

**Institution:** Keele University

**Unit of Assessment:** UoA9 Physics

## 1. Unit context and structure, research and impact strategy

### 1.1 Context, structure and strategy

The University of Keele is a broad-based research-intensive university delivering excellent research across its three faculties. Physics is part of the School of Chemical and Physical Sciences (SCPS), within the Faculty of Natural Sciences. Keele's mission contains both global and regional elements. At a global scale, Keele's mission is to make world-leading contributions to fundamental research, to answer some of humanity's key questions (e.g., "is there life outside our solar system?") and to tackle key societal challenges. Regionally, Keele's mission is to be an engine of development and regeneration in the economically and socially challenged region around Stoke-on-Trent via the Keele Deals (the new Keele Deals represent a £70m+ programme of research-based co-investment and impact planning with the LEP, the NHS, local authorities and regional partners).

### Physics research and impact strategy/vision

#### Strategy review and development:

During the last two REF cycles, research in Physics has been concentrated into a single, focused research theme, Astrophysics, in order to ensure critical mass and an internationally competitive environment. Following REF2014, Keele reviewed its research structure and strategy, in order to better address modern societal challenges and to improve research delivery. The review resulted in the creation of three major challenge-focused pan-institutional interdisciplinary institutes: the Institute for Social Inclusion (ISI), the Institute for Sustainable Futures (ISF) and the Institute for Global Health (IGH).

The review also led to the formation of SCPS in 2016 and the appointment of a new research-focused Head of School (Watkinson) and the creation of the role of School Director of Research in 2018 (currently Hirschi). This new role has provided the leadership needed to review and develop the School research strategy and structure, and to drive its implementation. A School Research Committee, chaired by Hirschi, was set-up to oversee research strategy and implementation. It is composed of representatives from each research area: Astrophysics (9 staff), Chemical Materials Science (8 staff), Synthetic Chemistry (7 staff) and Forensic/Analytical Science (7 staff) as well as representatives for early career researchers, equality, diversity & inclusion (EDI), postgraduate research and education research.

The key strategic decision following a review of School areas of research strength was that alongside further strengthening Astrophysics, it was the right time to establish a new interdisciplinary research group in "Materials Science and Renewable Energy", to capitalise on potential synergies between Physics and Chemistry research (building upon the Chemical Materials Science group) and between Physics and the Institute for Sustainable Futures, thus enhancing the vitality and sustainability of Physics research at Keele.

#### Current strategy and structure for Physics:

The current research groups and their aims are:

- The aim of the *Astrophysics group* (9 staff: Hellier, Hirschi, Jeffries, Maxted, Oliveira, Smalley, Taylor, van Loon, Wright) is to better understand planets, stars and their environments, our place in the Universe and our origins.
- The aim of the new *Materials Science and Renewable Energy group* (11 staff: 3 from Physics: Heckl, Morbec, Balakrishnan, 8 from Chemistry: Darton, Greenwood, Hawes, Hollamby, Jackson, Matthews, Ormerod, Radu, Zholobenko) is to develop world class research that enables better and sustainable materials and energy production methods.

Given the interdisciplinary nature of the Materials research, the 3 Physics (and 8 Chemistry) staff from this group are returned to the Engineering UoA 12 in REF2021. They are nevertheless an integral part of the Physics research environment and strategy.

To best achieve the above aims and enhance the vitality and sustainability of Physics research, our research strategy/vision is as follows:

- Continue to establish and lead or play a key role in international collaborations to pursue forefront research in Astrophysics.
- Support these collaborations with a range of research income streams for staff, PDRAs and PGR students and by winning competitive access to national and international research facilities.
- Recruit and attract the best people (staff, fellows, PDRAs and PGR students), via a robust EDI-aware recruitment process with research excellence at its core.
- Provide state-of-the-art physical infrastructure, research environment and support structure for staff, PDRAs and PGR students.
- Encourage and support staff at all career stages to take up leadership positions in their research disciplines.
- Develop partnerships with non-academic partners to enhance our research and its impact.
- Promote and improve research integrity, reproducibility and open science.

#### Interdisciplinary Research Strategy:

School-level Directors of Research meet regularly via the Faculty Research Committee and a University-wide Research Leaders' Network to review and improve the University Research Strategy, its implementation and interdisciplinary research opportunities. Using these platforms, Hirschi led the establishment of a faculty-wide interdisciplinary Materials Science and Renewable Energy theme to exploit opportunities on sustainability. The theme includes 4 researchers from the School of Computing and Mathematics and 3 from the School of Geography, Geology and the Environment. Furthermore, Hirschi and Wright, along with Polack (Director of Research for the School of Computing and Mathematics), led the establishment of a University-wide "Data Science Network" which includes more than 70 staff members across all 3 faculties and aims to develop inter-disciplinary research synergies in Data Science. The network will coordinate the academic research supported by a new Digital Innovation Centre (IC7), which is currently being built as part of the Keele Deal.

### **1.2 Achievements made during the REF2021 cycle and objectives for next REF cycle in relation to REF2014 and current strategies**

The research strategy set out in REF2014 was to establish and lead, or play a key role in, international collaborations to pursue forefront research in (1) stellar hydrodynamics, evolution and nucleosynthesis (ERC-SHYNE, Nugrid), (2) star formation, clustering and environments (Gaia-ESO, ESA Gaia), (3) galactic and extra-galactic environments (VISTA survey) and (4) binary stars (TESS, Plato). This has been successfully implemented (as detailed below) and has led to publication of over 500 refereed papers during the REF2021 cycle (over 55 per academic staff FTE returned), which have been cited more than 12,000 times (>1,300 per FTE; citation data in this statement have been obtained from the NASA ADS platform). This research was underpinned by a range of diversified income streams (including STFC, Leverhulme, EU) and by gaining competitive access to national and international research facilities (e.g. ESO telescopes, PRACE HPC). Keele provided support for these efforts in a range of ways, including ring-fencing staff time for research and match-funding STFC PhD studentships (for more details, see Sect. 2 for support for people and Sect. 3 for the research income).

#### (1) Massive stars and their impact with SHYNE, NuGrid, BRIDGCE UK, COST ChETEC, NSF IReNA, ChETEC-INFRA (Hirschi):

Hirschi led the SHYNE ERC project (2012-2017) which aimed to develop synergy between three-dimensional (3D) and 1D stellar models, computing the first 3D simulations of carbon burning in massive stars and improving the modelling of convection in stars. This project also delivered priority lists for nuclear physics experiments (guiding one experiment at nToF@CERN).

Hirschi's key role (PI for several years) in the NuGrid international collaboration (23 institutions in 10 countries) enabled comprehensive nucleosynthesis predictions (Pignatari+Hirschi+, ApJ, 2016). Within the [BRIDGCE](#) (.ac.uk) network (15 UK institutions), Hirschi is leading research on the evolution and fate of very massive stars towards black holes, pair-instability supernovae and Gravitational Waves (Belczynski+Hirschi+, A&A, 2020). Since 2017, Hirschi has been chairing a COST Action entitled "Chemical Elements as Tracers of the Evolution of the Cosmos" ([ChETEC](#).eu; CA16117; 2017-2021). ChETEC coordinates research between 200+ researchers from across 30 European Countries (leading to more than 100 refereed papers, 24 with Hirschi as co-author). In 2019, Hirschi was appointed to the steering committee of the world-wide US-led NSF AccelNet [IReNA](#) network of networks (2019-2023) to represent the ChETEC community. This will enable Hirschi to continue his international coordinating role in the next REF cycle. The ChETEC community successfully applied for a €5m EU infrastructure grant, which will start in 2021 (ChETEC-INFRA.eu). Hirschi will lead nucleosynthesis software tools development within this project. The research foci in the coming years will continue to be synergy between 3D and 1D stellar modelling of the progenitors of supernovae and gravitational wave emitting black holes.

(2) Comprehensive picture of star formation, clustering and their environments with Gaia-ESO, Gaia, WEAVE (Jeffries, Wright):

The Gaia-ESO survey (Smiljanic+, A&A, 2014) is the world's largest high spectral resolution survey using 350 nights on one of ESO's 8-m Very Large Telescopes, measuring the line-of-sight kinematics and chemical abundances of galactic populations as a complement to ESA's Gaia astrometry satellite. Jeffries is a co-I and steering group member and has been leading efforts to understand the dynamics and chemistry of young clusters and star forming regions, with continuous PDRA support from STFC during the REF2021 cycle. Keele expertise in spectroscopy, kinematics and age determination in young stars has led to significant and rapid exploitation of the ESA Gaia satellite DR1+2 data (Wright & Mamajek, MNRAS, 2018) and leading roles in new, massive spectroscopic surveys with e.g. WEAVE. WEAVE (first light in 2021) is a next-generation multi-object (~1000 targets) spectrograph recently installed on the William-Herschel Telescope. Wright is co-I on a major WEAVE survey of stars in short-lived evolutionary phases across the northern Galactic Plane and is leading the young stars component of this survey. In the next REF cycle, Wright will combine WEAVE spectroscopy with Gaia astrometry for young stars in and around multiple star forming regions, star clusters and OB associations, to study the dynamics of these systems and address questions regarding their formation, evolution and dispersal into the field. Wright and Jeffries will both play leading roles in developing community surveys featuring many European collaborators, with ESO's new 4MOST multi-object spectrograph in Chile.

(3) Galactic and extragalactic environments with the VISTA survey of the Magellanic Clouds, SKA Pathfinders, EDIBLES, EMU (Oliveira, van Loon):

The VISTA survey of the Magellanic Clouds (VMC) obtained multi-epoch YJKs images of the Magellanic System of unprecedented quality. Oliveira and van Loon are members of the core team, leading the star formation and 3-D galactic structure analyses, respectively. This enabled, for example, the determination of the 3D structure of the Small Magellanic Cloud from Classical Cepheids (Ripepi+Oliveira+van Loon+, MNRAS, 2017). Oliveira and van Loon also exploited data obtained from other satellites, telescopes and surveys (Herschel, SPIRE, VLT Flames Tarantula Survey) to gain new understanding about the MC and other extra-galactic environments: e.g. mass loss (PGR Goldman+van Loon, MNRAS, 2017) and star formation (Schneider+van Loon+ 2018, Science). In the next REF cycle, Oliveira will develop and apply the machine learning (ML) methodologies to star formation in external galaxies. van Loon will continue taking part in the ESO Large Programme EDIBLES studying Galactic interstellar sightlines and coordinating ISM studies within the ULLYSES HST-UV initiative. Keele's GASKAP involvement (van Loon leads the Magellanic OH masers component, Oliveira YSOs) using new technology and new analytical approaches is generating new discoveries (AGN dust at redshift one, stellar OH masers at low metallicity) and will place Keele in a front-row position to capitalise on SKA, JWST and LSST.

(4) Exploiting eclipsing binaries from TESS, CHEOPS and PLATO surveys to map out fundamental parameters of stars (Maxted, Smalley, Hellier and Taylor [publishing under Southworth]):

Building upon the expertise and dataset from the Keele-led time-variability sky-survey (WASP), Keele developed software tools to characterise the host star in these planetary systems (e.g. mass; Maxted+ A&A 2015-2020) and for analysing light and velocity curves of detached eclipsing binaries and transiting planets (Taylor's open-source JKTEBOP code has been used in over 300 papers led by over 50 authors so far). These have enabled the Keele team to play a key role in the current generation of transiting planet surveys. Maxted is a member of the CHEOPS Science Team (ESA's S-Class mission led by 2019 Nobel Prize winner Didier Queloz) and develops the pycheops software delivering an order of magnitude improvement in accuracy and is developing synergies between exoplanet and binary star research. In the next REF cycle, Keele will be contributing to preparations for the PLATO mission. In particular, Taylor and Maxted both lead PLATO work packages related to improving models of planet host stars ("Binary & Multiple stars" and "Benchmark stars"). Taylor will be responsible for selecting targets, allocating bandwidth and organising the analysis and follow-up observations for all science cases using these objects.

Establishment of a new "Materials Science and Renewable Energy" group and objectives for the next REF cycle: This new group was established in 2018-2019 with investment in infrastructure (Section 3.3) and new staff (Balakrishnan, Morbec) to harness the new opportunities opened by the reorganisation of the University research structure and strategy. In the next REF cycle, Morbec will lead the design and characterisation of novel 2D materials with state-of-the-art quantum mechanics simulations. Balakrishnan will lead the development and application of these novel 2D materials for applications in wearable technology, spintronics and pollutant sensors. In addition, Heckl, who transferred from the School of Computing and Mathematics in 2016, leads research in thermo-acoustics and applies it to the combustion of hydrogen. In particular, she will continue to lead the €4m EU POLKA MSC ITN (2019-2022), which builds upon her €3.7m EU TANGO MSC ITN (2012-2016). Combustion of hydrogen from renewable sources is an emerging technology that can replace fossil fuels and so provide carbon-neutral energy. This group will develop and exploit synergies with other scientists within the faculty and Institute for Sustainable Futures (ISF) (e.g. building upon Keele's hydrogen energy, HyDeploy, and smart energy network demonstrator, SEND, projects developing new low-carbon technologies).

### 1.3 Impact

Fulfilling Keele's global mission to answer some of humanity's key questions, Astrophysics research has impacted world-wide audiences and changed their awareness and understanding of our place in the universe via media reporting, the creation of documentaries and social media content based on our research results (see Exoplanet ICS).

Regionally, Keele's mission is to be an anchor institution and an engine of development and regeneration in the economically and socially challenged region around Stoke-on-Trent and North Staffordshire, an area that is significantly under-represented within higher education. The Astrophysics group's regional impact strategy is therefore to improve opportunity and performance by engaging, encouraging and enthusing children to go on to further study in STEM disciplines. This aim was achieved by our continuous commitment to public engagement with Stellar Astrophysics research at Keele, through our mobile planetarium, the Stardome. During the REF2021 cycle, groups that have visited the Stardome include 100 primary and 44 secondary schools, 4 Further Education providers and 2 other universities. The impact of the Stardome upon Widening Participation in HE was recognised when it was awarded Times Higher Education Award for *Widening Participation or Outreach Initiative of the Year* in 2015. The university has supported the running of the Stardome throughout the REF cycle through integration of the Stardome into one of the key workhorses of the government-funded [Higher Horizons+](#) (HH+) [Uni Connect](#) consortium, which geographically covers Staffordshire, Stoke-on-Trent, Shropshire and Cheshire, and is led by Keele University. The Head of HH+, Ant Sutcliffe, was named the widening access practitioner of the year at the 2020 NEON Awards, further demonstrating the success of our engagement programme. In order to further support Stardome activity, Keele has also hired an outreach officer, Scott Walker, funded by The Ogden Trust (a charitable trust that promotes the teaching and learning of physics), who has contributed significantly to the delivery of the Stardome impact.

The Stardome will continue to be a major vehicle for local engagement with children in an under-privileged area of the UK. New content drawing upon our current research will be developed for the next REF cycle (e.g., nucleosynthesis and gravitational wave progenitors). Further school engagement will be developed as “Masterclasses” in Nuclear Astrophysics in the context of the ChETEC-INFRA EU project. The Astrophysics group will also explore other avenues for knowledge transfer via the Data Science network set up by Hirschi and Wright.

For the newly created “Materials Science and Renewable Energy” group, the main targeted impacts will be economical and environmental, and targeted beneficiaries are local, national and international companies. There is strong potential for application of 2D materials in wearable technology, spintronics as well as sustainability (pollutant sensors) linked to the POLKA, HyDeploy and SEND projects. Keele staff will in particular explore the potential of heterogeneous structures based on 2D materials (graphene, MoS<sub>2</sub>) for photovoltaics, gas sensors and spintronics.

The Materials Science group will benefit from the Keele impact facilitation framework, established in recognition of the value and necessity of impact facilitation. Keele established the Research and Innovation Support Enhancement (RaISE) team in 2017 to support and manage research achievements and to maximise their societal potential. Local initiatives such as the annual Impact Acceleration Fund and the Celebrating Impact conference ensure that impact is a clear and realisable goal for our research community. At the individual level, specific impact is identified and nurtured through the annual staff performance review and enhancement process (which includes an embedded research planning process) and is supported by our School Director of Research.

The Keele Impact Acceleration Fund has been established to provide financial support for the development of impact by providing resources to prototype, engage industry, and maximise public awareness. Further support will come via the partnership and impact accelerator team, which helps identify and align research priorities to prospective impact by tracking key academic outputs and providing strategies for the identification, gathering, synthesis and linkage of evidence from this research to potential stakeholders. Direct business engagement will be further promoted by Keele’s knowledge exchange programme, which includes the ERDF-funded Keele Research Innovation and Support Programme (KRISP), Knowledge Transfer Partnerships (KTP) and Business Bridge (ERDF). These schemes present business and industry-led challenges to Keele staff, providing new opportunities for impact development while simultaneously creating a sustainable route for further growth of Keele’s research programme.

#### **1.4 Open research, research integrity and Reproducibility**

This unit is at the forefront of developing an open research environment; research outputs continue to be made openly available (via internal and external repositories), which began in advance of the current REF policy and is reflected in its 100% open access compliance for REF 2021. The Unit is committed to the principles of open research and research integrity for all aspects of our research: software, data and outputs. Concerning software, open-source codes are used and developed (e.g., pycheops by Maxted and MESA code by Hirschi) and the group has led several code comparison projects (e.g., Jones+Hirschi+, MNRAS, 2015) and benchmarking exercises (Taylor and Maxted roles in PLATO). We also make use of, and train our PGR students to use, open-source software (e.g., Python) and version control platforms such as git, to improve software development and reproducibility. Research data is also made accessible via dedicated discipline-specific websites and databases (e.g., ESO archive and international astronomical database: <https://cdsweb.u-strasbg.fr/> for observational data, [www.ChETEC.eu](http://www.ChETEC.eu) knowledge hubs for nuclear astrophysics expertise, facilities, datasets and software tools). Furthermore, all Astrophysics staff use the ArXiv e-print archive to make our outputs freely accessible. These efforts will be further supported and enhanced by the data science network activities during the next REF cycle.

The university has also developed a robust Research Misconduct Procedure that provides a fair and transparent process that protects all those involved, including the complainant. In order to embed research integrity within the research culture at Keele, as well as providing professional support, resources and training via RaISE, the University has also established an Academic Lead for Research Integrity and has appointed Faculty Research Integrity Champions.

## 2. People

Our staffing and recruitment strategy is aligned to Keele's People Strategy (2015-20) and driven by our strategic research aims as well as by the goal of attracting the most talented scientists to our school. This strategy commits the UoA to principles of equality, diversity and transparency. It aims at both ensuring vitality and sustainability research in Astrophysics and developing the new interdisciplinary research group in Materials Science and Renewable Energy. Recruitment is also used to maintain a good balance between young ambitious staff and experienced colleagues to mentor them. Finally, our aim is to improve the gender balance and provide equal opportunities to all staff.

Recruitment processes of our staff and PGR students follow high standards overseen by Keele's Human Resources (HR) Directorate. Positions are advertised internationally, which enables us to recruit the best people from the UK and abroad. All short-listed candidates are interviewed by a diverse Equality & Diversity-aware panel (including at least one female) following a standardised process for all candidates (adjustments are made for applicants with disabilities). Panel members are required to undertake recruitment training (including unconscious bias) at least once every two years. Recruitment in the REF2021 cycle evidences the successful implementation of our strategy:

- Prof Michael Watkinson, an experienced and internationally leading chemist, was recruited as the new head of SCPS in 2018 to improve the local research support structure (e.g. creation of a new school research committee and equality and diversity committee).
- Prof Maria Heckl, an expert in thermo-acoustics and hydrogen combustion, joined SCPS from the School of Computing and Mathematics (in 2016) and is leading research on renewable energy. In 2019, she successfully started the Polka EU MSC ITN to develop safe low-carbon combustion technology.
- Drs Nilanthi Balakrishnan (experimental material scientist) and Juliana Morbec (computational material scientist): Two new female junior lecturers working on 2D materials were strategically appointed in 2019 to develop Physics research in Materials Science.
- Dr Nicholas Wright, Ernest Rutherford Fellow, was given a permanent lecturer's position in 2016 to consolidate the Astrophysics research group following the departure of Dr James Reeves who is now a Professor at the University of Maryland in the US (since we recruit excellent and ambitious researchers, we expect some to take on higher positions at other institutions abroad).

Keele's staff development strategy is to support and enhance the career of research staff throughout their entire research life cycle, from early career researchers (ECRs) to senior staff, including promotion and succession planning to ensure the vitality and sustainability of Physics at Keele. The university and the unit have full and active commitment to Vitae's Concordat for Promoting Excellence in Research. Transition from a pure research position, such as a PDRA, to a permanent academic position as lecturer is a major step in the life of ECRs. Keele and SCPS provide strong support for ECRs to ensure a smooth transition. A new Masters in Higher Education Practice (MAHEP), including modules on research, was developed for ECRs (which all our recent appointees benefited from). Additional training and development courses include, in particular, PhD supervision and recruitment.

Mentoring is provided for all ECRs and probationary staff. Balakrishnan and Morbec are mentored by Hirschi and Watkinson. As part of this mentoring, research targets and the support needed to achieve these are initially set and then reviewed quarterly. Furthermore, new staff benefit from a reduced teaching load and no administrative duties, ensuring that they can establish a successful research portfolio. Balakrishnan and Morbec also received a start-up fund and a PhD student from school and Faculty research development funds to help establish independent research environments at Keele. This support is further complemented by a strong supportive culture and open-door policy within SCPS. The success of the extensive support for ECRs to set up an independent research group is evidenced by Wright securing a Leverhulme Trust grant in 2020 for a 3-year PDRA.

Staff at all career grades are supported via an annual appraisal process. This process identifies plans for both research and impact and the necessary support from the School to achieve these plans. In SCPS, staff are further supported by the newly established research committee and School Director of Research (support for grant writing, dissemination of funding opportunities). Once these plans are established, research-active staff are given teaching-load reductions (a flexible form of research leave/sabbaticals) to help them successfully drive active research projects and develop new projects. They can also access Faculty research development funds to develop new activities and initiatives. Hirschi was given several teaching-free semesters to lead his ERC project and to set-up his COST Action. Maxted received faculty funding to enable him to lead scientific preparations for the CHEOPS mission.

The support described above enables staff to progress in their career and be rewarded for their performance with promotions. In the REF2021 cycle, Hirschi was promoted to Professor and Oliveira to Senior Lecturer (both in 2018). Previous Head of School and Astrophysics group Lead Prof Evans retired during the REF2021 cycle. His leadership roles were distributed to Profs Hellier (UoA 9 lead, STFC consolidator grant PI) and Hirschi (School Director of Research) as part of our succession planning. Transitioning to management and leadership positions also represents an important step in an academic career and scientists are generally not trained or prepared for it. Keele has realised this skills gap and developed a strategic research leadership training programme in collaboration with Advance HE. Hirschi joined this training to step into his new role of School Director of Research. The training also served him well in managing the ChETEC COST Action involving more than 200 scientists in over 30 countries. Emeritus staff retain an office space in SCPS and provide input at various levels (Jackson, ex-PDRA, contributing to star formation research; Evans guidance on management).

Scientific research requires continuous academic knowledge development. This is supported via our vibrant programme of bi-weekly research seminars, which include a combination of Astrophysics, Materials Science and Renewable Energy topics. These are complemented by a seminar series in Chemical Sciences research. At University level, Keele's three interdisciplinary institutes provide an overview of today's grand challenges and the latest developments on the topic of sustainable futures. Keele's RaISE team further supports and facilitates knowledge exchange and impact from research in various ways (Sect. 1.3).

Thanks to our diverse funding streams (UK STFC and Leverhulme, EU ERC and international fellowships), more than 10 PDRAs in total (between 4 and 5 concurrently) were hosted over the REF2021 cycle, representing a slight increase over the REF2014 cycle. Many of these PDRAs came from abroad and benefited from the strong HR support (financial and practical help with visas and relocation packages). PDRAs have access to all development opportunities that staff have access to. They also participate in annual appraisal processes. They are given opportunities for supervision of PhD students and teaching-related opportunities to expand their CVs. This has enabled our PDRAs to successfully continue research careers in the UK, Japan, Switzerland and Germany.

## 2.2 Research students

The Astrophysics group has been a continuous recipient of STFC doctoral training partnership (DTP) grants (aka STFC Studentships) throughout the REF2021 cycle (match funded by Keele). The group also hosted students with overseas funding (ESO studentships, government grants like Iraqi MOHESR, Nigerian TETFund) or self-funding. This enabled 32 PGR awards during the 7-year REF2021 cycle (more than 3 per staff returned). This corresponds to a very significant 186% increase of the yearly average number of PGR awards compared to REF2014 and contributed greatly to the vitality and outputs (e.g. Goldman+van Loon, MNRAS, 2017) of the unit.

Keele continuously improves its governance, support and training for PGR students. In 2020 the Keele Doctoral Academy (KDA) was launched to create a unified platform for PGR provision. PGR students are allocated a lead and a secondary supervisor, who must both undergo supervisor training. All PGR students develop a training plan as part of their Personal Development and Learning Plan. Keele provides excellent training and progression monitoring (including 6-monthly

progress reporting) in accordance with its PGR Code of Practice. At UoA level, we enhance PGR training via our Journal Club, in which students explain research articles to the group. Students then receive feedback from their supervisors and other group members. Students have the opportunity to develop their teaching and communication skills by acting as demonstrators for undergraduate labs and problem classes and contributing to the group's public engagement activities (e.g. Stardome and observatory). The Faculty of Natural Sciences at Keele organises a yearly PGR Symposium that our students regularly attend and contribute to, providing an opportunity to present their work, practice communicating to different audiences, and exposing them to other research areas.

PhD students at Keele appoint a representative each year who relays enquiries to academic staff, in addition to providing representation on the School's Equality & Diversity and Sustainability committees. Many University committees, like the Sustainability Committee, have PGR representation, which gives citizenship opportunities to our PhD students. There is also a dedicated Physics PGR coordinator (currently Wright who created and maintains a 'welcome pack') who is responsible for the overall academic development of the PhD students and to ensure they are personally supported where needed, with particular attention paid to incoming international students.

The excellent research and PGR support at Keele described above is key to our success with PGR students. The number of PhDs awarded during the REF2021 cycle nearly tripled and contributed greatly to the vitality and outputs of the unit. Keele PhD students have a strong record of timely submissions, publication of refereed-journal papers (average 2 to 3 lead-authored refereed papers from their time at Keele), presentations at international conferences and moving on to jobs in academia (PDRAs in the UK, Germany, Switzerland, Chile and US; tenure position in Iraq and Serbia) or industry (as data scientists or flood risk modellers). The overall satisfaction scores in PRES 2019 were 91%, higher than the university (86%) and sector (81%) averages, and supervision (92%) and research skills (93%) were also very highly rated.

### **2.3 Equality and Diversity (and Inclusion, EDI)**

Keele is strongly committed to principles of equality, diversity and transparency (Disability confident employer, Institutional Athena SWAN bronze award, a Race Equality Charter (REC) Bronze Award (one of only 14 in the UK), Disability Confident Employer, Stonewall Champion, Aurora supporter, female staff promotion support, support for return from maternity, LGBTI Role Models, flexible working, part-time). Our school was awarded a Bronze Athena Swan award in 2018. The Athena SWAN action plan and EDI matters in general are supported and overseen by our school EDI committee, set-up during this REF cycle and over 90% of the plan has already been implemented. Examples include an EDI representative on all school committees and EDI matters being a standing item on the agenda of these committees (including the research committee), a suggestion box to raise issues anonymously and dedicated space and facilities for nursing mothers. Feedback from staff indicates these facilities have been beneficial.

One of the major goals is to improve the gender balance of the unit. Three of our latest recruits in Physics have been female. This has raised the percentage of research-active female staff in Physics from 11% to 33% over the REF2021 cycle, a very significant improvement. To further improve gender balance and other EDI areas and building upon our Athena awards, new recruit Balakrishnan led the efforts for our school to become a IOP Juno practitioner in 2020 and we are working towards Juno Champion status.

Members of staff come from different backgrounds and countries, providing a diverse workforce. Three of the latest recruits are not only women but also come from three different continents (Europe, Asia and South America), further enhancing diversity in our School.

All staff with REF responsibility received EDI training (e.g., on unconscious bias). The REF submission process for the unit was open and transparent. All research-active staff in Physics are returned to REF. Review of outputs was open to all returned staff. Drafts of the selected list of

outputs and the environment statement were shared with all staff with multiple opportunities for input and comments.

**2.4 The physical infrastructure supporting staff** is described in Sections 3.2 and 3.3.

### 3. Income, infrastructure and facilities

#### 3.1 Income

Our core research income strategy in 2014 was and still is to generate income from 1) UK/EU research councils funding and 2) UK and international facilities time competitively obtained by our staff. The strategy for the next REF cycle for the new Materials group will include a broader and more diverse range of funding streams via interdisciplinary and intersectoral consortia, charities and industrial partners exploiting synergies within the faculty-wide Materials research theme, the University-wide sustainability projects (SEND, HyDeploy) and Data Science Network.

##### 3.1.1 Research Income

In a very challenging funding landscape, we have successfully implemented our strategy by competitively winning UK and EU research grants (>£400k per staff member returned for the REF2021 cycle), which represents a 17% increase in income per FTE per year compared to REF2014. Three-year-long STFC consolidated grants provided continuous support (new grants in the REF2021 cycle provided £1,167,000 in 2014; £467k in 2017 plus top up of £150k in 2017-2018) for the exoplanets, star formation and extragalactic research themes. Hirschi's stars and nucleosynthesis research was supported by an FP7 ERC starting grant (SHYNE project: 2012-2017 with circa £1m income during the REF2021 cycle). Wright was supported by an STFC Ernest Rutherford Fellowship: £414k (income during the REF2021 cycle) and was made permanent in 2016. Keele's strong support for ECRs (section 2.1) to enable them to set-up their independent research group is evidenced by Wright being awarded a Leverhulme Trust fellowship (£164k) in 2020 for a 3-year PDRA to work on the structure and Dynamics of Star Clusters in 6D. These successes at obtaining PDRA funding also enabled the Astrophysics group to secure continuous support for PGRs via STFC doctoral training grants (aka DTPs) over the REF2021 cycle. Matched-funding support from Keele nearly tripled the number of PhDs awarded in the REF2021 cycle compared to REF2014.

In addition to these UK and EU research project grants, our strategy is to build and join collaborative networks to lever external funds and expertise and diversify income streams to support our research. Hirschi is the chair of the ChETEC COST Action (CA16117, 2017-2021; £291k at Keele for 2017-2019, the grant had to move to Portugal because of BREXIT in 2019), which provides funding for scientific workshops, training schools and collaboration visits. Additional support was secured via several other international schemes (e.g., ESO fellowships, MOHESR, TET-fund for PhD students). All these grants along with Keele's support enabled more than 500 research outputs gathering more than 12,000 citations.

In the Materials Science and Renewable Energy group, Heckl was awarded €4m for her POLKA MSC ITN (2019-2023) successfully building upon her previous network TANGO (€3.7m, 2012-2016). While her income is allocated to UoA12, it shows that we are already securing funding for renewable energy research.

##### 3.1.2 Income-in-kind including national and international facilities time:

###### Research Council Facilities

A major additional source of income for Astrophysics is via facilities time competitively obtained by our staff. Over the REF2021 cycle, the total research council facilities time represents a value in excess of £4.9m and more than doubles our research income for this REF period. This includes time awarded as PI on the following Research Council supported facilities: Diamond, DiRAC, XMM-Newton, ALMA, ESO (VLT, NTT), ING (INT, WHT), LT. This is also thanks to Keele staff playing major roles in international collaborations working together on ESO large programmes. Indeed, Jeffries is a co-I and steering group member of the Gaia-ESO survey (PIs Randich, Italy

and Gilmore, UK), the world's largest high spectral resolution survey using 350 nights on one of ESO's 8-m Very Large Telescopes. Oliveira and van Loon are core team members of the VISTA survey of the Magellanic Clouds (VMC, PI Cioni), which is part of the public VISTA survey. van Loon is also part of the following surveys: EDIBLES (284 hours on ESO-VLT) and NESS (516 hours on JCMT).

#### International facilities time and other major in-kind benefits (not included in REF4/b/c)

In addition to the STFC DiRAC computing time, Hirschi was awarded a total 55.3 million core-hours on the EU PRACE MareNostrum supercomputer in Barcelona to undertake his large-scale 3D hydrodynamic simulations (PI ex-Keele-PDRA Georgy, Switzerland; 42 million-hours on MareNostrum4 for proposal 2017174145 in PRACE Call 16; 13.3 million-hours on MareNostrum3 for proposal 2016143263 in PRACE Call 13) with a total estimated cash value in excess of €0.5m during the REF2021 cycle.

Additional observing time was awarded on the following facilities: NASA-Chandra (Wright: 87kiloseconds as PI= ~ \$0.5m at \$5k per kilosecond, 1000ks as co-I); SALT (South Africa, circa 100 hrs); SAAO (1.9m telescope: 34 nights; 1.0m telescope: 7 nights); MMT/HectoSpec (SAO) (PI Wright: 2 nights); STFC-AAT (PI Wright's PhD student Armstrong: 4 nights).

For the future REF cycle, Physics staff will continue to seek UK and international funding, join and build collaborative networks to leverage external funds and expertise and win facilities time. Hirschi has already secured funding for a 2-year PDRA at Keele as part of the 5 M€ EU ChETEC-INFRA infrastructure project that he is co-I of. The project will run for 4 years starting in May 2021. In addition, Maxted leads a program within the CHEOPS GTO program "ID-037 Eclipsing binaries with very low mass stars" that is currently (July 2020) allocated 300 orbits. The total mission costs are approximately €100m and the mission lifetime is 3.5 years, so this represents ~€2m of in-kind contributions for the next REF cycle.

### **3.2 Organisational support for research and impact**

A broad range of income streams necessitates strong institutional support. Across the university, research is now supported by the Research and Innovation Support Enhancement unit (RaISE), whose function is to support research funding applications and then subsequently support implementation and impact. The RaISE team is multi-functional and provides a holistic support hub for research and partnership development, project costing, contract and regulatory compliance. Administrative support for project delivery following contract signature and setup of financial codes is provided within the school. EU project support, from proposal preparations to monthly budget spend updates to best manage fluctuating exchange rates, has been key to successfully run large EU projects (ERC, COST Action, MSC ITN). The university also supports interactions with local business in Staffordshire (van Loon hosted a KRISP project for the AEON Engineering company based at the Keele Science and Innovation Park), and acceleration of local socio-economic developments via the Keele Deals.

The school research committee has representatives for ECRs and EDI to ensure that ECRs and minority groups are fully supported and that EDI matters are addressed (see also Section 2.3).

### **3.3 Research infrastructure and strategy**

The strategy for the Astrophysics group is to lead and play key roles in international collaborations (Section 1.2) and to exploit external computing and observing facilities nationally and world-wide. Key support from Keele is the provision and maintenance of the required dedicated IT facility for Astrophysics research to prepare, store and analyse large observational and theoretical datasets to maximise the scientific return on these large datasets as well as develop new software tools. The Astrophysics IT facility provides a total data storage capacity around 0.5PB (Peta-byte) hosted on fast many-CPU-cores and RAM-rich data analysis servers and comprises a heterogeneous computing architecture ranging from a large shared-memory node to nodes equipped with GPU acceleration cards via a standard distributed-memory computing cluster with 500+ CPU cores. The capital investment for this IT facility was funded by a mixture of STFC and ERC grants, whilst the hosting and running costs (comparable to purchase costs) are supported by Keele. Keele is

committed to further investment in computing facilities via its new Digital Innovation centre, which is at building stage.

The strategy for the new Materials Science and Renewable Energy group is to develop a local experimental facility within the school for the development of new materials, as well as exploit facilities such as the SEND project at Keele and external facilities such as those at industrial partners. To this end, SCPS and Physics have received significant financial investment from Keele University during the census period. A £34 million investment in a new Central Science Laboratory attached to the Lennard-Jones building, in which SCPS is based, increased both teaching and research capacity. The building includes large, shared offices for PGR students to facilitate discussions, exchange of ideas and avoid isolation. Over £2m was invested in equipment and included NMR and XRD instruments. Extra equipment (Physical Vapour Deposition system to grow 2D materials) has been purchased with the help of the school start-up and faculty research development funds following the appointment of Balakrishnan and further investments will continue in the coming years to develop a 2D material production and analysis laboratory. Keele funding also enabled the purchase of the necessary software tools to undertake materials computation (led by Morbec) on the Astro/Physics dedicated IT facility. The HyDeploy and SEND infrastructure at Keele also provides the framework for new Physics research projects in Renewable Energy.

Keele's strong support and rapid response meant that laboratory work could resume in July 2020, less than 4 months after the Covid-19 outbreak, which demonstrates the quality and resilience of research support at Keele.

The regional impact of Astrophysics research is supported by Keele via the Stardome and on campus Observatory, which enable a wide range of public engagement activities on and off campus and directly supported our Stardome impact case.

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

##### **4.1 Collaborations, networks and partnerships including interdisciplinary research**

###### **4.1.1 Support for collaborations, partnerships and interdisciplinary research**

During the REF2021 cycle, Keele reorganised its research structure and strategy to best support interdisciplinary research tackling global challenges (Section 1.1). Keele also re-structured its research and inter-sectoral collaboration support structure by creating the Directorate of Research, Innovation and Engagement (DRIE) who manage the RaISE team. At faculty level, the research development fund and PhD scholarships provide opportunities to develop new directions of research and new collaborations and partnerships between schools as well as with other institutions or non-academic partners. At the school level, support is provided to present results at conferences and to host conferences and visitors. This wide range of support enabled the establishment of the faculty-wide interdisciplinary research group in Materials Science and Renewable Energy and the University-wide Data Science network, which will both enhance the vitality and sustainability of Physics and interdisciplinary research in our Unit in the next REF cycle.

###### **4.1.2 Current and future national and international collaborations**

Leading and playing key roles in national and international collaborations is at the core of our research strategy. Keele's wide-ranging support enables Astrophysicists at Keele to set-up, lead or play a key role in a wide-range of collaborations and surveys described in Section 1.2 (CHEOPS, Gaia-ESO, ESA Gaia, ESO VMC, SHYNE ERC, NuGrid, BRIDGCE, ChETEC, IReNA, Tango ITN, Polka ITN). The large number of national and international collaborations is also reflected in the quality and co-authorship of our outputs.

##### **4.2 Responsiveness to national and international priorities and initiatives**

Sustainable and cleaner energy generation as well as the development of 21<sup>st</sup> century materials (e.g. wearable technology, sensors, spintronics) are very high on the national and international priority lists. The re-organisation of Keele's research structure and the range of support it provided

(hiring of new staff, investment in new buildings, research development funds and PhD scholarships) will enable the new Physics research group to respond and play a key role in these grand challenges in the next REF cycle.

#### 4.3 Contributions to and recognition by the research base

Leading or sitting on the steering committees of the international collaborations listed above, Keele Astrophysicists contribute substantially and in many ways to the research base. ChETEC COST Action Chair Hirschi has been coordinating interdisciplinary efforts, knowledge exchange via workshops, knowledge hubs (<http://www.chetec.eu/knowledge-hubs>) and an intersectoral working group and oversaw 1-2 training schools and around 5 workshops per year for the last 3 years. He will also contribute to coordination of research and training in Nuclear Astrophysics via the world-wide IReNA NSF network of networks. Taylor was awarded the Philip Leverhulme Prize for his work in 2017 and used this to support his “*Homogeneous Studies of Transiting Planets*” project.

Over the REF2021 cycle, members of the Astrophysics group regularly delivered invited talks at conferences, as well as invited seminars at institutions, and several lectures at post-graduate training schools. Examples of invited reviews at conferences are: Taylor at “BRITE” conference, Vienna, 2019; Oliveira at “ESO Magellanic Clouds” workshop, Garching, 2019; Jeffries at “Progress in young cluster astrophysics” Cool Stars 20, Boston 2018; van Loon at “Feedback in the Magellanic Clouds”, STScI 2015; Hirschi at “Nuclei in the Cosmos XIII”, Debrecen, 2014. Examples of lecturing at post-graduate training schools are: Smalley SOC+lecturer at “The Aarhus Spectroscopy Workshop”, Aarhus, Denmark, 2014 and at the “Spectroscopic data analysis with iSpec”, Wrocław, Poland, 2018. Hirschi’s 1-week graduate topical lecture series on “From Stars to Elements: Stellar Evolution and Nucleosynthesis” in Darmstadt, Germany, 2018 and lecture at the ChETEC training school: Software Tools for Simulations in Nuclear Astrophysics, Hull, UK in 2018.

Members of the Astrophysics group made a large number of contributions to the research base, which also indicates their national and international standing in the discipline: grant panel membership (van Loon STFC Astronomy grant; Oliveira Hubble Fellowship Program); time allocation committees (Oliveira chair of ALMA Star formation panel; Jeffries XMM-Newton; van Loon ESO, HST stellar Evolution/Physics panels; Taylor STFC ING and LT PATT; Hirschi UK DiRAC computing); proposals refereeing nationally (STFC, Leverhulme, Royal Society) and internationally (more than 10 countries); journal papers refereeing (Nature, MNRAS, A&A, AJ, ApJ), commissions and committees (Taylor secretary of IAU Commission G1 “Binary and Multiple Star Systems”; van Loon vice-President IAU Commission G3 “Stellar Evolution”, Chair of IAU Working Group on Red Giants and Supergiants, and SKA Science Working Group member “extra-galactic spectral line”; Oliveira member of the UK ELT Steering Committee; Smalley member of Kepler Asteroseismic Science Consortium and TESS Asteroseismic Science Consortium; Maxted and Taylor leading PLATO work packages “Benchmark stars” and “Binary & Multiple stars”; van Loon serving as editor-in-chief of the electronic AGB and Magellanic Clouds Newsletter with more than 1000 readers and as IAU Ombud set up in 2019).

Astrophysics staff organised scientific events at Keele: transiting planets conference (Hellier, 2017); COST Action kick-off meeting (Hirschi, 2017); SALT Board meeting (van Loon, 2018); van Loon and Oliveira organised the Mega-SAGE meeting and JWST Community Day (2017) and VMC meeting (2016); star formation and young stars in Cygnus meeting (Wright, 2018). Keele staff were SOC members of more than 15 international conferences.

Keele hosted many visitors linked to their international collaborations. Hirschi hosted an SNF Early Postdoc Mobility Fellowship (18 months funding: 2016-2018) for PDRA Battino. Other examples include a 7-month visit by international fellow Nanni (2014), Germano Sacco’s visits (Gaia-ESO/4MOST 2015 & 2019) and Monika Petr-Gotzens’ visit (VMC, 2018).

#### 4.4 Relationships and engagement with beneficiaries, users and audiences including contributions to society and economy

As explained in Section 1.3, our research has had a strong impact both globally (exoplanet ICS) and regionally (Stardome ICS) via our THE award-winning Stardome, which has now been integrated into the HigherHorizon+ Uni Connect consortium and receives external support from the Ogden Trust. Further intersectoral activities during the REF2021 cycle include Hirschi collaborating with Norwegian company Numascale as part of his ERC SHYNE project and van Loon hosting a KRISP project for AEON Engineering. Additional public engagement during the REF2021 cycle includes the following. Jeffries and Maxted hosted a yearly “Astrophysics Research Experience” week attended by 25-30 year 10-12 pupils (~40% female) since 2016 (2020 was Covid-cancelled) and targets schools/colleges with a high free-school meal percentage. The Observatory on Keele campus hosted over 3000 visitors a year throughout the REF2021 cycle and now also a Science Art and Artificial Intelligence project. Taylor organised a “Holst Planets concert” intertwined with exoplanets research highlights in Keele Chapel (2017, 250 attendees) and a “planets day” (2017; 90 year-6 children). van Loon and PGR Pennock organised RAS/IAU-OAD and Newton-Bhabha funded public engagement activities in India, and SALT-based schools' liaison between South Africa and Stoke-on-Trent, both based on Keele research on AGN and machine learning application. Jeffries is a major contributor to Astronomy Stack Exchange (rated 1st out of 22,000 worldwide users) and to Physics Stack Exchange (rated 7th most reputable contributor worldwide out of 180,000 users) and his questions/answers have been viewed 4.2 million times. Keele Physicists also made appearances in the media (TV/radio: 5-10 per year each), wrote articles in The Conversation with over 88,000 reads, delivered public talks and took part in Pint of Science outreach events.