Institution: Keele University

Unit of Assessment: B9 Physics

a. Overview

As a small research-led university with a strong commitment to excellence in research and teaching, Keele has concentrated its UoA B9 research into a single focused research group in astrophysics. The group teaches dual-honours degrees in physics and astrophysics, and pursues both observational and theoretical research in areas from exoplanets and star formation to stellar evolution, galaxy evolution and active-galactic nuclei. The Astrophysics Group forms a cluster within the multidisciplinary Research Institute for the Environment, Physical Sciences and Applied Mathematics (EPSAM) in the Faculty of Natural Sciences.

b. Research strategy

The Keele Astrophysics Group's strategy is to form collaborations pursuing forefront research, combining internal strengths with national and worldwide collaborators. In the REF period we published 450 papers in refereed journals (43 per academic staff FTE), which have been cited 7700 times (733 per FTE) (stats from NASA's ADS). Our main groupings and strategies are:

Exoplanets and WASP: The WASP consortium (Wide Angle Search for Planets) is the world's most successful ground-based search for transiting exoplanets, recently announcing WASP-100b, our 100th planet. This is an area that the 2010 US Decadal Review called "One of the fastest growing and most exciting areas of astrophysics". Only NASA's $600M Kepler mission has found more confirmed transiting exoplanets (Kepler currently claim 167 planets, with many more candidates, but at 100 times our cost). Our nearest ground-based competitor, the Harvard/Princeton-led HATnet project, has announced 46 planets.

Keele is a central part of WASP, operating the WASP-South facility that dominates Southern-hemisphere transiting exoplanets. By the end of the RAE 2008 period we had found our first two planets. Now, the Keele-led WASP-South has found 57 of the 58 brightest transiting-exoplanet systems in the Southern Hemisphere, plus more in the equatorial North, with 20 more not yet announced, and further discoveries being made at a rate of 1 or 2 a month. Keele has currently lead-authored the publication of 41 transiting-exoplanet systems, more than any other institute worldwide (Harvard CfA is on 39). WASP-South discoveries are all around stars brighter than V = 13 (with a median of V = 11), which compares with Kepler host stars being typically V = 14 to 16. Thus WASP planets are generally much better targets for future study. WASP-South is currently being tasked with finding the best exoplanet targets for the ESA CHEOPS mission, for JWST, and for possible missions such as ESA's EChO.

Related to exoplanets and the WASP project is a programme of understanding and parametrising eclipsing binaries and variable stars, particularly to provide fundamental parameters of stars to tie down stellar-evolution models. Highlights from such work include Maxted *et al*'s discovery of the first binary system containing two different types of pulsating star (Nature 2013, 498, 463). Keele academics involved in exoplanets and binary stars are Hellier, Maxted, Smalley and Southworth, who have produced 220 refereed papers in the REF period between them which have been cited 4500 times (from NASA's ADS).

X-ray astronomy and AGN: Led by Reeves, Keele's AGN programme exploits the major international X-ray satellites, collaborating with scientists from institutes including Leicester, Durham, NASA/Goddard Space Flight Center and JAXA/Japan. This has included Reeves being PI of 600 ks of time on NASA/Chandra, 830 ks of time on XMM-Newton and 1000 ks of time on JAXA/Suzaku. The highlight of the research over the REF period has been the discovery of ultra-fast outflows as a common phenomenon amongst luminous AGN. As a result of their large mechanical power, these outflows can provide the missing link between the growth of the super-massive black holes and that of their host galaxy. Reeves is currently collaborating with the NASA/NuSTAR team at CalTech, continuing the research from XMM and Suzaku. Overall, Reeves has led or co-authored 63 refereed papers over the REF period, cited 1360 times. Keele's observational work on galaxies and AGN is complemented by the theoretical work of McLaughlin, concerning AGN winds and their effect on the galactic environment.

Star formation, YSOs, clusters and the interstellar environment: Keele plays key roles in international collaborations on the world's leading facilities for research into the formation and demise of stars. Jeffries was one of the proposers and designers of the GAIA-ESO survey, a massive programme of over 300 nights on the VLT as a precursor to ESA's GAIA satellite. The aim is nothing less than a full chemo-dynamical survey of the Galaxy to understand the formation and evolution of all its constituents. Jeffries is on the Steering Group (with “builder” status) and Keele operates a pipeline for processing GIRAFFE spectra to verify and validate radial-velocity results. Oliveira and van Loon are part of the worldwide MEGA-SAGE consortium for exploitation of the NASA/Spitzer and ESA/Herschel satellites, and are core members of VISTA's ESO Public Survey of the Magellanic Clouds (VMC). Overall, Jeffries, Oliveira, van Loon and Evans have produced 102 papers in this area over the REF period, cited 1600 times (from NASA’s ADS).

Stellar Nucleosynthesis and Evolution: Hirschi plays a central role in international collaborations calculating stellar nucleosynthesis yields and the resulting stellar evolution. The Geneva group’s GENEC stellar-evolution code is recognised as world leading. Hirschi led the development of the nuclear reaction network in the current version. The NuGrid collaboration involves 15 institutes creating a framework for massively parallel nucleosynthesis simulations with up-to-date nuclear physics, for which Hirschi calculates the evolution and full nucleosynthesis for massive stars. The award of a €1.4 million ERC grant to fund Hirschi’s SHYNE collaboration enables Hirschi to open new lines of research, creating a bridge between experimental nuclear physics and astronomical observations, in collaboration with Rauscher (Hertfordshire), thus exploiting the investment in facilities such as FAIR at GSI in Germany. A second new area is moving from standard 1-D stellar models to 3-D models in collaboration with Arnett (University of Arizona) and others. Hirschi is an author on 25 refereed papers over the REF period which have been cited 700 times.

c. People, including:

i. Staffing strategy and staff development

We have an increase of one academic staff compared to RAE2008. Falk Herwig moved to lead a research group at the University of Victoria (Canada), and was replaced by the appointment to a lectureship of Joana Oliveira. John Southworth was a WASP/exoplanets PDRA at the start of the REF period, then won a five-year STFC Advanced Fellowship in 2010, and has now been appointed to a permanent lectureship. In 2013 he was awarded the Philip Leverhulme Prize, for

early-career "outstanding scholars ... recognised at an international level".

In RAE2008 we wrote that we had appointed "two RCUK Academic Fellows (Reeves and Hirschi), both of which carry a commitment from Keele to permanent positions". Both are now developing their careers with their first PDRA grants, Reeves obtaining an STFC-funded PDRA for work on AGN with XMM, Chandra and Suzaku, and Hirschi obtaining a €1.4 million five-year ERC Starting Grant for two PDRAs and two PhD students. During the REF period both Hellier and Jeffries were promoted to Professorships. Maxted, van Loon, Reeves and Hirschi have all been promoted to Readerships, and Smalley has been promoted to Senior Lecturer. Keele has also recently achieved the European Commission's HR Excellence in Research Award for implementation of the Concordat to Support the Career Development of Researchers.

Of PDRAs who have been at Keele during the REF period (in addition to John Southworth), David Wilson now works in the City with Barclays Finance; Nicholas Iro is now a researcher at the Observatoire de Paris, France; Alexis Smith is now at the Copernicus Astronomical Centre in Warsaw; Rachel Smith is now an editorial assistant with the Royal Society of Chemistry, and Marco Pignatari is now an AMBIZIONE research fellow at the University of Basel, Switzerland.

Five PDRAs are currently in post (covering areas of WASP/exoplanets, AGN/X-ray astronomy, the GAIA/ESO survey, and SHYNE/nucleosynthesis). The appointments show that we attract a strong international field, including Cyril Georgy (from a Geneva PhD and a PDRA at Lyon), Emanuele Nardini (from a Harvard/CfA PDRA and Università di Firenze, Italy), and Nobuya Nishimura (from a JSPS Fellow at NOAJ, Japan, and then a PDRA at Basel, Switzerland). Two PDRAs, Richard Jackson (5 lead-authored, refereed papers in the REF period) and David Anderson (10 lead-authored, refereed papers in the REF period), were previously Keele PhD students.

Scholars visting Keele over the REF period include:
* Dr Takuma Suda (Hokkaido University, Japan), 2008-2010 Marie Curie International Incoming Fellowship (£118,000).
* Prof. Krešimir Pavlovski (Zagreb), July 2010-May 2011, Leverhulme Visiting Professor, (£18,650 grant).
* Prof Thomas Rauscher, University of Basel, repeated visits over 2009-2011 (International Joint Project funded by the Royal Society (£10,000).
* 2010: Nugrid collaboration meeting at Keele (including Dr F. Herwig, University of Victoria; Dr M. Pignatari, Basel; Dr C. L. Fryer, Los Alamos National Laboratory; Dr C. Travaglio, Torino).
* 2012: WASP consortium meeting (including Prof. D. Queloz, Geneva; Prof. D. Pollacco, Warwick; Prof. A. Collier-Cameron, St. Andrews; Dr M. Gillon, Liege, Belgium; Dr A. Triaud, MIT, USA).
* Dr Casey Meakin, Uni Arizona, US and Dr Carla Froehlich, Uni North Carolina, US, 2013, for collaboration as part of the SHYNE project.
* From Alzahra University Tehran, Drs. Atefeh Javadi, Habib Khosroshahi, Taghi Mirtorabi, Fatemeh Nikzat & Maryam Rashid, for visits of up to 3 months over 2008-2011, funded by a Leverhulme Trust Senior Research Fellowship, for £29,374, and an RAS grant of £3,200.

ii. Research students

Increasing PGR students has been a strategic aim of Keele over the REF period. Numbers of astrophysics PhD students have risen strongly, owing to Keele/EPSAM "Acorn" matching funding

(£150,000 per annum across the Research Institute), adding to increased STFC studentship funding over the REF period, and to studentships from ERC grants and elsewhere. Thus there are currently 18 astrophysics PhD students, an increase from 5 in 2008.

PhD students at Keele are supervised and monitored to ensure a timely and productive completion. They are allocated a lead and a secondary supervisor. All staff must undergo supervisor training and can only act as lead supervisor once they have seen a student through to completion as a secondary supervisor. In their first weeks students complete a work plan and identify key skills and the path to attain them. This is updated as they go, and formally reviewed every six months by the RI PGR Committee, when they are graded and given feedback. A rigorous formal written and oral doctoral progression takes place after ten to twelve months with interviews conducted by the RI Postgraduate Research Director and two independent academics. At a 30-month review a comprehensive plan for the thesis is presented and discussed.

Astrophysics PGR students benefit from the RI structure and the excellent training and support environment it provides for PGR students. All PhD students take the Research Institute "Core Training Module" on generic research skills. In addition they take part in a Journal Club and present talks to the group, with feedback from their supervisors. Other faculty modules are available, and are selected in discussion with their supervisors. PhD students act as demonstrators for undergraduate labs and problem classes, for which they receive training in teaching.

In addition Keele is part of the Midland Physics Alliance Graduate School, giving access to a wide range of graduate-level courses across physics and astrophysics. These are presented by a consortium of eight Midlands universities and are delivered by remote lecturing. In 2012 EPSAM installed a £40,000 state-of-the-art, remote-lecturing facility in a dedicated room for this purpose.

Keele PhD students have a good record of timely submissions, publication of refereed-journal papers, and of obtaining good jobs. Over the REF period completing students include (paper counts are to refereed papers from the thesis): Iain McDonald (2009, 3 lead-author papers, now a PDRA at Jodrell Bank, Manchester); Sam Bentley (2009, 2 lead-author papers, now in industry in Southampton); Atefeh Javadi (2011, 3 lead-author papers, now a PDRA at IPM, Tehran); Michael Bennett (2001, 1 lead-author paper, now at Integrated Environmental Solutions, Glasgow); David Anderson (2011, 6 lead-authored papers, now a PDRA at Keele); Richard Jackson (2011, 4 lead-authored papers, now a PDRA at Keele); Andrew Lobban (2013, 2 lead-author papers, currently a PDRA at Leicester); Adam Patrick (2013, 3 lead-author papers, enrolled on a PGCE at Keele); Jason Gofford (finishing 2013, 2 lead-author papers, on 6-month STEP award at Keele); Mandy Bailey (finishing 2013, with a post as National Schools Officer, LJMU); Sarah Day (finishing 2013, 2 lead-author papers, starts a PDRA at Diamond in January 2014); Tregloan-Reed (will finish 2014, 2 lead-authored papers, with a NASA Postdoctoral Fellowship lined up at NASA Ames). Thus our students average 2 to 3 lead-authored refereed papers from their time at Keele and most who want to remain in research obtain a PDRA.

d. Income, infrastructure and facilities

In common with most astrophysics groups, the Keele Astrophysics Group's primary mode is exploiting the STFC-funded national facilities and international facilities. The group has a strong record of winning time on major facilities worldwide. Group totals over the REF period for major

RCUK-funded facilities (contributing to HESA income) include: ESO/VLT 18 nights; ESO/NTT 28 nights; La Palma WHT: 20 nights; La Palma INT: 30 nights; ESA/XMM-Newton: 980 ks; ESA/Herschel: 82 hrs. Thus the reported HESA income shows a significant increase over the REF period, to over £2 million per year (£1.2 million per FTE over the REF period).

The international non-RCUK facilities (not included in the HESA income reported in REF4) include (listing only time for which Keele was PI): NASA/Chandra: 600 ks; Japan/Suzaku: 1000 ks; NASA/Spitzer: 120 hrs; Opticon/CHFT: 3 nights; Opticon/CAHA 2.2m: 21 nights; Opticon/CAHA 3.5m: 10 nights; Opticon/NOT 3.5m: 7 nights; AAO/AAT: 12 nights; ATNF/ATCA: 85 hrs; IRAM/30m: 24 hrs; IRAM/PdBI: 18 hrs. Valuing the ground-based time at £8000 per night gives a total of ~ £500k. Valuing the spacecraft time at $5000 per kilosec gives an estimated value of $10 million (£6 million).

Keele built, owns and operates the private facility WASP-South, an array of survey cameras sited at Sutherland, South Africa. WASP-South performs a wide-field survey primarily for finding transiting exoplanets. It has run continually since 2006 with only 3% downtime. The build cost of £800,000 came primarily from HEFCE SRIF funding, supported by institutional funding, and represents a significant institutional investment in the Astrophysics Group. Keele is also a member of the SALT consortium, giving access to the 10-m SALT telescope at Sutherland, South Africa.

Computing: Good computer facilities are central to an astrophysics group. In addition to the usual desktop PCs, the Keele Astrophysics Group has:
* Access to the faculty CUDA cluster (85,000 GPU cores with 384 CPU cores and 1GB per CPU-core), costing £90,000 and funded using HEFCE Research Capital funding.
* An astro-specific cluster of 72 CPUs (value £40,000, funded from STFC and European grants).
* An 8-machine cluster dedicated to pipeline processing the data flow from WASP-South (50 GB per clear night).
* The SHYNE-project computer cluster (1056 CPUs including 288 shared-memory cores, with total shared memory of 576 GB), costing €280,000, funded by Hirschi's ERC grant.
* In September 2013 an astro group data-storage system of over 200 TB and a dedicated WASP-South archive, holding 200 TB, were funded using £70,000 of HEFCE Research Capital funding.

The Group has been supported by an STFC Rolling Grant since 2001, and now has an STFC Consolidated Grant. In the very tight first round of Consolidated Grants the Keele group was the only one out of 15 Rolling Grant groups that did not have a reduction in PDRA numbers, remaining at our current 3 STFC PDRAs. We also obtained our first ERC grant with Hirschi's ERC Starter Grant, currently funding 2 PDRAs. During the REF period WASP-South development was funded by an additional STFC Project grant, funding a WASP Project PDRA at Keele.

e. Collaboration and contribution to the discipline or research base

Virtually all the group's activity is entwined with national and international collaborations. Our main collaborations are currently:

The WASP collaboration is an international search for transiting exoplanets, which has now found over 100 such planets. Keele is a key WASP institution, running the WASP-South survey facility. Other key WASP partners are Warwick (running WASP-North and the WASP archive) and St. Andrews (WASP software). We have a major collaboration with the Geneva group led by Didier

Queloz (now joint Geneva and Cambridge). Discovery of WASP-South planets is the biggest programme for their CORALIE spectrograph at La Silla, using over 200 nights per year on the 1.2-m Euler telescope. A similar collaboration is with the University of Liege, with WASP-South planets being the dominant programme on their TRAPPIST robotic 0.6-m photometer at La Silla, amounting to approximately 120 nights of time per year.

The biggest contribution of WASP to the community is the large number of WASP planets available for studying transiting exoplanets around stars much brighter than most Kepler targets. Over half of the known transiting exoplanets around stars of V < 12.5 are WASP planets. There have now been 200 third-party papers on WASP planets, which is increasing fast and much exceeds the papers by the WASP consortium itself. In the last 12 months (Oct 2012 to Sep 2013) 45 refereed papers name a WASP planet in their title (37 of these are independent of the WASP project), which compares with 26 naming a Kepler planet. Papers in the REF period (to Oct 2013) mentioning WASP in the abstract have been cited 4800 times already (stats from NASA's ADS).

In Sept 2013 WASP reached agreement with NASA's Exoplanet Science Institute (JPL/CalTech) that they would host a permanent public archive of WASP light-curves (430 billion photometric data-points, and counting, on 31 million stars of V = 8 to 14), which will impact on many areas of stellar-variability science.

Southworth wrote and maintains the JKTEBOP analysis code for transiting exoplanets and eclipsing binaries. This is publically available and has so far been used in 86 third-party papers worldwide. Recognition in the exoplanets area includes the award of the 2010 RAS Group Achievement Award to WASP, and Southworth's STFC Advanced Fellowship (2010) and Philip Leverhulme Prize (2013).

X-ray astronomy: In pursuing research into AGN Reeves collaborates extensively with X-ray astronomy groups worldwide, including Leicester, Durham, NASA/Goddard Space Flight Center and JAXA/Japan. As a result of visiting adjunct faculty status at University of Maryland (Baltimore County), and visiting scientist status at GSFC, Reeves has PId NASA grants related to the Chandra X-ray observatory totalling over $180,000 in the REF period. A 2011 grant for $129,000 involved 400ks of Chandra time, 830ks on XMM-Newton and 3 orbits on HST. A research visit to Maryland/GSFC in 2012, funded by these grants, has led to 10 refereed papers so far.

Reeves is a member of the international Suzaku Science Working Group and has been an author on 37 Suzaku publications during the REF period, cited 723 times so far. Reeves is also a member of the science working group on the "Astrophysics of feedback" and contributed towards the science case for the proposed ESA L2 mission Athena+.

GAIA-ESO survey: Jeffries is on the Steering Group for the GAIA-ESO survey and was one of the original survey proposers. This spectroscopic survey will use over 300 nights of 8-m VLT time over the period 2012--2017. It is the largest and deepest of its kind, giving high-resolution spectroscopy of 10^5 stars, covering all Galactic populations, and providing precise radial velocities and chemical abundances where GAIA cannot. Keele is providing a parallel processing pipeline for all GIRAFFE spectra and is responsible for improving the accuracy and precision of radial velocities. The GAIA-ESO survey data will all be public, and already more than 300 European astronomers are working with the data.

MEGA-SAGE, NASA/Spitzer and ESA/Herschel: The SAGE programme, a NASA/Spitzer Legacy project, and the HERITAGE key programme on ESA's Herschel Space Observatory are wide international collaborations combining into the MEGA-SAGE consortium involving over a hundred scientists including Keele's van Loon and Oliveira. Keele leads aspects including SMC-Spec YSOs, SAGE-Spec and SMC-Spec far-IR spectroscopy. van Loon and Oliveira also participate in the VISTA public survey of the Magellanic Clouds (VMC) and the VLT-Flames survey of the Tarantula Nebula (VFTS). van Loon is also a key member of the Australian SKA Pathfinder public survey GASKAP.

Stellar nucleosynthesis: SHYNE, GENEC and NUGRID: With the award of a €1.4 million ERC grant, Hirschi leads the SHYNE project, a 5-yr project to develop software tools that connect nuclear physics, stellar structure and hydrodynamics. SHYNE includes collaborations with Arnett and Meakin (Arizona), Roepke (Wuerzburg), Rauscher (Hertfordshire) and Thielemann (Basel). SHYNE builds on Hirschi's role in the GENEC and NuGrid collaborations. GENEC is a collaboration involving Geneva and Keele, producing forefront stellar-evolution codes. NuGrid involves 15 institutes, with the main centres being University of Victoria (Canada), Keele, Basel University, LANL (USA), Arizona State University and the Observatory of Torino. The overall aim is producing stellar evolution with up-to-date nuclear physics and nucleosynthesis yields, over the full range of stellar masses, with Keele leading the work on massive stars.

Other indicators:
Time Allocation Committee memberships**:** Oliveira: Chair of UKIRT TAG (2007−2010); Member of the UKIRT Board (2009 to present); ESO Panel (2012). Reeves: Chair of AGN OTAC for XMM-Newton (2013); member of TAC (2010); STFC LT TAC (2009-2012). Jeffries: XMM-Newton TAC (2008, 2012, 2013); Chandra TAC (member in 2008, Chair in 2010). Hirschi: ESO OPC (Cycle 93); Maxted: ESO OPC (2010). Southworth: LT TAC (2012-).

Grant Panels: Jeffries: STFC Fellowships Panel (2009); US NSF Grants panel (2009); RAS Prizes Committee (2010-2012). Hellier: Chair of STFC Swift/XMM panel (2008-2011) and UKSpace Swift panel (2012-2013); STFC ERF Grant panel (2012); ESA Payload Selection Committee (2013).

Other Consortia/panels: van Loon: Chair of ESO Users Committee (2008—2010); Smalley and Southworth: members of Kepler Asteroseismic Science Consortium (co-authors on 12 papers); Southworth: member of MiNDSTEp consortium; Maxted: international advisory panel on Large Programmes for the Nordic Optical Telescope.

Conferences/SOCs/Invited reviews: IAU Symposium 256 on the Magellanic Clouds was held at Keele in 2008, organised by van Loon, Oliveira and Evans. The group totals 12 memberships of international conference SOCs and 24 invited review talks at international conferences over the REF period.