Institution: The Open University

Unit of Assessment: B7 Earth Systems and Environment Sciences

a. Overview

Research in Earth Systems and Environmental Sciences is one of The Open University's declared strategic priorities. Within the Open University (OU), this research is organised in a single research centre, CEPSAR (Centre for Earth, Planetary, Space and Astronomical Research) that also includes Chemists and Physicists. The strength of this approach is that it brings together scientists using similar scientific methods and equipment, to solve very different research challenges. Research in CEPSAR exploits synergies between terrestrial and extra-terrestrial problems and between past and future environmental change. For example, our research has included studies that compare and contrast planetary processes on Earth, Mars and other solar system bodies. We have also studied ecosystems and habitats on Earth, while searching for life-supporting habitats on other worlds, two fields that overlap in the area of microbiology, and underpin the emerging fields of astrobiology and astrochemistry.

Research in CEPSAR encompasses 58.3 FTE researchers and is structured in four research groups: Ecosystems and Sustainability (14 researcher FTEs); Earth Sciences (18.3); Planetary and Space Sciences (15); and Astronomy (11). There is synergy in CEPSAR research across all these groups, particularly related to a shared interest in scientific observation, and the development and application of analytical instrumentation to measure key natural processes.

CEPSAR's facilities include the Centre for Electronic Imaging (CEI), radiogenic and stable isotope suites, electron and ion beam analytical laboratories, geochemistry and environmental science laboratories, space instrumentation labs, a high-velocity impact laboratory, and a 750-core computing cluster. CEPSAR also supports the provision of analytical services and enterprise activity focused around technical consultancy. During the six years since 2008 CEPSAR has won £51.2m of external funding, including in-kind research funding, from a diverse portfolio of sponsors, including the Science and Technology Facilities Council (STFC), Natural Environment Research Council (NERC), European Space Agency (ESA), Engineering and Physical Sciences Research Council (EPSRC), European Union (EU), United Kingdom Space Agency (UKSA), and charities such as the Leverhulme Trust and the Esmée Fairburn Foundation.

The Director of CEPSAR has administrative and budgetary control for the Centre's research activity. Research is managed within CEPSAR as an integral part of the Faculty and the University Strategic Plan, which sets out high-level targets for research quality, income and impact. CEPSAR delivers research excellence through a vibrant academic community, including managing laboratory infrastructure, and support staff. CEPSAR also delivers specialist training for academic staff, research fellows and postgraduate research students, ranging from public engagement to lab protocols and Health and Safety.

b. Research strategy

The high volume of internationally excellent science produced by CEPSAR researchers has resulted in nearly 1300 peer-reviewed publications since RAE2008, with a mean citation rate of over 10 per FTE submitted: a testament to the success of the unit's strategic decision to focus on core thematic areas, while expanding selected interdisciplinary linkages. Research in several different fields has delivered significant impact including public engagement and citizen science, influence on policy, and impact on UK industry; these are reviewed in the impact narrative and detailed in our seven impact case studies.

In our strategic planning in 2008 we highlighted several areas we intended to develop, and many of the nascent ideas and concepts have come to fruition in the past six years. In Ecosystems and Sustainability we highlighted the quantification of carbon cycle processes as an important driver for future research. In Earth Sciences we identified the importance of understanding the links between solid Earth and other terrestrial spheres such as the atmosphere, oceans and biosphere, by combining the outputs of field and laboratory measurements with modelling-based research. In Planetary and Space Sciences we foresaw the key outputs from *in-situ* laboratory-based studies, including nanoSIMS, and continued involvement in major space missions. Our Astrophysics and Astrochemistry highlights included studying the history and formation of galaxies in the early universe, alongside ground-based observations focusing on exoplanet surveys and combined

modelling; we also highlighted the potential for outputs from our laboratory astrochemistry programme to be applied to observational astrochemistry. We have achieved or exceeded the objectives we set in 2008, while new research themes have emerged, including the expansion of ecosystems research to include microecology and microbiology, and a greater than expected involvement in the NASA Mars Science Laboratory mission focusing on the ChemCam and SAM instruments.

i. Ecosystems and Sustainability

The group encompasses an extremely broad range of expertise spanning ecology and conservation; marine, terrestrial and soil sciences; global change; natural hazards; pollution and environmental management. We work over an enormous range of scales from microbial community interactions to millennial climate system projections with the unifying goal of predicting responses to environmental pressures, how society interacts with the environment and the implications for the future of planet Earth and its inhabitants.

Strategic themes we have pursued are the interactions between the components of the Earth system including coupled human–environment systems, citizen engagement and involvement in the science process. The group has also had important inputs into public debates and policy in the areas of nuclear policy (*Nuttall*) and waste management (featured in an impact case study CS5). We have explored how microbial communities break down primordial rock, and their potential to increase rock weathering by an order of magnitude, enhancing atmospheric carbon dioxide drawdown and promoting nutrient availability for other organisms. Our studies of extremophiles have shown how high-intensity radiation could have acted as a selection pressure on cyanobacteria on the early Earth (*Olsson-Francis*). Work at the microbial scale in European forest soil systems has revealed the importance of priming (the presence of decaying matter covering the surface) on microbial activity and thus greenhouse gas release (*Sayer*).

We have delivered our strategic aims in the biodiversity field, highlights include leadership of an ESF funded consortium to survey the effect of excess atmospheric nitrogen deposition on species richness across deposition gradients spanning the Atlantic biogeographic zone (*Gowing*). The results demonstrated the cumulative, long-term impact of the deposition and identified a set of traits that characterised the species at risk. An eco-hydrological analysis of the Cape Flora (funded by NERC, Leverhulme and Defra) revealed a pattern of niche segregation mirroring that seen in European meadows (*Silvertown, Gowing*). These two research projects were linked by a landmark publication proposing nitrogen availability, through soil-moisture regime, as a key determinant of plant community composition and biodiversity (*Gowing*). Large-scale collaborative grants in biodiversity have been pursued successfully, complemented by novel applications of citizen science through the Evolution MegaLab and iSpot projects, involving thousands of volunteers in active data collection and analysis. In probably the largest evolutionary study of its kind, we tested the hypothesis that climatic warming has led to evolutionary change in banded snails: an important model organism in ecological genetics (Silvertown).

Citizen science has also played a key role in the long-term monitoring of active volcanoes, where successful prediction of future seismicity on the basis of combined gravity, seismic, gas release and lake chemistry measurements has led to uptake of the group's methodology as an international standard (*Rymer*). A Branco-Weiss fellow (v*an Manen*) is quantifying the impact of active volcanoes on their environment and local population by tracking volcanic gases from source to sink. Citizen science is integrated into the environmental volcanology research, monitoring changes over a long timescale on several volcanoes (*Rymer*), illustrated in an impact case study (CS3). Long-term monitoring in hostile environments is also a feature of the group's contribution to research on sensitive Antarctic ecosystems (*Brandon*), an area that provided the basis of an impact case study (CS2) on public engagement related to the polar environments.

The group has led a NERC network to mobilise the UK methane research community (*Gauci*), integrating work on terrestrial ecosystem methane emissions from the poles to the tropics, while the group's own research has demonstrated the importance of wetland trees as a conduit through which methane produced in the soil is released to the atmosphere (*Gauci*). Discovery of ‘old carbon’ being flushed out of the Indonesian rain forest after major fires showed that human activity is rapidly eroding soils that have taken thousands of years to develop (*Gauci*), contributing to an impact case study (CS4). Appointments (*Bruhn, Spessa*) have been made to strengthen significantly the area of land–atmosphere fluxes, bringing in world-leading expertise in several

areas, including the dynamic modelling of wildfire (*Spessa*), a fundamental Earth system process and an essential control on almost all biomes. Fire dynamics depend on climate, land use and vegetation interactions and are thus sensitive to global change. The group now hosts the lead developer of SPITFIRE (*Spessa*), widely regarded as the most realistic process-based model of fire activity, fire–vegetation interactions, and emissions from biomass burning. The group also hosts lead developers of the GENIE intermediate complexity Earth system model (*Edwards*), the only UK-based modelling group to contribute to the millennial-scale climate projections in both the fourth and fifth assessments of the Intergovernmental Panel on Climate Change (IPCC). Earth system modelling activity focuses on uncertainty quantification and model coupling for policy analysis. Leading a major EU consortium project in this area (ERMITAGE), the group has developed novel techniques to analyse the spatiotemporal feedbacks between environmental, technological and economic dynamics. Earth system modelling highlights also include the first probabilistic calibration of terrestrial carbon storage (*Holden, Edwards*). The group also made a significant contribution to the debate on the limits of helium, which is an important and limited natural resource used in several industries, and to the debate over natural resources for nuclear power generation including uranium and thorium (*Nuttall*).

ii. Earth Sciences

Achievements since 2008 have been across two interrelated strategic themes, 'Paleoenvironments' and 'Dynamic Earth systems', that are also strategic for future development. Significant achievements from the paleoenvironment group include the development of a new proxy based on UV damage to spore and pollen wall chemistry (*Gosling*); NERC funding was awarded to exploit this proxy for determining past insolation variation. The potential for exploiting this development for paleoaltimetry *(Harris)* exemplifies effective synergy between our research groups. Research into the quantification and mechanisms for past global anoxia using new isotope techniques developed at the OU (*Cohen*) have provided the first ever quantitative estimates of the expansion of global marine anoxia during past hyperthermal events in the Mesozoic and Paleocene (*Cohen, Coe*). These studies of the past indicate that global ocean anoxia will increase substantially as a result of anthropogenic global warming, confirm inferences from present-day observation, and demonstrate that the geological record contains valuable information about Earth's future. A study of early Eocene hypothermal events (*Sexton*) quantified their frequency and the magnitude of the carbon released. Observational and theoretical studies on sedimentary cycles in the Mesozoic and Paleogene (*Kemp, Coe, Cohen*) have confirmed their importance as regulators of climate throughout Earth history. Drill-core lake sediments recovered from the Boltysh impact crater showed that the impact predated the Chicxulub impact by a few thousand years, and provided evidence for global carbon cycle perturbation in the early Danian period (*Gilmour, Kelley)*. Variations in North Atlantic ocean circulation patterns during the Pleistocene have been shown to be responsible for variations in precipitation, vegetation communities and biodiversity in the Amazon rainforest (*Gosling, Sherlock*). Interdisciplinary work has also linked biodiversity–climate interactions, forcings and feedback mechanisms by combining modelling and environmental data (*Holden, Gosling*).

Dynamic Earth systems research has encompassed research into magmatic and tectonic processes and the quantification of their rates and timescales. Laboratory studies, modelling and measurements of natural samples, funded by NERC, Leverhulme and commercial bodies, have combined to develop new ways of probing noble gas behaviour in crustal and mantle rocks during tectonic recycling (*Kelley, Sherlock, Warren*). Highlights include the identification of a mechanism by which noble gases may be transported from crustal levels by subduction into the mantle; the development of a framework for understanding Ar-Ar ages in terms of fluid flow and deciphering their significance in igneous and metamorphic terrains; and the development of novel techniques to measure Ar-Ar ages on ultra-small samples, including authigenic K-feldspar growth in sandstones, excess argon distribution in high-pressure rocks, and pseudotachylite development on faults and in meteorite impacts.

Further examples of OU advances underpinned by our geochemical innovation include pioneering the methodology for high-precision measurements of Sr isotopes and their application to understanding early solar system behaviour and redox systematics of the Earth's oceans (*Charlier*), and developments in understanding trace element budgets and fluxes at oceanic spreading ridges and plate collision zones (*Jenner*). Significantly, our volcanology programme has (i) contributed to understanding the atmospheric and environmental impacts of large volcanic

eruptions by quantifying the amounts sulphur and chlorine released by Deccan volcanic eruptions (*Blake, Widdowson*); (ii) developed a method for forecasting explosive eruptions using remote sensing (*van Manen, Blake*); and (iii) quantified syn-eruptive timescales (sub-minute) in Earth's most recent super-eruption (*Charlier*). One of our new appointments has been instrumental in developing a global satellite-based volcano warning system, the EVOSS project (*Ferrucci*).

Our tectonics programme, supported by NERC, the Royal Society and Swiss National Science Foundation funding, has been at the forefront of international research into mountain-building processes, relating mineral chronometry to tectonic events and testing thermomechanical models for orogenic evolution (*Harris, Argles, Warren*). Significant progress in understanding the subduction and exhumation behaviour of continental crust in subduction and continental collision zones has resulted from combining results from finite element modelling and natural pressure-temperature-time paths. New avenues for research that are planned include linking accessory phase 'age' with metamorphic 'stage' by developing methods to geochemically fingerprint geochronometer crystallisation reactions and modelling these reactions via phase diagrams.

iii. Planetary and Space Science

Research within the Planetary and Space Science (PSS) research group has met objectives for making advances in studies of the origin and evolution of the solar system, the processes of planet formation, and how the evolution of planets has influenced the evolution of life. Research has included: (i) laboratory-based analysis of extra-terrestrial materials from the Moon and Mars, as well as from asteroids and comets; (ii) space-based observation of planetary bodies; (iii) theoretical models and simulation. Complementing these activities has been development of spaceflight instrumentation and associated control software. Highlights of how we have achieved our strategic aims since 2008 include:

Laboratory-based analysis: Key isotope measurements were performed on meteorite falls including Tissint, a new Martian meteorite, Sutter's Mill, a CM chondrite regolith breccia, and the Chelyabinsk meteorite, which exploded and injured over 100 people in Siberia in 2013 (*Franchi, Grady*). The first measurements of oxygen isotope reservoirs of fine-grained cometary dust using nanoSIMs have been reported (*Franchi*), and processes affecting the transport and location of water on other solar system bodies explored (*Anand*, *Grady, Schwenzer*).

Laboratory instrumentation development has been a specialism of the group, including noble gas measurements that have made significant contributions to our understanding of the timing and conditions of processes in the Martian surface environment (*Kelley, Schwenzer*). Compound specific carbon isotope studies have provided new insights into conditions in extra-terrestrial and terrestrial environments (*Gilmour*).

Space-based observation: The group made significant contributions to recent studies of Mars, including work on Martian fluvial conglomerates at Gale crater (*Schwenzer*) and habitats for life on Mars and icy moons (*Grady*). Work on remotely sensed images of Martian periglacial deposits and their terrestrial analogues (*Balme, Lewis*) has profound implications for understanding Martian surface history and has led to major roles on missions including the NASA Mars Science Laboratory (*Lewis, Schwenzer*). We have also made significant contributions to missions studying the Moon (*Anand*) and Mercury (*Rothery*).

Theoretical modelling and simulations: The group has used new data from the Mars Reconnaissance Orbiter on the thermal structure and distributions of dust and water ice in the atmosphere to improve models of Martian climate (*Lewis*). Simulations have also been used to develop instruments intended to measure planetary thermal properties (*Hagerman*) and EU funding for Near Earth Object research produced landmark publications on YORP and Yarkovsky effects (*Green*).

Spaceflight instrumentation: Electronic imaging research has influenced several major ESA missions including GAIA and EUCLID (*Holland*), with the benefit to UK industry illustrated in an impact case study (CS7). The ROSETTA space mission, on which The Open University leads an instrument (*Wright*), will rendezvous with Comet 67P/Churyumov-Gerasimenko in 2014. A small lander containing an Open University-built mass spectrometer will land and measure a range of physical parameters late in 2014 (*Wright*).

We have developed a series of projects with ESA and UKSA, increasingly contributing to their core work in short research projects such as L-VRAP, CAFÉ, DUSTER and WatSeN (*Grady, Holland, Wright*).

PSS research has been increasingly integrated with the Astronomy research group (e.g. in

exoplanet research), a synergy that was strengthened with the appointment of *Fraser* to Astronomy (see below), and the development of astrochemistry research. Similarly synergistic collaborations with the Earth Science group have been developed on understanding geological processes and evolution of Mars' surface (*Charlier*, *Kelley*), and the work of UKSA Aurora Fellow in studies of bacteria in extreme environments (*Olsson-Francis*).

iv. Astronomy

The group combines terrestrial and space-based observations, laboratory work and theoretical modelling to study subjects in our Universe ranging from cosmology to exoplanets, using large-area optical/infrared/radio surveys, time-domain astronomy and laboratory/observational astrochemistry.

The large-area optical/infrared surveys delivered some of the major advances in the field, probing the physics of star formation (*White*), dust evolution (*White, Fraser, Bernard-Salas*) and the cosmic evolution of star formation in the distant universe (*Serjeant*). These studies include statistical detection of the galaxies dominating the mid-infrared to sub-mm extragalactic background, and the development of a breakthrough gravitational lensing detection technique based on bright sub-mm fluxes (*Serjeant*) that is revolutionising lens discovery. Optical cosmological results include striking links between galaxy properties and those of their host dark matter halos, including the first measurement of the relationship between galaxy stellar mass and dark matter halo mass in the early Universe (*Wake*). The group has invested in membership of the SALT (optical) and LOFAR (radio) telescopes, and its members are active users of major international ground- and space-based international facilities, focusing, for example, on the discovery of exoplanet compositions and on pioneering galactic plane mapping at the longest accessible radio wavelengths by studying carbon radio recombination lines to measure turbulence directly in the diffuse interstellar medium.

Highlights of our time-domain astronomy research include HST observations of the transits of the 'extreme hot Jupiter' exoplant, WASP-12b (*Haswell*), detecting Fe II and Mg II resonance lines in the extended gas surrounding the planet. *Haswell* also discovered that the entire WASP-12 planetary system is embedded in a diffuse cloud of gas lost from the planet, which led to an innovative method for detecting hitherto unknown close-in planets, including small rocky planets, around bright nearby stars. The time-domain theme also includes modelling (*Kolb, Norton, Haswell, White*); stellar variability (*Kolb, Norton, Clark*); and the behaviour and evolution of stellar systems (*Norton, Kolb, White*), including our breakthrough magnetar discovery in Westlund 1 (*Clark*) and uncovering the true stellar population of the Kepler field (*Kolb*). Our ESO/VLT-supported radial velocity studies revealed the central role of binary interaction in massive stellar evolution, central to the production of magnetars and potentially the physical mechanisms driving GRBs (*Clark*). Work on main sequence close binary systems at the short-period cut-off has increased the number of known systems by a factor of 20, identified systems with short merger timescales and discovered new multiple hierarchical systems (*Norton*). Infrared radial velocity spectroscopy of the counterparts to eclipsing high-mass X-ray binaries has led to the first neutron star mass determinations in four systems, increasing by 50% the total measured this way (*Norton*). 3D hydrodynamic modelling of accretion flows in magnetic cataclysmic variables showed that four types of accretion flow are possible and that triple-points in the period ratio versus magnetic moment plane divide the parameter space into regions with characteristic flows (*Norton*).

Astronomical and planetary sciences research has been strengthened by the development of an Astrochemistry research programme combining laboratory (*Mason, Fraser*), observational (*White, Bernard-Salas*) and modelling work (*Fraser*). This has been delivered: the first definitive observations of fullerenes in interstellar space (*Bernard-Salas*); laboratory simulations of Titan's ionosphere leading to the identification of nitrile anions detected by Cassin CAPS instrument (*Mason*); identifying the potential for electron-induced chemistry within dusty mantles of ISM grains as a source of complex (prebiotic) molecular formation (*Fraser, Mason*); the first measurements of icy particle aggregation, using microgravity facilities to test very low velocity collisions, proving that icy particles in protoplanetary discs do not stick, forcing a fundamental reassessment of planet formation mechanisms (*Fraser*); the first laboratory determination of the CO_2 ice formation rate compared with H_2O and H_2 gas formation, proving that CO_2 and H_2O ices form concurrently in interstellar clouds (*Fraser*); the first combined 2-5 micron observations of interstellar ices in low luminosity YSOs and background stars, opening a new parameter space for ice observations in the ISM that are the precursors to JWST science (*Fraser*); and the compilation of the first UV spectral

database of astrochemical/planetary ices (*Mason*), which has been used to explore chemical composition of Jovian and Saturnian lunar surfaces and chemical composition of KBO ices. In an astrobiology context, laboratory experiments have shown that ozone can be produced by irradiation of many oxygen-containing planetary ices such that ozone may not be a unique/suitable biomarker in exoplanet habitability studies (*Mason*), and that irradiation of bacterial samples shielded by dust may see enhanced damage due to production of a cascade of secondary electrons through the regolith (*Mason, Olsson Francis*).

Members have PI/co-PI roles in the Herschel NEP Legacy Survey (*Serjeant*), SCUBA-2 All-Sky Survey (*Serjeant*), AGN WG in Herschel ATLAS Legacy Survey (*Serjeant*), e-MERLIN Gravitational Lensing Legacy Survey (*Serjeant*), many projects in the all-sky AKARI IR-survey (*White, Serjeant, Fraser*), LOFAR NEP survey (*White*), including the head of SDSS-IV MANGA survey design (*Wake*), and an Instrument co-I on the Planck HFI Foregrounds programme to study Galactic emission (*White*). The group has been a core partner of the world's largest collaboration project to study surface chemistry under astronomical conditions EU FPVII LASSIE ITN (*Mason, Fraser*) and led (*Mason*) the EU Chemical COSMOS network. The group's experimental facilities are part of Europe's largest planetary science network, combining the expertise from 40 institutions (Europlanet), which from 2014 is chaired by *Mason*. The OU leads pipeline development, data reduction and archiving of stellar variability for the NASA-STEREO star/exoplanet survey (*White*). The group is also involved in the planning for PLATO2.0, EChO, SPICA, Euclid, Gaia, FIRI and other international space missions.

Our development plans from 2014 onwards:

Strategic plans have been developed by each of the individual research groups and prioritised on the basis of track record and future potential. The recent announcement of an STFC consolidated grant award 'Astronomy and Planetary Science at the OU' including 9 PDRAs, and our NERC Doctoral Training Partnership, CENTA, are an outstanding start to the post REF2014 environment in CEPSAR.

Our development plans have been underpinned by University investment in seven four-year fixed-term research fellows, visiting international professors, a renewed five-year plan for the Centre for Electronic Imaging to nurture and develop our relationship with the company e2v, and refurbishment of the ecosystems and microbiology laboratories. Realising our plans requires both gradual evolution of CEPSAR's capabilities and agility to respond to external drivers. These plans will be underpinned by the diversification of our funding portfolio, including achieving a greater proportion of non-RCUK and enterprise income, and increasing OU focus on research impact.

CEPSAR will:

- provide a research environment that supports a broad programme of internationally excellent research focused on developing areas where we can set the agenda, particularly where research crosses boundaries, such as links between planetary science and Earth processes, between environmental and social change, and between modern and paleoenvironments;
- develop close working collaborations with other universities and laboratories, to build critical mass and pool expertise to support space mission and technology development;
- recognise our unique capabilities in communication and science engagement. Our portfolio will involve both engagement and active participation of the public in science. Our 'Citizen Science' programme will build on our ability to reach large audiences, supported by a specialist Faculty-based media team;
- target new investment on those areas identified as having strategic promise.

Strategic goals in the four individual disciplines are:

i. Ecosystems and Sustainability

- To deliver high-impact interdisciplinary research on the effects of contemporary environmental change;
- To improve our understanding of ecosystem function in response to contemporary environmental change, relating to biodiversity, carbon dynamics, water and nutrient availability and exchange;
- To combine empirical studies of contemporary and past environmental change with modelling expertise to improve our understanding of the future state of global ecosystems;

- To integrate economics and societal issues into empirical and modelling studies of global environmental change including the impacts of natural hazards.

ii. Earth Sciences

- To exploit our analytical capability for developing novel methodologies for the identification of the mechanisms and the quantification of the rates of key processes in the Earth system;
- To assess mechanisms, feedbacks and timescales in environmental and climatic change through integration of empirical data and modelling outputs covering timescales from abrupt natural hazard events to millions of years;
- To develop the field of 'biotic sensitivity' to global change across geological time as the biotic analogy to the field of paleoclimatology.

iii. Planetary and Space Science

- To maintain and build high scientific credibility for our analytical expertise, particularly measurement of light-stable isotopes using conventional mass spectrometry, *in-situ* analysis of samples (e.g. nanoSIMS), and by developing instrumentation for space mission measurements;
- To develop expertise in planetary surfaces using modelling, remote sensing and the use of analogues on Earth, and secure further science team involvements in future planetary space missions;
- To pursue relevant scientific and technical involvement in future missions such as JUICE, BepiColombo, Hayabusa 2, MarcoPolo-R, Mars2020, Mars Sample Return, Lunar Resurs and Footprint;
- To strengthen activity in the area of space instrumentation development, with funding from traditional areas (EU, UKSA, RCUK), and develop academia-industry collaborations for funding sources such as ESA 'Invitations to Tender';
- To update analytical infrastructure, exploit the performance of existing instruments, and continue to develop and expand the laboratory analytical programme, in order to ensure involvement in upcoming sample-return missions, and maintain access to the most important planetary samples.

iv. Astronomy

We will develop our international excellence around two themes:

- The Compositional Universe: exploiting the spectroscopic discovery space from ALMA, JWST, SPICA, SOFIA and IRAM to study galactic star formation, evaporating exoplanets, and the physics of galaxies in the distant universe. We will further develop our laboratory/observational astrochemistry research to focus on the development of molecular compositional diagnostics;
- The Time-Domain Universe: exploiting the discovery space of new and future telescopes e.g. Gaia and LSST, in studies such as galactic and extragalactic stellar populations. A focus for development is stellar binarity, a process second only to the mass of a star in determining stellar evolution, yet often ignored in both galactic and extragalactic population contexts.

c. People, including:

i. Staffing strategy and staff development

At the core of the research environment in CEPSAR are its staff and students.

Since 2008, The Open University has made significant strategic investment in research-active staff and infrastructure in Earth Systems and Environmental Science, consolidating effort around four main research groupings within CEPSAR. We have recruited five lecturers and one senior lecturer, confirmed the transfer of four RCUK fellows to lecturing positions, and recruited six externally funded research fellows. The University has also invested in seven four-year research fellows and developed a programme of visiting international research professors. The quality of the CEPSAR research environment is also demonstrated by the progression of our career-young staff in achieving fellowships and moving to senior positions at The Open University and elsewhere. Senior staff work with, mentor, and assist in the development of career-young researchers including post-doctoral research assistants and PhD students. Our staffing strategy has included significant succession planning that we discuss in some detail here using the main research grouping structure as a framework to illustrate our strategy.

i. Ecosystems and Sustainability group

The research area has expanded significantly since 2008 and benefited from University support since it is regarded as a priority area for investment. The expansion included the recruitment of *Sayer* to a lecturer position. The University has further invested by recruiting *Holden, Bruhn* and *Spessa* to four-year research fellowships, while *van Manen* was awarded a Branco-Weiss fellowship (2011).

ii. Earth Sciences

This research grouping has maintained its high profile, with several promotions and strong research performance in income and outputs. *Gosling* transferred from an RCUK fellowship to a lecturer position, *Warren* was awarded a NERC advanced fellowship (2010), *Kemp* a NERC fellowship (2011) and *Montoya* a NERC fellowship (2012). Strategic University support attracted *Jenner* to a four-year University fellowship, and *Ferrucci* was recruited to the discipline on a Research Professorship.

iii. Planetary and Space Sciences

Staff appointments have maintained the group as one of the main UK centres for planetary science. *Hagerman* and *Balme* have transferred from Aurora research fellowships to lecturer positions, *Anand* from a RCUK fellowship to a lecturer position. *Olsson-Francis* was awarded a UKSA Aurora fellowship (2010). *Schwenzer* was appointed as a four-year research investment fellow.

In 2008 the Centre for Electronic Imaging was established as a joint venture with the UK company e2v. Professor *Andrew Holland* was appointed to lead the Centre fo in 2008, with the further appointment of two five-year research fellows, *Hall* and *Greg*, a four-year fixed term senior research fellow, *Stefanov*, and an STFC IPS fellow, *Burgon*. The University also supports a 50% group manager. The group has attracted ~£6.5m external funding from ESA, STFC, EU and the Regional Growth Fund, forming the basis of an impact case study (CS7).

iv. Astronomy

This research grouping has expanded since 2008 with the transfer of RCUK fellows *Lewis* and *Clark* to lecturer positions, the recruitment of a senior lecturer, *Fraser*, and several internal promotions of early-career and mid-career staff. The size of the research grouping was further augmented by the inclusion of University investment fellows *Bernard-Salas* and *Wake*.

The Open University has an excellent record of developing the careers of external research council fellowships, for example, *Barry* (NERC Fellow) is now permanently employed by Leicester University; *Stevens* and *Oliver* (Leverhulme Fellows) are now lecturers at Lancaster and Southampton Universities respectively. Many of our post-doctoral researchers move on to research fellowships and employment in the science arena; for example, since 2008 *Dixon* has moved to a fellowship at Oxford, *Pearce* has moved to a fellowship at Southampton, *Etaxaluze* moved to a fellowship at Harvard, and *Ball* has been appointed instrument engineer at the European Space Agency, while *deBoer* is an Associate Professor at Stockholm.

The University and Faculty strategies aim to maintain an environment that promotes and encourages excellent research. Workload is planned and managed to ensure that the OU meets its founding principles of being a high-quality research and teaching university, and ensures that staff undertaking research have appropriate time, monitored by annual career development and staff appraisal. These appraisals ensure that research objectives are clearly stated, support and development needs are discussed and agreed, and there is appropriate evaluation and reflection on performance. A well-resourced, dedicated, central Research Career Development Team has grown its provision every year since 2008, providing opportunities for researchers at all stages of their career, and has excellent evaluation feedback. The Open University is a signatory to the Concordat to Support the Career Development of Researchers and actively works to implement its seven principles. Our commitment to the Concordat has been recognised with the European Commission HR Excellence in Research Award.

Equality of opportunity is a core value of the University. Its recruitment and selection procedures provide mechanisms to assess and appoint the most able and effective employees while ensuring that all individuals are treated with objective fairness and sensitivity. We are committed to the development of women's careers in research, including active measures in recruitment, retention, progression, mentoring and career development, and in 2013 were awarded an Athena Swan institutional Bronze Award.

ii. Research students

We have a vibrant postgraduate research student environment graduating 10–15 PhD students per year. Evidence for our record on student progression and completion is found in the graduation of 78.42 PhD students, and 92% of our students completing their project within four years. Our students have gone on to find employment in academia, as post-doctoral researchers, and in industry.

A comprehensive Research Career Development Programme is provided for research students from induction to viva, complementing the research methods training provided by postgraduate taught courses and weekly workshops. Face-to-face and online careers services provide personalised advice and the OU Library offers frequent dedicated sessions. An annual research poster competition feeds into the Vitae competition. A new dedicated web portal provides access to a 'Virtual Research Environment', providing in one place a range of skills training, news, careers services, supervision, library, social media and administrative resources ensuring parity of access regardless of physical location. Our infrastructure for PhD research meets or exceeds the requirements of all Research Councils and Quality Assurance Agency standards. As well as at least two supervisors, students are assigned a mentor who they meet regularly. Progress and training is monitored through six-monthly progress reports, with initial MPhil registration upgraded to PhD following satisfactory performance via a presentation and mini-viva assessed independently of the supervision team. Progress and probationary reports are seen and approved by the Associate Dean and are coordinated and supervised by the University's Research Degrees Office. Full-time students are allocated workspace and a networked computer, and all students have full access to the Library, computing resources and printing. A hardship fund and other financial and pastoral support are available via the Research Degrees Office.

Students have the opportunity to attend national conferences, and at least one international one during their term. Several OU students have won prizes at national and international conferences (e.g. Mottram, Best student presentation prize at the William Smith meeting 2013 and Pangala, British Ecological Society, Anne Keymer Prize 2011). Students are expected to attend weekly CEPSAR seminar series appropriate to their subject area, as well as journal clubs that are run in research groups and disciplines such as Astronomy, Cosmochemistry and Isotope Geochemistry.

We are a member of the NERC doctoral training partnership consortium, CENTA, with Birmingham, Leicester, Loughborough, and Warwick universities. In 2013 we joined the SEPNet consortium, a Physics network, and have participated in several European training networks including Lassie and PIMMS.

d. Income, infrastructure and facilities

Since 2008 we have secured £51.2m external funding, £26.4m direct funding and £24.8m in-kind funding. Direct funding included £17.9m from RCUK, £3.2m from the EU, £2.8m from charities and learned societies, £1.3m direct from industry, and £0.7m from government bodies such as Defra and the Environment Agency. Our in-kind funding included £20.2m from ESA and UKSA, and £3.7m telescope time. The University strategic support of research includes investment in baseline research support staff, and the provision of a high-quality laboratory infrastructure including recent upgrades to microbiology, micropaleontology and environmental science suites. The Centre for Electron Imaging has increased its laboratory footprint in recent years and, in addition to undertaking research in the development of CCD and CMOS technologies for highly resilient devices used in high-resolution imaging during space missions, now delivers masterclasses and training to industrial partners.

The Faculty sustains a 750-core high-power computing cluster shared with the Maths, Computing and Technology (MCT) Faculty, supported by a project officer based in Science and another in MCT. The Faculty research design and engineering facility, capable of producing a range of in-house bespoke experimental equipment, is supported by a laboratory manager, a project officer and two technicians, and we use the cross-faculty electronics workshop.

Key details of these facilities are listed below:

Ecosystems and Sustainability: Facilities are overseen by a lab manager, five externally funded project officers and seven externally funded technicians. The facilities include a suite of four environment chambers capable of varying atmosphere composition (e.g. CO_2) in long-term experiments; category 2 microbiology labs; biodegradability laboratories (including bespoke respirometers and biodegradability test equipment); ICP-AES; Hg analysis; ion chromatography;

total organic carbon and nitrogen, and a suite of GCMS capable of molecular analysis.

Earth Science: A Cameca SX100 electron microprobe supported by a project officer, and an ICPMS with laser ablation and associated chemistry labs. Our radiogenic and stable metal isotope mass spectrometry facilities include a suite of ultra-clean labs, two 'Triton' thermal ionisation mass spectrometers, and one 'Neptune' multicollector ICPMS mass spectrometer currently supported by a project officer and several project-based staff, analysing isotopes of Sr, Nd, Cr, Os, Mo, Te, Fe, U, and Th; noble gas analysis and Ar-Ar dating capability includes two mass spectrometers with automated gas clean-up and laser extraction supported by an externally funded project officer and a technician.

Planetary and Space Science: Cosmochemistry research facilities are overseen by a laboratory manager and cosmochemistry research technician and include a state of the art CAMECA nanoSIMS supported by a project officer and technician; a FIB SEM supported by a project officer; mass spectrometric analysis of light element stable isotopes of C, O, N and H including compound-specific analysis supported by the laboratory manager and a part-time project officer. Space science facilities include a High Velocity Impact Laboratory with a unique vertical firing capability, and planetary environment laboratories supported by a technician and project-based staff. Space instrumentation development laboratories are supported by three project officers, who support space mission instrumentation and translational research activities. Large projects and space mission activities are also supported by two project managers.

Astronomy: Facilities include state of the art astrochemistry laboratories hosting the UK's only microgravity facility and a suite of apparatus capable of simulating conditions in the interstellar medium and on planetary/lunar surfaces, supported by a laboratory manager and a technician who also support physics and chemistry laboratories. The Astronomy group is also a major user of the University's central computing cluster.

We have achieved a significant increase in non-RCUK income streams since 2008, including several ESA-funded projects for which we tendered successfully. For example: WatSeN – a project to design a suite of instruments for a mole to be deployed as part of the Geophysics and Environment Package on ExoMars; DUSTER – a project to design a space-ready device to remove dust built up on photocells during space missions; and CAFÉ – Concepts for Activities in the Field for Exploration some of which feed into an impact case study (CS6).

The University also supports online library services that provide staff and research students with online access to a world-class collection of over 85,000 academic journals. Our online services include one of the UK's largest open-access research repositories, Open Research Online, with over 23,000 OU publications and about 40,000 visitors a month from around 200 countries. The University also includes substantial research content in our iTunes U site, one of the largest and most popular in the world; and pioneering public engagement sites such as iSpot and the Evolution Megalab. The Wolfson Foundation's initial £1m investment in our OpenScience Laboratory was matched by £2m of University funding to provide a world-leading capability for online science teaching and research, able to excite a new generation of students across the world. Our public engagement commitment has been recognised with RCUK funding as a Public Engagement with Research Catalyst to embed public engagement with our research at all levels and enabling us to implement a rewards scheme recognising researchers for excellence in public engagement, issue calls to researchers for projects on public engagement with research, and provide structured opportunities for user communities and other stakeholders to engage with OU researchers and research. The OU is also a signatory to the NCCPE Manifesto for Public Engagement.

e. Collaboration and contribution to the discipline or research base

Our collaborations include leadership of some major European projects such as the Floodplain Meadows Partnership funded by the Esmée Fairburn Foundation (impact case study CS1), EUROPLANET, linking the research infrastructures of more than 100 laboratories in Europe and around the world, LASSIE (Laboratory Astrochemical Surface Science in Europe), and the ERMITAGE Project (Enhancing Robustness and Model Integration for The Assessment of Global Environmental Change).

We have also contributed to The Open University's remote telescope and virtual microscope assets during the development of the OpenScience Laboratory and are working with charities such as the Daphne Jackson Trust and Earthwatch to develop citizen science.

We make significant contributions to public debate on climate change (*Brandon*), and to the development of the next IPCC report on climate change (*Gauci, Edwards*). We also made a significant contribution to the debate on natural resources, specifically the limits of helium as a natural resource, and uranium and thorium for nuclear power (*Nuttall*).

Our industry collaborations include the Centre for Electronic Imaging, which supported e2v's CMOS capability and associated jobs creation by contributing to its successful £3.8m Regional Development Fund application. Other translational research, funded by BAE Systems, has resulted in an atmosphere analyser which has been tested at sea. A series of projects with industrial partners in the UK Space sector indicate significant benefit in securing business and safeguarding jobs (case study CS6).

Our work on biodegradation and waste management has influenced industry and government agencies, helped to quantify the biodegradability of municipal waste, and attracted industrial partnerships for testing and consultancy (impact case study CS5). We have also developed and delivered analytical services for industry from several of our research laboratories, offering physical testing, bespoke measurements of chemical composition, and Ar-Ar dating.

We have strengthened links with external partners including the Rutherford Appleton Laboratory (joint research students), our Affiliated Research Centres (joint research projects with HR Wallingford, including a £16m project co-funded by HEFCE to use smart city technologies to manage demand for water, energy and transport) and through involvement in doctoral training partnerships (including the CENTA NERC DTP and SEPNet, the South East Physics Network).

We also make wide-ranging contributions to the academic community at different levels, from leadership of learned societies and national awards, to our support for special interest groups and engagement activities.

Role in Research Councils, learned societies or professional bodies:
EPSRC Peer-review college: *Mason*. NERC: Peer-review college: *Charlier*, *Coe, Cohen, Gauci, Kelley, Mason, Sherlock*; Chair of award panels: *Brandon, Rogers*; Committee adjudicating call for 'new technologies for environmental applications' co-chair: *Kelley*; MethaneNet director: *Gauci*; Centre for Ecology and Hydrology: Strategy group: *Gowing*. STFC: Astronomy Grants Panel: *Franchi, Green*; projects peer review panel: *Holland*; Ernest Rutherford: fellowships panel *Fraser*, grants panel *Franchi*; Education Training and Careers Committee: *Haswell*; ING Time Allocation Committee: *Clark*. NASA: Cosmochemistry Grants Panel: *Gilmour*. Geological Society: Council: *Coe, Rogers*; Science Committee: *Harris*; Publications Committee secretary: *Rogers*; Higher Education Network treasurer: *Argles*; Climate Change Committee: *Cohen*, Metamorphic Studies Group: chair, *Harris*; treasurer, *Warren*; Volcanic and Magmatic Studies Group: treasurer, *Widdowson*; Geochemistry Group of Geological & Mineralogical Societies: Chair, *Anand*. Meteoritical Society: President: *Grady*. Royal Astronomical Society: Vice President: *Norton*; Research Fellowship Panel: *Norton;* Council: *Fraser, Norton*; Honorary Auditor: *Haswell*. NASA Lunar Science Institute: UK node chair: *Anand*. Astrobiology Society of Britain: Committee: *Olsson-Francis*. British Ecological Society: Tropical Ecology Special Interest Group chair: *Gosling*.

National or international advisory board membership:
STFC: Solar System Advisory Panel, chair: *Grady*; Particle Physics, Astronomy and Nuclear Physics Science Committee (PPAN): *Franchi*; Near Universe Advisory Panel: *Franchi*. UKSA: Aurora Advisory Committee: *Balme*; Advisory Board for ELIPS (microgravity) and ISS scientific exploitation: *Fraser*; Technology pathfinder programme Committee: *Holland*; UKSA Solar Orbiter Oversight Committee: *Holland*. International: NASA ATP 2012 review panel: *Kolb*; Japan: RIKEN X-ray laser detector Advisory Group: *Holland;* European Parliament Biodiversity Committee and reviewer panel: *Gowing*; IPCC Fifth assessment Report (AR5) Climate Change 2013 The Physical Science Basis, expert reviewer: *Gauci*; International Subcommission on Jurassic Stratigraphy: *Coe*; Ramsar Convention (International Treaty), Science and Technical Review Panel on 'Wetlands, Carbon and Climate Change' invited expert: *Gauci*; IAVCEI Commission on Volcano-Ice Interactions, Science Advisory Panel: *McGarvie*. UK National Committee for Antarctic Research: *Brandon*; Wildlife Trust for Beds, Cambs & Northants: Trustee, Director and Chair, *Gowing*; Great Fen Project consultant: *Gauci*, Joint Technical Advisory Group: *Gowing*; Natural England Agri-environment Scheme, external assessor: *Gowing*.

Significant research collaborations, and consortia memberships:
Chair, ESA Topical Team for Exploitation of Planetary Materials: *Anand.* Senior Research

Scientist, Planetary Science Institute, Tucson, USA, Visiting lecturer, Université de Paris Sud: *Balme*. Lead, PACS observations in Herschel Key Program 'The Evolution of the Interstellar Dust': *Bernard-Salas*. Visiting researcher, Auckland University and GNS: *Blake*.
External researcher on the Spanish research networks `High mass stars in the infrared' and `Multiplicity and evolution of massive stars'; Invited member of the ISSI-funded international research team on the physics of star clusters; eMerlinCOBRaS legacy survey team; VISTA-VVV and VLT/FLAMES 30 Dor legacy surveys; *Clark*. DESIRE (UK - French collaboration) management team: Invited fellow, Isaac Newton Institute for Mathematical Sciences, Cambridge: *Edwards*. ESA Science Study Team for MarcoPolo-R M3 mission; NASA Genesis Science Team; NASA OSIRIS-REx Science Team; UKCAN management committee: *Franchi*. SPICA SAFARI consortium Co-I of the ICAPS/ISS icy-dust aggregation experiment; Co-I, E-ELT METIS instrument and Member of METIS UK Science board: *Fraser.* Co-I, Boltysh Meteorite Impact Project: *Gilmour.* Co-I, Darwin Initiative Project, South African National Botanical Institute: *Gowing*. Chair, UKCAN management committee: *Grady.* ESA Science Study Team member and UK lead for MarcoPolo-R M3 mission; Co-I Rosetta GIADA instrument; NASA Stardust NExT Science Team; EU FP7 NEOShield consortium: *Green*. Co-I Rosetta MUPUS instrument; JAXA visiting associate professor; Joint Science Team for the Japanese Hayabusa-II mission: *Hagermann*. Co-leader, international expedition to eastern Tibet with China University of Geosciences, Wuhan: *Harris*. Co-lead PLATO Public Engagement WP; SuperWASP exoplanet discovery consortium: *Haswell*. Co-I, Euclid VIS; Co-I, Gaia Data Processing & Analysis Consortium; Co-I, JUICE Janus Camera: *Holland*. Co-I, Boltysh Meteorite Impact Project: *Kelley*. SuperWASP exoplanet discovery consortium: *Kolb*. Co-I, NASA MRO Mars Climate Sounder; Co-PI for entry, descent and landing science on ESA ExoMars EDM; UK Lead developer of the ESA Mars Climate Database: *Lewis*. Chair, Europlanet consortium; Chair, ESF Cost Action 'The Chemical Cosmos'; Co-chair, EU Framework VII E-infrastructure VAMDC, LASSIE, PIMMS, SUPP@VAMDC, ARGENT: *Mason*. Co-lead PLATO Public Engagement WP: *Norton*. UK PI, EXOMars TGO 2016 NOMAD instrument; Co-I, ExoMars 2016 lander AMELIA and DREAMS instruments; Co-I, ExoMars 2018 Rover PanCam instrument: *Patel*. Co-I, NASA MSL Participating Scientist team: *Schwenzer.* PI, Herschel NEP legacy survey; Co-PI, e-MERLIN gravitational lensing legacy survey; Co-PI, AGN working group of H-ATLAS; UK coordinator, JCMT Nearby Galaxies Legacy Survey; Coordinating team for JCMT SCUBA-2 All-Sky Survey; Lead of lensing WP and Galaxy Evolution WP in ESA Euclid Galaxy/AGN and Strong Lensing WGs; Co-I ESA-JAXA SPICA: *Serjeant*. Survey Design Lead, management team member, SDSS-IV MaNGA Survey; Co-PI of AAOmega-SDSS-UKIDSS (AUS) survey: *Wake*. Chair, LOFAR Galactic Science Working Group; Co-I, ESA PLANCK-HFI; Management Board, LOFAR-UK; Co-I ESA-JAXA SPICA; Co-proposer ESA NEAT; Co-proposer ESA EcHO: *White*. PI, Rosetta Ptolemy instrument: *Wright*.

Journal editorships:
Geophysics, Geochemistry, Geosystems: *Blake*. Associate Editor, Meteoritics and Planetary Science: *Franchi*. Editorial Board, Impact Studies (Springer Verlag): *Gilmour*. Editor, monthly international Exoplanet Newsletter: *Norton*. Editorial Board, Journal of Physics B: Atomic, Molecular and Optical Physics, European Journal of Physics, Comments in Atomic and Molecular Physics; Editor in Chief European Journal of Physics D, Editor EPJ Techniques and Instrumentation: *Mason.* Editor, Journal of the Geological Society of London; Editor, Central European Journal of Geology: *Sherlock*. Editor, Bulletin of the British Ecological Society: *Sayer*. Editorial Board, Advances in Astronomy, and Associate Editor of The Journal of Astronomical and Astrophysical Research: *White*.

Awards:
Commander of the Most Excellent Order of the British Empire: *Grady*. RAS Team Award (SuperWASP): *Norton, Haswell*. Ecological Engagement Award, British Ecological Society: *Silvertown*. Murchison Fund, Geological Society: *Sherlock*. Sir Arthur Clarke Award for Team working on the HERSCHEL-SPIRE space mission: *White*.