panel (Longmore);
- ➔STFC Education, Training and Careers Committee (Davies, 2016-2019);
- ➔STFC Astronomy Grants Panel (Davies);
- ➔STFC Astronomy Advisory Panel (Mazzali);
- ➔RAS Committee on Diversity in Astronomy and Geophysics (Habergham-Mawson);
- ➔Equality Challenge Unit Athena SWAN Panel (Font, 2018-2019);
- ➔New Frontiers in Research Review Panel (Font);
- ➔Newton Fund Review Panel (Longmore);
- ➔STFC Rutherford Scheme Review Panel (Davies);
- ➔DiRAC Astronomy and Cosmology Panel (Crain);
- ➔all major UK postdoctoral fellowship panels, including STFC ERF, Royal Society URF, RAS Fellowship; UKRI FLF, Stephen Hawking Fellowship (Bastian, Davies, Font, James, Martig, McCarthy);
- ➔survey planning panels, including the UK SKA Science Advisory Committee (Longmore), and the STFC MOONS Oversight Committee (Steele).

International collaboration and contributions: All our researchers have established international collaborations with the very best institutions worldwide. For example, we have successful international partnerships with: Max Planck Societies (MPA & MPIA in Munich and Heidelberg); UC Berkeley; Caltech; Harvard; NASA; Penn State University; University of Tokyo; University of Sydney amongst many others. The fraction of ARI papers co-authored with international partners is approximately **90%** and consequently our contribution to the international reach of LJMU is highly significant. In the US News Global University Ranking for 2020, the ARI was ranked number 6 in Space Science for the "percentage of total publications with international collaboration''.

A recent research contribution is **EWASS & NAM 2018**. The ARI hosted the joint meeting at the ACC Conference Venue located on the iconic Liverpool Waterfront. The 4-day meeting consisted of over 40 separate symposia and special sessions, along with interactive workshops, the award of prestigious prizes and plenary talks covering a diverse range of topics related to science, outreach and diversity. The meeting also showcased various North West regional and national space-related technology projects. The meeting was attended by stakeholders, funding agencies, senior political figures, local dignitaries and industry partners. With 1,400 delegates attending from 57 countries, EWASS 2018 represented one of the largest gatherings of European astronomers and space scientists.

Leadership of large international collaborations: ARI staff have significant leadership roles in numerous large international collaborations, including:

- ➔Euclid Independent Legacy Scientist (Baldry);
- ➔GROWTH management board (Copperwheat, Darnley, Perley, Steele);
- ➔HST UV Legacy Survey Advisory Committee (Bastian);
- ➔ESO European Extremely Large Telescope (EELT) Advisory Committee (Longmore);
- ➔ESO Public Surveys Panel (Baldry);
- ➔ALMA REBELS management board (Smit);
- ➔Virgo Consortium core membership (Crain, McCarthy);
- ➔WEAVE leadership roles (see Section 1);
- ➔APOGEE Survey Scientist (Schiavon);
- ➔Maunakea Spectroscopic Explorer Science working group co-chair (Schiavon)

➔PLATO stellar SED modelling working group chair (Davies)

Contributions to the economy

ARI staff and research students have led engagement activities with local and national industry over the REF period. Notable examples include the placement of 7 PhD students for 6-month work placements as part of the STFC-supported Centre for Doctoral Training in Big Data Science run jointly with the University of Liverpool. These include placements at IBM Research at the Hartree Centre (Warrington); Imaging3D Ltd. at Sensor City (Liverpool); Radius Payment Solutions (Crewe); AlgoLib Ltd (Liverpool) and the Asteroid Mining Company (Glasgow). Many of these internships were initially established through our participation in the **LCR 4.0** programme. The companies reported a positive business impact resulting from the work, for example changing the strategic focus of the Asteroid Mining Company from spectroscopy to photometry in their design of space-based instrumentation.

Examples of projects underway led by staff include a series of contracts with a major UK defense contractor to develop alternative methods of celestial navigation in the event of GPS failure, and a collaborative project with the University of Liverpool and industrial partners on the tracking of low-earth and geostationary satellites that is based on our previous research work optically tracking the Gaia Satellite on behalf of ESA. Technology group staff are also leading a project working with the joint LJMU-Liverpool University enterprise **Sensor City** to develop and characterise 3d printing technologies for opto-mechanical applications.

Contributions to wider society

ARI staff members take seriously their commitment to engage with wider society (i.e., beyond academia). Recent examples include:

Astro-ecology: As described in Section 1 (Impact) and **ICS 2** & **3**, the Astro-ecology group has had a direct impact on two key challenges facing society in the 21st century: biodiversity loss and climate change.

Public engagement: The core programme of PE and Outreach by the ARI typically delivers over 100 activities each year to an annual total of around 10,000 people. Activities that engage with groups under-represented in STEM are a key priority. Much of this is carried out through partnerships and collaborations with non-STEM organisations and civic organisations. The arts are a particular area of collaboration, with exhibits or residencies with Tate Liverpool, FACT Liverpool and the London Design Biennale, and collaborations with artists from street theatre to visual arts. For example, a collaboration with the theatre company Unlimited Theatre on a children's play that encouraged ambition in STEM, won several national awards, including the Charity Award for Arts and Humanities.

In 2018 the Astro-ecology group held an interactive exhibit at the National Science Museum in London titled, "Astro-ecology: using drones and space science to save endangered animals" as part of the "We are Engineers" festival, which was attended by ~5.5k public visitors per day. In 2020 the group was invited to run the flagship citizen science project for **British Science Week 2020**. Members of the public were asked to help identify Spider monkeys in thermal infrared video footage and provided ~1M classifications. The Astro-ecology team's work has featured heavily in international media, including two BBC Nature documentaries, "Primates" and "Nature from the Air", which reached a large, world-wide audience.

Nationally we have run several projects including the STFC-funded **Astronomy for Remote and Island Schools project**, which successfully targeted remote communities that normally have little chance to engage with researchers.

Global Challenges in SE Asia: Over the past 3 years ARI has participated significantly in international engagement in SE Asia afforded by Newton and GCRF funding. We have developed international, multi-disciplinary partnerships grants with both educational and industrial impact. As

an example, the ARI has a long-standing MoU with NARIT (Thailand) to facilitate collaboration, knowledge transfer and research links. NARIT operates a 2-m conventional telescope, and has a mission to significantly expand astronomical research in Thailand. The ARI has supervised two Thai PhD students who now hold permanent academic posts in Thailand. ARI has recent and ongoing collaborations with NARIT in including enabling technology (ST/N006631/1, PI Steele), education (ST/P005616/1, ST/T007117/1; PI Newsam), mechatronics (ST/P005659/1, ST/R006571/1, ST/T00715X/1; PI Copperwheat) and data exploitation (ST/P005640/1; PI Smith).

ARI has also developed a collaboration with LAPAN (Indonesian Space Agency) in support of education and training programmes associated with a planned large robotic telescope in Indonesia. This has been facilitated by collaborative visits in Indonesia and the UK covering both computer science and astronomy education (funded by Newton Fund and GCRF).