Institution: University of Exeter

Unit of Assessment: UoA 9, Physics

a. Overview

Physics and Astronomy (herein referred to as Physics) at Exeter is a vibrant and dynamic unit that has grown significantly since RAE2008 with category A staff numbers increasing from 28 to 41. Physics is part of the College of Engineering, Mathematics and Physical Science (CEMPS), which has seen similar growth. Natural Sciences and Engineering at Exeter are first within the UK in the 2013 CWTS Leiden rankings based upon citations. Research was consolidated within four research groups, Astrophysics (APG), Biomedical Physics (BPG), Electromagnetic and Acoustic Materials (EMAG), and Quantum Systems and Nanomaterials (QSN), prior to RAE2008. Each group has an Academic Lead (AL) who is also a key member of the College Management Group. Together with the Head of Discipline and Director of Research, the ALs form the Physics Research Strategy Group. The research groups provide critical mass for internationally excellent research themes that attract scholars and funding from disparate sources within an international market. Staff members have focused their interests around the group themes, and research strategy has developed with thematic advancement in mind. Undergraduate teaching is informed by research. MPhys students are engaged through a 2-yr project undertaken in one of the research groups, leading to a steady flow of new postgraduate students. Research themes within Physics link to cross-disciplinary themes identified and strongly supported by the University Science Strategy including Exoplanets, Functional Materials, and Translational Medicine and Systems Biology, leading to collaborations with Engineering, the College of Life and Environmental Sciences (CLES) and the University of Exeter Medical School (UEMS).

b. Research strategy

Exeter is an ambitious university that joined the Russell group in 2012, lies within the UK top 10, and aims to advance from the world top 150 to the top 100. Ambitions within Physics are commensurately high and have led to research themes that embrace areas of emerging vibrancy and commercial significance, addressing fundamental questions, or leading to betterment of the human condition. At RAE2008 the broad strategy was to strengthen all 4 groups by staff recruitment (11 in 5 yrs), spend £10M on infrastructure, and increase links between groups. This has since been achieved with 24 category A staff appointed as 11 left or retired, £4.3M spent on refurbishment of the Physics building, and £50M budgeted for the Living Systems building next to Physics that will accommodate part of BPG. Medical Imaging (MI) has been located within Physics since 2004, but will move to UEMS in 2014 providing further space for expansion of Physics. New collaborations between groups include ultrafast optical measurements and electrochemical biosensing applications of graphene (BPG, EMAG, QSN), acoustic metamaterials (BPG, EMAG), and coherent phonons (EMAG, QSN). The groups, their interests, and their strategies since RAE2008 are described below. The total numbers of research assistants and students (at 31st Oct 2013) are shown, with numbers jointly supervised with other groups/departments in parentheses.

ASTROPHYSICS (APG): Professors Baraffe (AL), Bate, Chabrier, Naylor, Pont; **Associate Professors** Harries, Patience; **Senior Lecturers** Matt, Sing; **Lecturers** Browning, Brunt, Dobbs, Hatchell, Kraus; **Postdoctoral Fellows** 12; **PhD Students** 18.

APG research activities are devoted to stellar/planetary formation and evolution, and to exoplanet research. The group focuses on some of the most fundamental problems in star and planet formation, from the collapse of molecular clouds to the formation of proto-stars and proto-planets, and the detection, characterisation and modeling of exoplanets. The group currently holds 6 ERC grants. Its strength and originality rely on complementary expertise in theory (Baraffe, Chabrier), numerical simulation (Bate, Browning, Dobbs, Harries, Matt) and observation (Kraus, Naylor, Pont, Patience, Brunt, Hatchell, Sing). The group conducts observations with world leading telescopes and state-of-the-art numerical simulations to study forming stars, their planet-forming discs, and exoplanets. This research helps us to put our Sun and the solar system into context and understand the variety of stars and planetary systems that exist in our Galaxy.

APG has increased its theoretical capacity and numerical expertise through links with Zhang, Gilbert and Thuburn in Applied Mathematics, and experts from the Exeter Met Office working on

the Global Circulation Model, which APG applies to exoplanet atmospheres. APG strategy for the next 5 years is organised within three themes.

Stellar and sub-stellar structures (low mass stars, brown dwarfs, exoplanets) physical processes and evolution. Evolutionary models will be developed based on improved micro-physics and descriptions of convection, dynamo generation and magnetism.

Star and planet formation based on the combination of multi-wavelength observations and numerical radiation hydrodynamics simulations. Expertise has extended towards star-disk interaction and expansion of star formation to larger scales (i.e extra-galactic) is envisioned.

Exoplanets. Observational strategy relies on direct imaging and transit methods using premier international facilities (HST, Gemini, GranTeCan, VLT). The theoretical approach is to strengthen exoplanet atmospheric dynamics using numerical tools developed at the Met Office and is essential for the interpretation of the wealth of observational data expected within the next decade.

BIOMEDICAL PHYSICS (BPG): Professors Soeller, Stone, Winlove (AL); **Senior Lecturers** Moger, Petrov; **Lecturer** Palombo; **Postdoctoral Fellows** 14 (6); **PhD Students** 19 (8)

BPG applies insight derived from fundamental biophysics research to major problems in biology and clinical medicine. Core research has three principal themes.

The extracellular matrix, its biophysical properties and constituent macromolecules (Winlove). Fundamental studies of molecular elasticity in proteins will increase understanding of ageing and disease and develop materials for prostheses, tissue engineering and regenerative medicine. Characterisation of the micromechanical properties of tissues will be used to identify key early changes in the development of diseases from arthritis to diabetes. Research on the biomechanics of cartilage and the intervertebral disc is already being taken into the clinical arena.

Cell membranes. Fundamental research (Winlove, Petrov) has highlighted changes in the cell membrane in oxidative stress that underlie conditions ranging from sepsis to diabetes. This will be used to define new markers of disease and targets for therapeutic intervention. Through collaboration on membrane processes underlying bacterial invasion of host cells, new treatments and preventive measures against biological weapons will be developed. Advances in super resolution microscopy will continue to provide insights into processes such as calcium signalling in muscle cells (Soeller).

Physical methods for biomedical research including physiological investigations and clinical monitoring. Nonlinear optical microscopy (Moger), novel diagnostic Raman and mid-IR imaging (Stone, Palombo), and fluorescence and optical super-resolution microscopy (Soeller) are providing new insight into structure-function relations in living systems and biomedical optics. Complementary laboratories are being established in Physics and UEMS to develop systems for clinical Raman spectroscopic diagnosis, currently of pre-cancerous and cancerous targets.

A key strength is that the first two themes are underpinned by the third. Strength in optical imaging will be further developed within additional laser laboratories in the new Living Systems building. The interdisciplinary environment will strengthen collaboration with Biosciences and UEMS, while new collaborations with the pharmaceutical and agrochemical industries will also be developed.

ELECTROMAGNETIC AND ACOUSTIC MATERIALS (EMAG): Professors Barnes, Hicken, Sambles (AL), Vukusic; **Associate Professors** Hendry, Hibbins; **Senior Lecturers** Ogrin, Kruglyak; **Lecturers** Anders, Bertolotti, Horsley (proleptic), Philbin; **Postdoctoral Fellows** 9 (1); **PhD Students** 25 (2).

EMAG explores the interaction of photons, from x-ray to microwave wavelengths, with matter, and investigates how photons may be manipulated using electromagnetic materials that possess structure from the nm to cm scale. Materials synthesis and nanofabrication, and characterisation using novel imaging techniques, ultrafast measurement and synchrotron sources are combined with both numerical and analytical theory in the pursuit of four principal themes.

Metamaterials and transformation optics. Metamaterials was targeted for development and, with Transformation Optics, has seen a step-change in activity with the EPSRC QUEST programme grant (Barnes, Hibbins, Horsley, Philbin and Sambles). The underlying concepts have

since been carried over to the development of acoustic metamaterials (Hibbins and Sambles).

Natural photonics explores naturally occurring structures and optical materials inspired by nature (Vukusic), attracting support from industrial sponsors and DARPA, and linking with Engineering (Eichhorn). The new and related area of wave propagation in disordered materials (Bertolotti) provides greater scope to develop joint work with BPG, e.g. on scattering through turbid media.

Plasmonics and quantum optics. Active plasmonics explores gain materials at optical frequencies (Barnes) and photon induced carrier modulation at THz frequencies (Hendry), e.g. in graphene (with QSN). Quantum electrodynamics (Anders, Horsley and Philbin) is used to understand the optical response of nanomaterials and will bridge through to biophysics (Anders).

Spintronics and magnonics research concentrates on the dynamic processes (Hicken, Kruglyak) induced and experienced by spin-polarised electrons in micro and nanostructured magnetic materials (Ogrin). Work on magnonic crystals links to metamaterials, while a plasmonic approach is being taken to near field magneto optical sensing (Hicken, Barnes, Hendry).

The group has strengthened links with Engineering, e.g in phase change materials, and will consolidate its strength by leading a centre for doctoral training (CDT) in Metamaterials.

QUANTUM SYSTEMS AND NANOMATERIALS (QSN): Professor Srivastava; **Associate Professors** Russo (AL)**,** Usher, Portnoi; **Senior Lecturer** Plaut; **Lecturers** Foteinopoulou**,** Mariani, Horsell, Shytov; **Postdoctoral Fellows** 4 (2); **PhD Students** 15 (3); **Research Assistant** 1.

QSN studies the fundamental laws of quantum mechanics mostly evident at low temperatures and in systems with reduced dimensionality. A £5M HEFCE/EPSRC award led to the formation of the multidisciplinary Centre for Graphene Science. QSN members study fundamental properties of electrons, phonons and photons in atomically thin materials such as graphene, dichalcogenides, and more recently topological insulators, and their applications through a £1.1M EPSRC Graphene Engineering grant. The group's strongest asset is its range of complementary expertise.

Quantum transport studies and exploits quantum mechanical phenomena such as quantum interference (Russo and Horsell) and the quantum Hall effect (Usher) in nanoscale structures. Novel electronic devices are being designed and fabricated, to allow the quantum behaviour of charge carriers in a wide range of materials to be studied, with the potential for fundamental breakthroughs and application as multifunctional electronic and optoelectronic devices.

Thermodynamic properties of the equilibrium and non-equilibrium states of quantum systems and nanostructures. Fundamental information is obtained about the density of states through quantum capacitance (Russo) and quantum Hall measurements (Usher). The density of states above and below the Fermi energy and collective electronic and phononic excitations are probed by magneto-optical measurements including Raman scattering and photoluminescence (Plaut).

Theoretical condensed matter focuses on the electronic (Portnoi, Srivastava, Shytov, Mariani), mechanical (Mariani), thermal (Srivastava) and optical (Portnoi, Foteinopoulou) properties of systems in which fundamental aspects of quantum mechanics are prominent. This theoretical activity is strongly linked to the quantum transport and thermodynamic studies which benefit from the original theoretical models developed in house.

c. People, including:

i. Staffing strategy and staff development

Staffing strategy has been closely **linked to the research strategy** outlined in section (b).

APG made appointments within: **stellar and sub-stellar structures**, Baraffe (Jan 2010) in stellar/planetary structures and evolution, Browning (Aug 2011) as an expert in simulation of stellar convection and magnetism, and Chabrier (May 2010) as a world-renowned scientist in dense matter physics, and stellar and planetary physics and formation; **star and planet formation**, Hatchell (Sept 2009) for observations of low- and high-mass star formation and as coordinator of the JCMT Gould's Belt Legacy Survey of Local Star Formation, Dobbs (2011) to expand numerical star formation to larger scales, Kraus (2012) to strengthen observation of proto-planetary disk structures, and Matt (May 2013) to strengthen theoretical and numerical research on star-disk interaction; **exoplanets**, Pont (May 2008) for expertise in exoplanet transit data analysis and

development of advanced data analysis techniques essential for very high-accuracy transit spectroscopy, and Sing (Dec 2009) for complementary expertise in exoplanet transmission spectra, including detection of elements in exoplanet atmospheres. Aigrain worked on exoplanents but moved to Oxford (Dec 2009). McCaughrean worked on observational star formation, leaving in October 2009 to become head of the European Space Agency's Research and Scientific Support Department (formally resigning in June 2012). Bastian and Ercolano were appointed (Oct 2009) for their respective expertise in galactic star formation and in protoplanetary disks but left in Nov 2010. All departures were to prestigious institutions as described later.

Within **BPG**, Stone (Apr 2012) and Soeller (Nov 2012) were professorial appointments within a University-wide strategy to develop research at the physics-life science interface. Their interests lie within **physical methods for biomedical research**, although Soeller extends **cell membranes** towards calcium signalling in muscle. Stone applies Raman microspectrometry to clinical monitoring and diagnosis, while Soeller brings expertise in super resolution microscopy. Palombo (June 2013) was appointed to work with Stone and brings valuable expertise in biophysical chemistry, while funding is in place for junior appointments to support both Soeller and another senior appointment in physical cell biology. Jewell used a Royal Society Fellowship to move from photonics to biophysical research in Oct 2010 but departed to pursue a career at the Met Office in Sept 2012, while Dehghani moved to Birmingham in 2008.

Since 2008, **EMAG** has expanded by building on established expertise. Philbin (Aug 2012) and Horsley (Sept 2012) were appointed in **metamaterials and transformation optics**, to underpin microwave and acoustic metamaterials work, and Bertolotti (Oct 2013) extends **natural photonics** research towards the optical response of disordered media, linking to the less ordered metamaterials being explored by Hibbins and Sambles. Within **plasmonics and quantum optics**, THz research has blossomed as Hendry developed into a leading independent researcher. Anders (Aug 2013) brings expertise in quantum information that broadens fundamental work in plasmonics. The theme also benefits from the appointment of Philbin, Horsley and Bertolotti, Bertolotti also extends activity in nanophotonics, which will be expanded further due to its increasing international importance, and to benefit from increased activity in nanomaterials across the university and through strategic alliances such as that recently established with the functional nanomaterials group at Tsingua University. Within **spintronics and magnonics**, EMAG's UK leadership in fast magnetic processes was strengthened by the proleptic appointment of Kruglyak (Jan 2008), working in magnonics and linking to Hicken's spintronics and Hendry's THz work, and expertise in micromagnetic simulation brought by Hrkac's appointment in Engineering in Aug 2012.

Within **QSN**, staffing strategy has been to appoint early career staff with demonstrated ability to produce pioneering interdisciplinary research and expertise in a wide range of nanoscale systems. New appointments were taken up by Horsell (Oct 2009), Russo (Dec 2009) and Martin (Jan 2011) in experimental **quantum transport** in nanoscale systems, including superconductors, organic semiconductors and ferromagnetic semiconductors. **Theoretical condensed matter** was strengthened by appointing Mariani (Jan 2010) and Shytov (Oct 2009) in the analytical theory of electro-mechanical systems and disordered quantum transport, and Foteinopoulou (Sept 2009) in analytical and numerical simulation of optical properties of complex nanostructures. Following the untimely death of the group's leader (Savchenko) in 2010, extra managerial support was provided by academics from other groups. Strategic direction came from Barnes (EMAG), Usher and Russo (QSN). External advice has been provided by visiting professors Robin Nicholas (Oxford) and Simon Bending (Bath). Career development was overseen by Naylor, as Head of Discipline at the time, while Russo gained experience of group management. Martin left for Singapore in Aug 2012.

Physics provides support for the **career development** of **all** researchers from postgraduate students to the professoriate and follows institutional guidelines that ensure consistency with the Concordat to Support the Career Development of Researchers and respect equality and diversity. All research assistants and academic staff participate in the university Performance Development Review (PDR) of one formal plus two follow-up meetings each year. PDR allows staff to review the past year, plan for the future, identify learning and development opportunities, exchange experience, clarify roles and responsibilities, suggest improvements and changes, and develop a formal record of experience and learning. Staff make use of the Professional Development Opportunities (http://www.exeter.ac.uk/staff/development/) offered by the university. The benefits

are improved communication, identification and pursuit of common goals, and better planning for learning and development of the individual. The university is committed to the development of its staff and to their promotion as they achieve their goals, accelerated promotion being achievable on merit alone. From Apr 08 – Mar 13, there were 12 promotions within the research only (R) job family, while there were a further 5 promotions from R to teaching and research (T&R) contracts, demonstrating Physics' ability to nurture home grown talent. A number of younger staff already have excellent reputations and have won ERC and EPSRC fellowships (listed below). Mentoring within the group structure helps them become international leaders in their own right. This includes guidance on building research profiles, acquiring funding, developing collaborations and expanding their capabilities. In the same 08-13 period there were 3 promotions from Lecturer to Senior Lecturer (SL) and one to Associate Professor, 4 from SL to AP, and 1 from AP to Professor.

Personal research fellowships held/obtained during the census period are/were Bastian (STFC Advanced 2009-10), Baraffe (ERC Advanced 2013-18), Bate (European Young Investigator, 2005-10, and ERC Advanced 2014-19), Browning (ERC starting 2014-19), Chabrier (ERC Advanced 2010-15), Dobbs (ERC starting 2011-16), Ercolano (STFC Advanced 2009-10), Hendry (EPSRC Early Career 2014-19), Hibbins (EPSRC Advanced 2004-09), Horsley (EPSRC Early Career, Theory, 2010-13) Jewell (Royal Society Research 2009-12), Kraus (STFC Rutherford 2013-18), Kruglyak (EPSRC Advanced 2008-13), Pont (STFC Halliday, 2008, STFC Advanced 2009-14), Sing (ERC starting 2014-19), and Stone (National Institute of Health Research Senior 2007-12).

International recruitment within the census period has allowed staff of high quality to be recruited from Lyon (Baraffe, Chabrier), Paris (Matt and Bertolotti), Auckland (Soeller), Toronto (Browning), Geneva (Pont), Arizona (Sing), Harvard (Ercolano and Martin), Michigan (Kraus), Crete (Foteinopoulou), Berlin (Mariani), Tokyo (Russo), and Utah (Shytov). Bastian and Ercolano have since moved to Munich, while Martin went to Singapore.

Physics is committed to supporting **equality and diversity** and is working towards the silver Athena Swan award, having achieved Juno practitioner status for gender equality.

ii. Research students

Physics recognises the key contribution made by PGR students to its research and has steadily increased PGR numbers from 45 in 2007/8 to 66 in 2012/13. PGR applicants come to Exeter via diverse routes. Exeter UG students may approach individual staff, external students approach staff after learning about their research or on the recommendation of colleagues at other institutions, applicants may have decided to first approach the admissions tutor, while other applicants apply after attending international fairs. All applicants are asked to make an on-line application in which a preferred area of study may be specified. Recent recruitment campaigns have been organised by the university, with selection being devolved to the College and then to Physics. After being logged by the university the application is sent to the Physics admissions tutor. If the choice of supervisor is clear then the application is forwarded to the relevant individual, but otherwise to the most relevant research group. Staff members are encouraged to correspond with applicants to define projects, and their enthusiasm and advocacy are recognised as an important aspect of the recruitment process. Once applicant and potential supervisor have reached agreement an offer is made subject to financial support. Financial support is considered separately and according to the source. Decisions upon doctoral training account awards from research councils are devolved to Physics where applicant quality, strategic importance, and market trends are considered within the prioritisation process. Decisions upon awards from university funds are made on a College or university wide basis, but informed by Physics' own prioritisation.

The CEMPS PhD training programme is described at length within the postgraduate handbook http://intranet.exeter.ac.uk/emps/pgr/handbook/. Postgraduates enjoy a very close relationship with their supervisor, typically with daily contact and weekly meetings dedicated to their research, and are expected to fully participate in the meetings of their research group. A flexible approach to training is adopted within the Individual Study Package whereby supervisors construct a (http://intranet.exeter.ac.uk/emps/pgr/handbook/techtraining/guidelinesforphysicsindividualstudyplans/) personalised training programme that includes transferrable skills sessions available across the university, short courses for the cohort e.g. use of statistics, specialised courses arranged by bodies such as the IoP, and independent study reviewed at weekly meetings with the supervisor.

Postgraduates frequently assist in undergraduate teaching, including the supervision of projects within the research laboratories, during years 3 and 4 of the MPhys undergraduate programme. Consequently a strong research culture permeates the entire department with Physics receiving the Best Research Community award in the University's Student's Guild Teaching Awards for 2013. During the assessment period emphasis has shifted from PhD thesis **submission** within 48 months, as required by the research councils, to **completion** within 48 months. Rates of completion within 48 months have risen from 46% in 2008/9 to 78% in 2011/12, while across the assessment period 93% of students completed within 5 years. The incidence of students failing to complete is very small and usually the consequence of overwhelming personal circumstances.

d. Income, infrastructure and facilities

Income

Exeter has aggressive growth targets for its science and engineering research funding portfolio with the aim of being a first-tier partner in any future concentration policy introduced by the UK research councils (UKRC). In the FYs 08/9 to 12/13, new Physics awards were £3.9M, £7.0M, £3.8M, £4.5M and £5.9M respectively. The figure for 09/10 includes Physics' £2.3M share of the £5M EPSRC Exeter-Bath Graphene Centre and £1.6M of a £3.3M EPSRC Knowledge Transfer Award. The grant income (spend excluding in-kind income) shown in REF4b shows a decrease in 12/13 as income from these large awards tapered off. However, from 10/11 new awards grew at 28% per annum, leading to income growth in due course. Further income growth of 11% per annum is assumed within the current business model, which will be delivered by a progressive and rigorous internal peer review process that has underpinned the growth in awards already achieved, and by increased staff numbers, after accounting for the fact that there is typically a delay between the appointment of new and particularly young staff and the generation of awards. The proportion of income obtained from UKRC fell from 75% to 64% from 2008/9 to 2011/13, while income from other UK government sources increased from 9% to 11%, income from non-government organisations increased from 8% to 10%, and income from EU sources increased from 9% to 15% in the same period, reflecting a deliberate strategy to reduce reliance on UKRC.

Consultancy, contract research, and professional services are an important activity within some groups. For example, within **BPG** Moger developed novel non-linear optical imaging techniques for industrial applications with Leopharma, Syngenta, GSK, Unilever and Nanomeric, while Soeller and Stone have acted as consultants for Simula (Norway) and Unilever respectively. Within **EMAG** Sambles has been a member of the Defence Science Advisory Council, and provides consultancy to Dstl, QinetiQ, Atlas and the Counter Terrorism Centre. Vukusic performs credentialising of bio-inspiration technology in the eye-care industry for Bausch and Lomb, while Hicken provided reports to Crown Technology on inductive anti-theft tagging of metallic objects that led to EPSRC funding.

Infrastructure and onsite facilities

Physics at Exeter provides the environment and infrastructure necessary to pursue internationally excellent research, including a large mechanical workshop staffed by time-served apprentice toolmakers, a stores for materials and office and laboratory consumables, a Helium liquefier, site licenses for essential software (Microsoft Office, Matlab, LabView and NAG libraries), a seminar room with videoconferencing capability, and a weekly Colloquium programme. The success of the RAE2008 submission led to further investment in Physics infrastructure by the university with the phased refurbishment of the foyer and floors 1 – 7 of the office tower (£3.3M), various labs within the two-storey slab block building (£518k) and matching funding of £500k for the ground floor graphene centre clean rooms. A new £50M Living Systems building will connect Physics to Biosciences, both physically and scientifically, and accommodate relevant Physics activity. The University contributed £500k towards an upgrade of the supercomputer facility at the end of 2011, to increase current performance to 20 Tflops or more. As of 31st Oct 2013, research infrastructure was supported by 10 FTE research technicians, 4 experimental officers and 1 computer systems manager. Each research group operates specialised facilities appropriate to its needs.

While the observational activities of **APG** are carried out at international facilities (see below), the environment for data analysis and interaction between group members is vitally important, and 2 floors of contiguous office space was refurbished in 2009 and 2011 to accommodate APG. Theoretical work in computational fluid dynamics for astrophysical applications exploits the

University of Exeter supercomputer for which Bate was PI from 2006-2011 (http://hpc.ex.ac.uk) and which was upgraded at the end of 2011. The system manager is a member of APG who regularly attends meetings of the UK's HPC Special Interest Group (http://www.hpc-sig.org/) sharing his experience with other experts across the UK

Facility	Users		08/09	09/10	10/11	11/12	12/13	Total	13-
Diamond	Hicken, Ogrin, Petrov, Stone	shifts[i]	54	36	45	75	*48*[vi]	258	51
		£k	671	328	326	488	*307*[vi]	**2120**	327
ESRF	Ogrin	shifts				18		18	
		£k				60		**60**	
GEMINI	Aigrain, Bastian, Naylor, Patience	hours[ii]	22.6	47.1	72			141.7	
		£k	23	93	176			**292**	
ESO	Naylor, Patience, Sing	hours	38	30	43.7	85.8	10.7	208.2	6.6
		£k	588	461	188	1481	107	**2825**	
ESA[iii]	Aigrain	hours	NA	NA				NA	
		£k	53	62				**115**	
INT	Naylor	hours					40	40	40
		£k					25	**25**	
WHT	Naylor, Patience	hours	16			24		40	32
		£k	68			51		**119**	
UKIRT	Naylor	hours	8		3			11	
		£k	17		17			**34**	
Herschel	Hatchell, Patience	hours		55.4				55.4	
		£k		522				**522**	
JCMT	Brunt, Hatchell	hours		32		28	63	123	
		£k		68		61	134	**263**	
Liverpool telescopes	Naylor, Patience, Sing	hours			48.5	20	8	76.5	32
		£k			33	13	5	**51**	
HST	Pont, Sing	orbits	16		124	23	10	173	
		£k				264	25	**289**	
Sub-Total		**£k**	**1420**	**1534**	**740**	**2418**	**603**[vi]	**6715**[vi]	
ALS[iv] (Berkeley)	Hicken, Kruglyak, Ogrin	shifts	21	24	57	30		132	12
		£k	130	149	353	186		**818**	74
BESSY (Berlin)	Ogrin	shifts		6	6			12	
		£k							
SSRL (Stanford)	Ogrin	shifts		6				6	
		£k							
IRENI (Wisconsin)	Stone	days					4	4	
		£k					6	**6**	
HLD (Dresden)	Russo	days			30			30	
		£k			16			**16**	
CTIO 1.3m (Chile)	Pont	hours				54.4		54.4	
		£k							
OHP[v] 193cm	Pont	hours	88	40				128	
		£k							
Total			**1583**	**1683**	**1076**	**2604**	**609**	**7555**	

Table 1. Awards recorded by HEFCE and at other facilities to which RCUK does not contribute lie above and below the dashed line respectively. Notes: (i) 1 shift = 8 hrs, except at BESSY and SSRL where 1 shift = 12 hrs; (ii) 1 night of telescope time has been counted as 8 hours; (iii) participation in CoRot satellite mission; (iv) $10k per shift includes full cost of recovery for operation and maintenance; (v) Observatoire de Haute-Provence (OHP) is in France; (vi) Diamond beamtime additional to that recorded in REF4c for 12/13 has been included.

BPG possesses a suite of techniques for characterising mechanical and electrical properties of cell

membranes and has a well-equipped laboratory for bio-electrochemistry. It operates a multi-photon imaging and spectroscopy laboratory that is unique within the UK, combining multiple multi-photon contrast mechanisms in a single microscope, and offering unrivalled flexibility in stain-free imaging of multiple species within a sample. Most recently an optical tweezers apparatus has been established, a fluorescent ratiometric imaging system has been purchased, and new laboratories have been constructed to house fluorescence and super-resolution microscopy and a vibrational spectroscopy suite for analysis of cells and tissues. BPG leads the operation of a whole-body magnetic resonance imager (MRI) as a university facility at UEMS. The group will move into a refurbished 2nd floor of the office tower in summer 2014.

EMAG has nanofabrication (dual beam SEM and electron-beam lithography/focussed ion beam milling, nano-sphere lithography, inert gas and reactive ion mills), evaporation and sputter deposition systems, holographic grating fabrication, bio-sample electron microscopy preparation, and access to a rapid prototyping (3D printer) facility for sample fabrication. Microwave measurement facilities include 4 Vector Network Analysers (70 kHz - 110 GHz), collimated beam microwave systems for characterisation of meta-materials and metasurfaces at microwave frequencies, spectrum analysers and sampling oscilloscopes to 50 GHz, and a variety of pulse generators and microwave synthesisers. Optical measurement apparatus includes bright and dark field microscopy, imaging scatterometry, and ellipsometry. High frequency optical measurements are performed with 2 time resolved Kerr microscopes, a multi-wavelength micro-Joule amplified laser system with optical cryostats and superconducting magnet systems for fs optical pump-probe experiments, and a milli-Joule amplified system for pump-probe and THz spectroscopy. Apparatus for x-ray Ferromagnetic Resonance, x-ray photoemission electron microscopy, and coherent x-ray holographic imaging is deployed at different synchrotron radiation sources. A sonar tank system for characterising acoustic metamaterials in water has recently been installed. The group's office space on the 6th floor of the tower block was refurbished in 2012.

Over the last five years, **QSN** has developed new clean-room facilities that house an electron beam lithography system, a high vacuum evaporation system, a reactive ion etcher, and characterisation apparatus such as optical and atomic force microscopes. There are facilities for transport measurements, including a dilution refrigerator with 18 T magnet, and an ultra-low noise mK magnetometry set-up. Optical spectroscopy facilities include lasers of various wavelengths from UV to NIR, a 9T optical-access He-3/He-4 magnet-cryostat, and double and triple spectrometers with photomultiplier and CCD detectors. A computer cluster supports the theoretical work. The group's office space on level 3 was refurbished in 2013.

Usage of major national and international facilities (Principal Investigator time only)

Facilities usage in Physics is mainly of telescopes by **APG** and synchrotron sources by **EMAG.** Time awarded from Aug 08 – July 13, and equivalent cash value where available, are tabulated together with time since Aug 13 in Table 1. The value of time recorded by HEFCE amounts to £6.4M while the total value of time for the same period amounts to £7.6M. However these totals exclude 662 hrs (£352k) on JCMT for the Gould Belt Survey (2007-14) led by Hatchell and 22.16M core hours (£928k) on the STFC DiRAC supercomputers awarded to Bate from Dec 12 – Nov 15. A table containing facility reference numbers for all time awarded is available upon request.

e. Collaboration or contribution to the discipline or research base

Full details of collaborative research projects and contributions to the research community are described upon the staff pages of the departmental website at http://emps.exeter.ac.uk/physics-astronomy/staff/academicstaff/ with examples being provided below.

Support for and exemplars of research collaboration

The scale and form of collaboration is strongly influenced by the nature of the research carried out within each group. **APG** undertakes large-scale observational surveys with multiple international partners such as the JCMT and Gould Belt Surveys (Hatchell, facilities time, ST/J001627/1, PPA/A/R/2003/00173), the binary star survey (Patience, ST/F003277/1, Leverhulme F/00144/BJ) and the Penn State-led MYStIX survey (Naylor). Numerical and theoretical work is carried out in smaller consortia e.g. with Rostov-on-Don (Baraffe, Royal Society JP101297, 10-02-00278 and 11-02-92601) and Michigan (Harries, NASA Origins 08-SSO08-0063).

Within **BPG** there is extensive collaboration with clinicians, for example with Gloucestershire Hospitals (GHs) and Bristol University (Stone, NIHR/II-LA-1111-20007 £689k) and the Royal Devon and Exeter Hospitals (STFC Biomed Network 2529 £37k). The success of the bioimaging suite led to Moger collaborating with pharmacologists at the London School of Pharmacy (EP/G028362/1, £213k), and King's College London and GlaxoSmithKline (EP/G061564/1 £1.3M), leading to follow on funding (EP/K502339/1), while collaboration also occurs at external facilities such as the IRENI Beamline of the Wisconsin Synchrotron (Stone). The development of new measurement techniques has led to projects with instrument manufacturers such as HALO X-ray Technologies Ltd and Radius Diagnostics Ltd (EP/K020196/1 £766k), Renishaw plc, and Zeiss (Soller, NZ$140k via Auckland Uniservices). EU-funded projects support all aspects of the groups research e.g. MINERVA (Stone, Ref.317803 €7.3M).

The **EMAG** group pursues academic collaboration with funding from a wide variety of sources. Hibbins, Barnes, Philbin and Sambles share the QUEST programme grant (EP/I034548/1, £4.6M) with Oxford and Queen Mary, Vukusic collaborates with 5 US institutions including Harvard (USAF FA9550-10-1-0020, DARPA-BAA 09-71), Kruglyak coordinated EU grants MAGNONICS (€3.5M) and DYNAMAG (€0.9M), Hicken holds an EPSRC-NSF grant with UC Berkeley (EP/J018767/1, £358k), while Barnes was appointed to the Chair of Complex Plasmonics at Twente (Netherlands). The nature of the group's research leads easily to collaboration with industrial researchers. An EPSRC KTA grant (EP/H50012X/1, £3.2M) supported work with QinetiQ from 08/09 for 3 years. Hicken's longstanding collaboration with HGST has been supported by EPSRC (EP/C52022X/1, £273k) while Hicken, Barnes and Hendry currently have EPSRC support to work with Queens Belfast and Seagate (EPSRC EP/I038470/1, £637k). Ongoing research collaborations with QinetiQ, DSTL, Sonardyne/Wavefront, BAE Systems and Seagate all provide PhD studentships.

Within **QSN** the graphene centre is an Exeter-Bath collaboration (EP/G036101/1, £4.9M) with associate members from at least 20 institutions world-wide (http://emps.exeter.ac.uk/physics-astronomy/research/graphene/people/associates/). Russo has held EuroMagNET II grants (€48k each) with Regensburg and Tokyo and a EPSRC-JST UK-Japan strategic grant with Tokyo (£90k, EP/J000396/1), while Portnoi coordinated two EU FP7 networks (TerACaN, €86k, QOCaN, €96k), participated in a further 5 networks, and held two Royal Society grants to collaborate with partners in Russia. The group's strength in theory is manifest in international collaborations that require minimal funding but lead to high quality output e.g. Shytov with MIT and University of California at Berkeley (USA) (Nature Physics 8, 653-657 (2012) and Science 10, 734-747 (2013)).

Support for and exemplars of interdisciplinary research

Interdisciplinary research is pursued by all of the research groups. Within **APG** Pont and Baraffe have organised interdisciplinary conferences between astrophysicists, planetary scientists and geophysicists (Exoclimes 2010, 2014; GCM workshop 2011 Exeter). Work with Applied Mathematics was supported by a consolidated STFC grant (2012-15), while APG has joint publications with the Met Office, two of their staff being seconded to APG for 1 day each week. Collaboration with CLES on photochemistry in exoplanets is being pursued with a jointly supervised PhD student. Almost all research within **BPG** is collaborative and interdisciplinary. Moger uses physics-based multi-photon techniques to characterise biological tissues in collaboration with biologists (BB/I020004/1, BB/K013602/1) and medics in Exeter, and chemists at Syngenta. Petrov and Winlove have EPSRC **"**Bridging the Gaps" funding for projects with Sports Science, PCMD and Biosciences at Exeter. Winlove holds collaborative grants from ARC (Grant # 19432), BHF (PG/11/17/28788), Diabetes UK (12/0004305) and DSTL (DSTLX100002918) with staff from the Medical School and Bioscience. Stone runs various projects with clinicians at Gloucestershire Hospitals, Royal Devon and Exeter Hospitals, North Staffordshire Hospitals, NHS Innovations South West and the Wellcome Bioinformatics Network at Exeter. Within **EMAG** Hendry's super-chiral sensing work with Glasgow embraces chemistry, physics, engineering and biology (Nature Nano **5**, 783 (2010)). Vukusic receives samples from biological specimen suppliers and entomologists, and materials scientists, and publishes in cross-disciplinary journals. Hicken collaborates on phase change materials with Exeter Engineering (EP/F015046/1). Barnes, Hibbins, Horsley, Philbin, and Sambles interact strongly through the QUEST programme grant (EP/I034548/1) with Engineers at Oxford and QMC. Within **QSN** the graphene centre interacts with biologists, chemists, pharmacologists and engineers. Russo collaborates with Exeter Engineering

on transparent organic electronics (EP/J000396/1) and transparent electrodes (Adv. Mater. 24, 2844 (2012)), with Tokyo Engineering on ionic liquid gating (PNAS **108**, 13002 (2011)), and with ICFO Barcelona on plasmonics (Royal Society International Exchange). Russo and Horsell collaborate with Exeter Engineering on manufacturable approaches for graphene (EP/K017160/1).

Influence of collaboration with users upon research and strategy

The research activity and strategy of the BPG and EMAG groups has been strongly influenced by interaction with end users. **BPG** collaborates with biological scientists and clinicians to ensure that it addresses questions of real biological importance and develops physical methods that are applicable in a biological or clinical environment. Initial interaction through CARS microscopy led Moger to develop a new platform for drug delivery based on polymer nano-particles with London School of Pharmacy and Kings College London (EP/G061564/1), which is now being commercialised in collaboration with Nanomeric and UCL (EP/K502339/1, TSB 130523). Stone has spent his research career working closely with clinical teams to identify the need for novel tools translated from new physical scientific advances. Continued collaboration with QinetiQ following the EPSRC sponsored KTA informs the impact agenda within **EMAG**, as do CASE studentships with Sonardyne, BAe, DSTL, QinetiQ and Seagate. Visits by leading industrial scientists have led to PhD studentships e.g. "Magnetic metamaterial elements for VHF, UHF and SHF frequencies", from DSTL in Sept 2011. Collaborations with technologists have revealed aspects of biological photonics of potential benefit to product designers, guiding selection of specimens and samples, and leading to grants (USAF FA9550-10-1-0020, DARPA-BAA 09-71). Collaboration with Crown Technology on inductive tagging led to EPSRC funding for ferrite-based planar cavity resonators. Collaboration with HGST led to studies of magnetisation dynamics within nanostructured materials relevant to hard disk read sensors, while interaction with Seagate Technology led to studies of spin transfer torque in sensors and high frequency magnetisation dynamics of the writer structure. Metamaterials research has been drawn together in a new centre for doctoral training (CDT) in which input from 10 industrial partners will influence the training and research undertaken.

Leadership within the research community and esteem indicators

All research groups have staff who are recognised leaders within the academic community, as evidenced on their web pages (http://emps.exeter.ac.uk/physics-astronomy/staff/academicstaff/), having acted as reviewers for leading journals and funding agencies, served on funding and facilities panels, been members of organising and publications committees of international conferences, given many invited talks at international conferences**,** and in some cases received prestigious prizes for research**.** Of particular note within **APG**, Chabrier was the recipient of the “Grand Prix Jean Ricard” of the French Physical Society in 2010 and the Eddington Medal of the Royal Astronomical Society in 2011, Baraffe received a Royal Society Wolfson Research Merit Award in 2010, Patience received the Newcomb-Cleveland Award (2008), and Kraus won the Philip Leverhulme prize (2013). Bate chaired the organising committee of "The Origin of Stellar Masses" in Tenerife, 2010. Within **BPG** Winlove is a founder member of Back to Back, a spinal research charity, while Stone was recently Director of Science for the Institute of Physics and Engineering in Medicine, is currently Vice President (Academic) and a Council member, and was awarded the NHS Chief Scientific Officer’s National R&D Award for 2009. Within **EMAG** Sambles has been a member of EPSRC Council since 2008 and chair of the EPRSC Resource Audit Committee since 2011, chair of the EPSRC major facilities prioritisation panel in 2010, chair of the Programme grant panel in 2013, a member of the Royal Society Sectional Committee 2 since 2010, Rank Lecturer at Photon 2008, awarded the IoP Faraday medal in 2012, and became President Elect of the Institute of Physics from October 2013. Vukusic received the British Association Lord Kelvin Award in 2008 and the 2013 Royal Society Kohn Award. Barnes was associate editor of the Journal of Modern Optics (2008-2013). Within **QSN** Portnoi was awarded visiting professorships by the International Institute of Physics (Natal, Brazil) in 2010-2013 and the International Centre of Condensed Matter Physics (Brasilia, Brazil) in 2008 and 2009, Mariani was keynote lecturer at the Graphene Workshops in Bremen (2011) and Santa Barbara (2012) and his PhD student, Claire Woollacott won a Cavendish medal and a £3000 cash prize in the 2013 SET for Britain poster competition, for graphene research published in Physical Review Letters. Russo was keynote lecturer at the Graphene Workshop in Regensburg (2011), CarbonHagen in Copenhagen (2012), and at Printed Electronics USA in Santa Clara (2012).