2018 - AAP Project Summaries (permission to publish confirmed)			
Project number	**PI / Lead Contact**	**PI institution**	**Project title (with link if available)**
1	Prof Martin Barstow	Leicester	Large UV/OPTICAL/IR Surveyor (LUVOIR)
2	Dr Justin Bray	Manchester	Cosmic Ray Observatory at Murchison (CROM)
3	Prof Michael Brown	Manchester	The Simons Observatory:UK B-mode telescope
4	Prof Michael Garrett	Manchester	UK National Radio Astronomy Observatory (UKNRAO)
5	Prof Walter Gear	Cardiff	A new wide-field submm camera on the James Clerk Maxwell Telescope (JCMT)
6	Dr Keith Grainge	Manchester	Phased Array Feed receiver for the Lovell Telescope
7	Dr Pamela Klaassen	UKATC	The Atacama Large Aperture Submillimetre Telescope (AtLAST)
8	Prof Stefan Kraus	Exeter	Planet Formation Imager
9	Dr Nathan Mayne	Exeter	ExoMet
10	Prof Richard McMahon	Cambridge	4MOST: megascale wide field multi-object optical spectroscopy in the Southern Hemisphere
11	Dr Sami Mikhail	St Andrew's	Comparative Exoplanetology
12	Prof Simon Morris	Durham	Blue MUSE
13	Prof Nikolay Nikolov	Exeter	Precision wide-field spectrograph for atmospheric characterisation of exoplanets from the ground
14	Dr Kieran O'Brien	Durham	Giga-z
15	Dr Kieran O'Brien	Durham	KIDSPEC
16	Dr Kieran O'Brien	Durham	TRICKSI – the TRansient Identification Camera using KID Superconducting Instrumentation
17	Dr Ian Parry	Cambridge	A 12U CubeSat (SUPERSHARP) for direct imaging of exoplanets
18	Prof Dimitra Rigopoulou	Oxford	The Far-Infrared Spectroscopic Explorer (FIRSPEX)
19	Prof Giorgio Savini	UCL	PRISTINE-UK
20	Dr Francesco Sankar	Soton	Pioneering Panoptic Spectroscopy -- UK participation in SDSS-V
21	Dr Danny Steeghs	Warwick	Gravitational-wave Optical Transient Observer (GOTO)
22	Prof Iain Steele	LJMU	New Robotic Telescope (NRT)
23	Dr Marcell Tessenyi	UCL	Twinkle – a mission to unravel the story of planets in our galaxy
24	Prof Mark Thompson	Herts	The Receiver Factory: SKA Band 5 receivers for MeerKAT, AVN and e-MERLIN

25	Dr Amaury Triaud	Birmingham	Extending the search for nearby Earth-like worlds to the Northern Hemisphere
26	Dr Ruben Sanchez-Janssen	UKATC	CASTOR
27	Dr Colin Snodgrass	Open	GravityCam
28	Prof Richard Ellis	UCL	A Dedicated Wide-Field Spectroscopic Survey Telescope
29	Dr Jonathan Eastwood	ICL	Virtual Centres of Excellence (ViCE) Programme

Note

The Astronomy Advisory Panel (AAP) received a total of 47 project summaries in response to the 2018 Priority Projects exercise. Permission to include the above summaries has been given. It is hoped to add to this in due course.

Priority projects –

summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: Large UV/OPTICAL/IR Surveyor (LUVOIR) **Principal Investigator/Lead Contact: Prof Martin Barstow**

Project outline

Large, flagship space missions such as HST or JWST require decades of development. HST was first conceived in the 1960s, while JWST planning began before HST was launched. JWST and its successor WFIRST are yet to be launched, but ideas for the next advance are now being developed as part of the NASA science & technology definition studies for the US Decadal Survey. One of four studies is for a 10-15m class space telescope, the Large UV/optical/IR Surveyor (LUVOIR). LUVOIR is one of the most exciting astrophysics missions ever conceived, to answer the question “Are we alone in the Universe”. It will be able to detect and characterise exoEarths in orbits within the habitable zones of nearby stars, through a combination of direct imaging and low-resolution spectroscopy, and search for spectroscopic signatures of life. In addition, it will be a general purpose observatory with a broad instrumentation suite including: coronographic imager and low-resolution spectrograph; high resolution UV spectrograph with coronograph; wide field imager; multi-object spectrograph; polarimetric spectrograph.

Scientific case

The key science goal, driving mission requirements, is the search for Earth-like planets within the habitable zones of solar-like stars and spectroscopic identification of bio-signatures. The survey will extend out to 20pc from the Sun, a volume needed to identify ~100 candidate systems and yield statistically interesting results on the frequency of life-bearing planets. The broader science goals promise to transform astronomy, from studies of the earliest seeds of galaxies (>10 billion years ago), to the birth of galaxies like the Milky Way (6–10 billion years ago), to the birth of stars like the Sun in the Milky Way (5 billion years ago), culminating in the birth of planetary systems like our own (now) and the exploration of our own planetary system. At each epoch, the radically sharp vision and sensitivity of a large space telescope will reveal things previously unseen, including how galaxies, stars, and planets do their part to establish the conditions for life.

Leadership & potential team members

A large UVOIR telescope will need to be a multi-agency mission combining at least two partners. While it can build on the significant heritage from the HST and JWST, there will be significant development programmes required to reach minimum TRL levels for the subsystems by the mid-2020s, to fly a mission in the mid-2030s. Investment in these is essential to position UK institutions to participate in this mission. Significant expertise in several subsystems provides an important opportunity for the UK, including: detector systems; flexible electronics; segmented mirror co-phasing techniques; deformable optics for applications in space; free form optics manufacturing (for complex optics / coronagraphs).

The proposer of this project is the UKSA observer on the NASA study and coordinates European interest in the project. Participation in technology development and instrument programmes will be of interest to a range of space and ground-based instrumentation groups, including: University of Leicester, ATC Edinburgh, UCL/MSSL, Open University, Cardiff University. There is also significant interest in the science programme from exoplanets to galaxy evolution. There are several UK members of a Europe-wide consortium supporting the project, including: S. Aigrain, R. Davies, C. Lintott – Oxford, A. Ferguson, B. Biller & C. Evans, Edinburgh, B. Gaensicke – Warwick, S.L. Casewell – Leicester, S. Rugheimer – St Andrews, C. Snodgrass – Open University, C. Knigge – Southampton,

Societal and Economic Impact

This project will involve the development of cutting edge technology to achieve its science goals. These challenges will require industrial contributions (e.g. Teledyne for CCD sensor development) and contribute to economic impact through that route. Sensor technologies in particular have a long track record of feeding applications far beyond the space industry.

The search for life the Universe is a fundamental piece of research that excites everyone and provides huge scope for public engagement. The results will potentially have a fundamental philosophical impact which will require significant engagement and discussion in advance of the mission.

Scale of investment

LUVOIR will be a multi-billion pound/dollar/euro flagship project. It is likely to be led by the US, with a significant contribution from ESA and other partners, following the HST/JWST model. Both missions are also good examples of UK contributions (FOC and MIRI respectively). Strong UK heritage in sensors and spectrograph systems would provide natural leadership of an instrument consortium along MIRI lines. Such a contribution will most likely be medium to large in scale, dependent on the number of international partners.

Priority projects – summary outline for Advisory Panels

Project Name: Cosmic Ray Observatory at Murchison (CROM)
Lead Contact: Justin Bray

Project outline

The objective of this Project, CROM, is to exploit the low-frequency component of the Square Kilometre Array (SKA), located in Murchison in Western Australia, to study high-energy cosmic rays. The SKA, a £650m radio telescope now nearing the end of its design phase, can function as a cosmic-ray observatory if it is enhanced with relatively inexpensive particle-detection hardware. The scope of CROM is the construction, deployment and commissioning of this hardware (based on current preparatory work) and its operation as a cosmic-ray science instrument.

Key stakeholders are the SKA Organisation; the High Energy Cosmic Particles Focus Group, which oversees this aspect of the SKA's science programme; the University of Manchester and Karlsruhe Institute of Technology, which are developing the particle-detection hardware; and Curtin University, which operates the Murchison site.

The exceptional characteristic of CROM will be the precision of its measurements, extending the current success of radio cosmic-ray measurements. This dictates CROM's science drivers: to resolve the composition and spectrum of cosmic rays around the critical transition from galactic to extragalactic origin, and to search for extremely high-energy gamma rays from the galactic centre.

Scientific case

CROM will allow unprecedented precision in the reconstruction of cosmic-ray air showers, currently a limiting factor in studies of the cosmic-ray composition and spectrum. In particular, it aims to distinguish between individual nuclear species in the energy range 10^{17}-10^{18} eV, and to identify any component of gamma rays among them. The major competitors in this energy range are the HEAT subarray of the Pierre Auger Observatory, the IceTop array, and the cosmic-ray mode of the LOFAR radio telescope, which are likely to undergo further upgrades in the near future.

CROM can achieve these goals on a lower budget by making use primarily of infrastructure built for the SKA, which will be the world's most extensive array of radio antennas. The SKA can be used for CROM commensally, with no impact on its operation for other science goals. CROM can also piggyback on data-transfer and computing infrastructure built for the SKA, in comparison to which its requirements are trivial.

Leadership & potential team members

Preparatory work for CROM is being carried out at the University of Manchester, and there is strong UK involvement in the SKA, which has its headquarters at Jodrell Bank Observatory. Participation in CROM will be driven by the SKA High Energy Cosmic Particles Focus Group, which includes both senior figures (Heino Falcke, Ron Ekers) and up-and-coming researchers such as its current chairs (Stijn Buitink, Justin Bray).

Societal and Economic Impact

CROM will (as it already has, in its preparatory phase) engage students in the development of cutting-edge high-frequency opto-electronic systems, equipping them to work in fields ranging from communications to biological sensing to radiological medicine. The key technology exploited in the particle-detection hardware is the silicon photomultiplier (SiPM), a class of device undergoing rapid development, on which project personnel work with and provide feedback to representatives from several manufacturers. Assembly of the hardware will involve working with a range of local firms, giving them experience with precision optical systems.

The operation and exploitation of the assembled CROM hardware will be an exercise in big data management and analysis, developing the participants skills and conceptual knowledge of this field. By bringing in experts to examine low-level radio data, it will also feed back into the success of the (much larger) SKA project, as similar efforts have for the LOFAR telescope in the past.

The UK public are highly responsive to the renewal of cosmic-ray science in this country, a field in which it was once a global leader. The ~160,000 annual visitors to Jodrell Bank Observatory will be able to learn about this work both in tours and through an additional exhibit in the Discovery Centre.

Scale of investment

CROM is a small-scale Project, with a projected cost of ~£1m for the particle-detection hardware, and an additional similar amount for its initial operation and exploitation, for a total of ~£2m. The UK would be the primary funder, but Australia, as the host country, would also be expected to make a contribution. For preparatory work, a grant application to the Australian Research Council for funding of £107k, with an additional contribution from Curtin University, is currently at an advanced stage (positive reviewer comments received; awaiting confirmation). If successful, it is likely that further funds could be solicited from these institutions for the expansion to the full-scale CROM.

Science & Technology Facilities Council

Priority projects – summary outline for Advisory Panels

Project Name: The Simons Observatory:UK B-mode telescope
Principal Investigator/Lead Contact: Michael Brown

Project outline

The **Simons Observatory:UK B-mode Telescope (SO:UKBT)** is a proposal for a future UK Cosmic Microwave Background (CMB) Polarization Telescope. It will operate as an integral part of the wider US-led Simons Observatory (**SO**, first light expected in ~2021), which will consist of multiple telescopes sited in the Atacama desert in northern Chile. Such a major contribution to the SO is **the cornerstone of the UK CMB community's future roadmap**, as outlined in the community's 2016 white paper.[1] The **objectives** of the **SO** are (i) more precise measurements of secondary effects on the CMB (weak gravitational lensing, Sunyaev-Zel'dovich effects) and (ii) more precise measurements of CMB polarisation. The **scientific drivers** for (i) are to constrain new physics such as neutrinos, dark matter and dark energy, while objective (ii) will facilitate a range of early Universe science, with a particular focus on searching for the B-mode polarisation signal expected from inflation in the early Universe.

The **scope** of the envisaged UK-based work includes instrument development, deployment and operations, data processing and analysis, and theoretical support. The **key stakeholders** include the astronomy and astroparticle communities, both within the UK and internationally. For example, the 2013 and 2015 *Planck* cosmological parameters papers have each accrued more than 5000 citations to date, demonstrating that the results of CMB experiments reach far beyond the immediate CMB community. UK **areas of excellence** include instrumentation, analysis and theory support. The UK has a long track record of innovation in CMB instrumentation, having deployed a series of cutting-edge experiments throughout the last four decades (e.g. the ground-based **VSA** and **QUaD** experiments, and the UK's major contributions to the ***Planck*** satellite). In tandem, many of the most important developments in CMB theory and analysis techniques were developed in the UK.

Scientific case

There is a general international consensus that the scientific objectives listed above are the key targets for future CMB experiments. For example, understanding the **physics of neutrinos** and **dark energy** are amongst the highest priority objectives for the international particle physics and cosmology communities respectively, while a detection of the primordial B-mode signal would provide us with **a probe of physics at Grand Unified Theory (GUT) energy scales** (~10^{16} GeV), far beyond the energies accessible to ground-based particle physics experiments.

Achieving these objectives will require orders-of-magnitude improvements in instrument sensitivity over current capabilities. Recognising this fact, the US CMB community has come together and agreed to work towards a **single future ground-based experiment**, termed "CMB Stage 4" (**CMB-S4**), encompassing arrays of telescopes located at multiple ground-based sites, with first observations expected ~2027. CMB-S4 was strongly endorsed by the (US) Particle Physics Project Prioritization

[1] Available at http://www.jb.man.ac.uk/~mbrown/UK_CMB_White_Paper.pdf

Panel (P5) in their 2014 report. It is now seeking funding and is welcoming international partners.

The **SO represents** a stepping-stone between the currently operating "Stage 3" experiments (e.g., BICEP, PolarBEAR, ACT, SPT) and CMB-S4. Crucially, the project is already funded (~$70M from the Simons and Heising-Simons Foundations), making it **the only "beyond Stage-3" experiment currently funded**, and construction is underway. The SO:UKBT concept envisages building and operating a small aperture facility that would provide 50% of the SO's total sensitivity to the primordial B-mode signal. This constitutes a major enhancement of the SO and would have a **lasting international impact** in terms of the UK gaining seats at the "top table" of the SO project. Moreover, the SO:UKBT will be constructed as a "CMB-S4-ready" telescope, capable of accommodating CMB-S4-grade receivers, once these have been developed. Hence the SO:UKBT will also leverage **a leading role for the UK in CMB-S4**.

Exploitation of the SO:UKBT will require considerable computing infrastructure. While much of the main pipeline analysis will be conducted using HPC facilities in the US (e.g. NERSC), UK scientists would still require access to local HPC facilities for development and testing purposes. Dedicated facilities or the use of central facilities (e.g., National Data Centres) would both be viable options. A rough estimate for the SO:UKBT's computing requirements, based on purchasing a dedicated resource, would be **~£0.5M**.

Leadership & potential team members

The SO:UKBT project will be conducted by a UK consortium, currently including groups at Cardiff, Cambridge, Imperial, Manchester, Oxford and Sussex Universities. Within the wider SO, UK scientists already co-lead three (out of five) science working groups, while there is one UK scientist on the SO Theory and Analysis Committee. It has also been agreed with the SO collaboration that, if the UK were to contribute at the ~20% level discussed here, this would leverage significant UK representation on the SO Planning Committee (Executive Board), which is the highest decision-making body within SO.

Societal and Economic Impact

The CMB addresses topics in cosmology and astrophysics that **greatly appeal to the wider public**. For example, UK researchers within the *Planck* project put on exhibits at the Royal Society Summer Science Exhibitions in 2009 (jointly with *Herschel*), 2013, and 2016, each of which received 3000–5000 visits in person, and several times that in online content. In terms of **capability & skills development**, PhD students working in this field are highly trained in state-of-the-art technology development and advanced data analysis techniques. Many pursue successful careers in industry (e.g. in engineering, finance and health physics) where the transferable skills acquired during their PhD are highly valued.

An example of an **industrial partnership** resulting from UK-based CMB research is the close working relationship between the Cardiff group and **QMC Instruments** (www.terahertz.co.uk). A major joint development activity with this SME has been the production of a new THz camera for personnel and cargo scanning, with obvious applications in the security sector. This activity builds on CMB technology and has led to the formation of a new spin-out company, **Sequestim Ltd**, which is currently developing a demonstration unit to be deployed in airports. Transition-Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs) are both **key enabling technologies** for the CMB area. The UK has world-leading fabrication capabilities in both (at Cambridge and Cardiff). Scope for wider application includes multiple areas of astrophysics in addition to industrial applications (e.g. the security scanning described above).

Scale of investment

The SO:UKBT is a medium-scale project. It requires STFC funding at the **~£15M** level, over a 5-year period, beginning in 2019/20. At such a level, the UK would be contributing **~20%** of the total SO.

Priority projects – summary outline for Advisory Panels

Project Name: UK National Radio Astronomy Observatory (UKNRAO)
Principal Investigator/Lead Contact: Mike Garrett, Paul Alexander, Michael Jones

Project outline

We propose to establish a UK National Radio Astronomy Observatory (UKNRAO), to provide a coherent approach to the UK's radio astronomy programme leading into the era of the Square Kilometre Array (SKA). The UK has established a leading role in the science and engineering of the next generation of radio telescopes, in particular the SKA but also e-MERLIN, LOFAR and other smaller-scale experiments. The recent STFC review of Radio Astronomy reinforced the previous very strong support both for the science but also the breadth of the UK involvement, while stressing the need for continued strong community engagement and science support. The UKNRAO would bring leading University Groups, National Labs and industry together in a partnership with STFC to provide a coherent approach to:

- Focussing UK leadership in radio astronomy in order to compete with the best institutes world-wide and ensure best return to the UK from its investment in the SKA,
- Scientific and data analysis support for the UK science community for the SKA (i.e. UK-node of a Regional Science Centre), the upgraded-MERLIN+, EVN, LOFAR2.0, ALMA and other facilities,
- Operations of e-MERLIN+/VLBI and the LOFAR2.0-UK station,
- Engineering development for the SKA and e-MERLIN+ (noting the likely emergence of SKA National Technology Centres),
- Support of specific science facilities (e.g. Lovell, AMI, C-BASS),
- Core funding to guarantee the UK's technical capability and to enable a proper career structure for the young engineers and scientists who are delivering the UK's leading role in the SKA, including facility fellowships to support the next generation of scientists and engineers specialising in radio astronomy.

We envisage a structure based on the highly successful model for the Alan Turing Institute. UKNRAO would be a company limited by guarantee, with core members consisting of STFC plus the universities with key relevant technical capabilities. All UK universities would be eligible to join as members. STFC would fund activities of all members through its usual grant mechanisms. Technical activities would be distributed amongst the members, but co-ordinated via the UKNRAO Board.

Scientific case

The science case for the SKA, e-MERLIN+ and other UK radio astronomy projects are well established and widely acknowledged to represent leading science challenges, from following the baryonic history of the Universe since before the first stars and galaxies to using pulsars as networks of natural clocks for innovative experiments in gravitational physics. Here we consider the added scientific value a National Observatory offers. The UK has always been one of the leading nations in radio astronomy but historically the capability to design, build and operate radio telescopes has been distributed in the Universities, at Cambridge, Manchester and more recently Oxford. As the scale and cost of facilities increases, economies of scale and co-ordination have become more important. The SKA development programme has led to a new and highly successful degree of co-ordination between the UK institutes, industry and funding agencies. The UKNRAO would formalise and enhance this co-ordination, which is essential given the scale not only of the design and construction of new facilities, but of the computing infrastructure needed to deliver science from them. The SKA is at the cutting-edge of data science in terms of both the *volume* and *velocity* of data (the SKA will

deliver science-ready data at an average rate of 1 PB per day). A key aspect of the new observatory will be the development of new techniques, and the scientific support and training of the community in an end-to-end process that will focus on the preparation and exploitation of pipeline data products, advanced peta-scale data analytics and image-processing technologies. This will enable the widest possible science participation in the most challenging science areas.
A coherent UK approach and support for SKA, EVN and e-MERLIN as our own leading facility will enable truly novel science projects, as explored in the recent SKA/e-MERLIN synergy workshops. Our proposed structure will provide a flexible partnership for the UK to continue to play a leading role in technical and engineering developments for the SKA, e-MERLIN+, LOFAR2.0, MeerKAT and other facilities. This will be important in an era in which the SKA project will wish to deal with partner countries via a single point of contact. The UKNRAO would also play a key role in coordinating new radio astronomy experiments – the present call for proposals has produced responses for a wide variety of new projects, including eMERLIN+, Receiver Factory (MeerKAT Band 5), UK Simons Observatory, UK-LiteBIRD, NextBASS, and Cryogenic PAFs, several of which already have common proposers and key technologies. UKNRAO would provide a mechanism for technical and scientific co-ordination between these projects, making best use of total resources. The scale of computing infrastructure required for SKA support in particular is very significant with even modest-scale science projects requiring peta-scale support. We strongly support the concept of a common Cloud and HPC infrastructure on which the domain specific requirements are developed as is currently being delivered by IRIS and Dirac.

Leadership & potential team members

The core members of UKNRAO would be STFC and Oxford, Cambridge and Manchester Universities. Membership would be open to all UK universities and additional members would likely include Bath, Bristol, Herts, Durham, Edinburgh, Glasgow, Leeds, Southampton, Sussex, Cardiff, UCL, and UCLAN. A broad Board membership from the UK community will ensure that the UKNRAO maintains relevant and up-to-date science goals, while core membership by STFC (representing national labs as well as funding) plus the technical lead universities will ensure focus and efficiency in delivery.

Societal and Economic Impact

Radio astronomy has a unique societal and economic impact through its combination of high-impact science and advanced technology. Radio astronomy has a very high existing national outreach profile particularly through activities based at Jodrell Bank, and there are many existing radio astronomy-based international development projects (Newton Fund and GCRF) with activities in Africa, Mexico, Thailand and Columbia. These will all be enhanced and supported by the establishment of the UKNRAO. Industrial applications and spin-offs include continued development of innovative software solutions for cloud computing and advanced data analytics. The UK is currently leading SKA engineering developments for radio astronomy that are closely aligned with the telecoms industry, and future developments will continue the spin-out/start-up success we have demonstrated through the SKA project, including new phased-array telecoms technology, high-speed digital processing spin-outs etc.

Scale of investment

This is a medium-scale proposal. We envisage the observatory funding incorporating both existing and newly proposed projects, as well as including core funding for staff to ensure continuity of capability. For example, a core guaranteed funding of £6M/yr (£30M over a five-year period) would encompass the existing e-MERLIN+ operations budget of ~£2.5M/yr, but also provide access to other facilities and coherent science support across SKA, e-MERLIN, ALMA, LOFAR2.0, EVN/JIVE, MeerKAT etc., incorporating the anticipated UK contribution to an SKA Regional Centre, plus support for core engineering and science teams. Specific projects would still be able bid to STFC or other agencies for support beyond this level. In addition to STFC funding, we also expect income from the SKA Observatory Development Programme (expected to be of order €20M/yr globally) and international funding (European or its replacement) for cooperative experiments – current income from these sources for the relevant partners exceeds €2M/yr.

Priority projects – summary outline for AdvisoryPanels

Project Name: A new wide-field submm camera on the James Clerk Maxwell Telescope (JCMT).
Principal Investigator/Lead Contact: Walter Gear, Cardiff University

Project outline
Our understanding of the evolution of galaxies was revolutionised in the late 1990s when it was discovered that roughly half the light produced by stars over the history of the Universe is absorbed by dust and re-radiated in the far-infrared to submillimetre region of the spectrum. Large surveys at these wavelengths continue to confirm this picture, but are limited by the mapping speed of existing cameras. The next breakthrough in submm cosmology will come from much larger (>100 deg^2) confusion-limited surveys, which require a massive increase in pixel counts and field-of-view. The same improvements will also allow the first complete study of the plane of our own Milky Way galaxy at high angular resolution. We propose to exploit the UK-invented LEKID detector technology to build a new 850+450 μm camera for the JCMT (the UK is currently a partner in this East Asian Observatory operated facility) with increased field-of-view and sensitivity to improve mapping speed by an order of magnitude over the current SCUBA-2 camera. Over 100 UK active astronomers from 17 Universities contribute funds for the UK's participation in JCMT, with matched funding from STFC. This project will allow the UK and JCMT to continue to lead submm investigation of star-formation over the history of the Universe.

Scientific case
Submm continuum from dust heated by young hot stars is critical for exploring both the processes driving star formation in our own and other galaxies, and also for investigating the formation and evolution of galaxies since they first formed (the epoch of reionisation). A large area cosmological survey will produce statistically significant samples of submm galaxies (SMGs) at high-z and sample the general galaxy population rather than the extreme or highly lensed objects currently available. Tracing the dust-obscured star-forming population at z>4 traces the rate of production of metals at these early epochs and will also allow investigation of how SMGs trace large-scale structure and in what environments they form. A large Galactic plane survey will allow an unbiased census of temperature, luminosity, mass and spectral energy distributions of star forming regions and cold interstellar medium structures in all environments of the Galaxy at unprecedented resolution, tracing the cold dust, which forms the bulk of the dust mass and to which the Herschel satellite was not sensitive.

JCMT is the largest submm single dish telescope in the world on an outstanding site. Other facilities are either on poorer sites and operate at longer wavelengths such as LMT in Mexico, and IRAM 30m in Spain, or are smaller such as APEX 12m in Chile. This camera will keep JCMT at the world-leading edge of submm imaging for the next decade, and will give UK astronomers a head-start in winning ALMA observing time by providing unique samples of rare sources. This instrument will also provide a stepping-stone towards any future planned larger single-dish facility such as the proposed European AtLAST project. The computing facilities required for processing of data from such a large camera are significant but within the capabilities of most Universities' capacity.

Leadership & potential team members

The LEKIDs detector technology, the current state-of-the-art for ground-based submm cameras, was invented at Cardiff. The UK has led the world in submm imaging technology and astrophysical exploitation for the past 20 years, since Gear acted as project leader for the first SCUBA camera. UK astronomers are world-leaders in the exploitation of submm imaging with JCMT, ALMA and other facilities for cosmological surveys e.g. Dunlop (Edinburgh), Geach (Herts), Eales (Cardiff) and Smail (Durham) as well as star-formation studies e.g Ward-Thompson (UCLan), Hatchell (Exeter), Hoare (Leeds), Fuller (Manchester), Moore (LJMU). Technological capability for submm astronomy is concentrated at Cardiff, Cambridge and UKATC (Edinburgh). Data analysis, scientific exploitation and theoretical interpretation is spread widely across the 17 UK Universities currently involved in the JCMT consortium, as well as other UK institutes. The JCMT is currently operated by the East Asian Observatories (EAO), a joint corporation formed by the national observatories of the 4 largest East Asian economies, China, South Korea, Japan and Taiwan. Scientific exploitation of the camera would be undertaken jointly with EAO astronomers and Canada, the other partner. There are also possibilities for technical collaboration with East Asian and Canadian groups on instrument construction, although this would have to be traded off against managerial complexity.

Societal and Economic Impact

Astronomy is very successful at engaging the wider public with science, and there is a great deal of public interest in the high-redshift evolution of the Universe. The images produced by a large-scale Galactic plane survey have huge potential PR impact. The detector technology involved has ongoing potential applications in security scanning and medical imaging, and has led to a recent spin-out company, with contracts funded by UK Border Force. This project would be the largest scale development yet of this UK-invented technology. There are also extensive training opportunities for PhD students and technical staff and for collaboration with the major East Asian economies, with potential for knowledge exchange and spin-outs.

Scale of investment

This would be a small-scale project with estimated cost £6-7M. This could be offset by collaboration with East Asian and/or Canadian partners, however this would bring additional managerial complexity.

Priority projects – summary outline for Advisory Panels

Project Name: Phased Array Feed receiver for the Lovell Telescope
Principal Investigator/Lead Contact: Prof Keith Grainge (keith.grainge@manchester.ac.uk),Prof Ben Stappers, Prof Simon Garrington, Dr Mike Keith

Project outline

Phased Array Feeds (PAFs) are effectively multi-pixel radio cameras that massively boost the field-of-view (FoV) of radio telescopes and hence their survey speed. PAF development is critical to the future of radio astronomy. Previous advances have been made by improvements to low noise amplifiers and by increases in processed bandwidth, but there is little scope for further improvements in sensitivity in either of these dimensions in the radio waveband. Only PAFs offer order-of-magnitude improvements in survey speed for a given antenna, and this programme will allow the UK to establish a lead role in this field.
The potential of PAF receivers is now being realised: the ASKAP (arXiv:1509.05489) and APERTIF PAFs deliver 36 time the FoV of a standard receiver, while the FLAG receiver (arXiv:1803.04473) has recently demonstrated comparable sensitivity to a single pixel feed, critical to which is cooling to cryogenic temperatures. JBCA is the UK-leader of an international consortium (including Italy, Netherlands and Sweden) that has successfully built a prototype cryogenic PAF called PHAROS, which is now being significantly upgraded to PHAROS2. We propose to build on this PAF expertise, with the goal of delivering a full science instrument for deployment on the Lovell telescope. The installation of a state-of-the-art cooled PAF will enable new single dish science projects by expanding the FoV, and hence survey speed of the instrument by ~30 times. It will also allow the Lovell to have the same field-of-view as the smaller antennas in the e-MERLIN/EVN interferometer, dramatically improving the survey speed of the UK's National Radio Astronomy facility for the most challenging projects that require the sensitivity provided by the Lovell's collecting area.

Scientific case

We have assessed that the optimal frequency band in terms of new science opportunities for a cryogenic PAF is 2-4 GHz. Using the PAF on the Lovell will greatly benefit any survey science programme, with the following projects as highlights:

- Exploring new parameter space in the emerging field of fast transient research, for which the FoV provided by a PAF is key. This includes multi-messenger astrophysics, finding electromagnetic counterparts of gravitational wave sources, fast radio bursts, and pulsars. When surveying for these transients the detection rate goes linearly with FoV, while for follow-up high FoV allows either simultaneous monitoring of multiple sources or rapid search at decent sensitivity in the case of poor localisation of the detection. Integration with the eMERLIN network will enable real-time, high-precision localisation of any discovered transient, followed by notification to the wider follow-up community. In short, the wide-field search plus simultaneous precision localisation capability is currently unique to radio astronomy.

- Resolving and separating star-formation and accretion-dominated activity, and understanding the interplay and feedback between these symbiotic processes throughout the cosmic evolution of galaxies. S-band frequency capabilities allied with the increased survey speeds of the Lovell telescope PAF will transform e-MERLIN's already unique position in resolution/sensitivity phase-space for this area up to and beyond first phases of the SKA.
- The first statistically significant, blank field, detection of weak lensing at radio wavelengths will be enabled by developments in survey speed, surface brightness sensitivity and resolution. This is a breakthrough objective of the radio weak lensing community, enabled by e-MERLIN, and a key stepping stone toward future SKA programmes.

Since PAFs directly sample the electric field in the focal plane, they also allow the possibility for novel calibration techniques, tailoring of the aperture illumination function, rejection of RF interference, excellent band-pass performance and suppression of the effects of pointing errors; each of these capabilities will enable new science.

Leadership & potential team members

The University of Manchester have a strong team working on PAF research. Our current work includes: leadership of the PHAROS2 project, together with responsibility for the cryogenic and vacuum systems, front-end receiver chain, assembly and testing; design of a cryogenic SKA prototype PAF; deployment of a room-temperature ASKAP PAF and backend on the Lovell telescope. We are members of the SKA PAF Consortium, comprising researchers from Australia, the Netherlands, Italy, Germany, Sweden, China and Malta. Grainge chairs the SKA PAF Consortium Board. We are collaborating with Canada on novel designs for large cryostat windows. We expect to continue to work with all these international partners, and there is likely to be great interest in deploying copies of the PAF receiver on other large radio telescopes.

Societal and Economic Impact

PAFs are one of the key technologies that will be investigated as part of the SKA Observatory Development Programme for future deployment on the SKA. Deploying a cryogenic PAF on the Lovell will give the UK a leadership role in this development programme which will then allow UK industry to bid for construction contracts if and when PAFs are fitted to the SKA. There is likely to be significant interest in cryogenic PAF systems from other projects too e.g. ngVLA, EVN, AVN, MeerKAT, FAST etc.

There are great opportunities for knowledge exchange from this PAF project since the technology is used extensively for radar systems, for example in the fields of aerospace and in automotive anti-collision. We have previously worked with Leonardo UK, Edinburgh (formerly Selex Galileo) on PAFs and plan to re-engage with them for this project. The key technologies that will be developed for this proposal are: low loss antenna array elements; high-volume low-noise amplifiers; large scale cryogenic and vacuum systems; digital signal processing for beam formation.

Scale of investment

Small scale (expected cost is £3.3M).

Priority projects – summary outline for Advisory Panels

Project Name: The Atacama Large Aperture Submillimetre Telescope (AtLAST)
Principal Investigator/Lead Contact: Pamela Klaassen (UK ATC/STFC)

Project outline: The submillimetre is a crucial region of the EM spectrum to study the origins and evolution of galaxies, stars and planets. We propose the UK become the majority stakeholder in a new generation, 50 m-class submm telescope to be built in the Atacama Desert in Chile (AtLAST). The telescope will focus on large-scale surveys of the submm sky with detailed imaging and spectroscopy of phenomena that extend over several degrees but have significant structure on scales of a few arcseconds. With an unprecedented wide field-of-view and large wavelength range AtLAST will provide the ideal complement to the exquisitely detailed images from ALMA (on sub-arcsec scales). Indeed, a large single-aperture telescope such as this has been strongly recommended by the ALMA Board as a key complementary facility to its long-term development plan. AtLAST will probe each of the major scientific challenges identified in the STFC Science Strategy, and represents a timely opportunity for the UK to lead a major facility that fills the science/wavelength gap between our two current top-priority astronomy projects, the ELT and SKA.

The AtLAST project consists of working groups carrying out feasibility studies on science, site, telescope design, and instrumentation. The science working group is led by P. Klaassen (UKATC, STFC) and J. Geach (U. Hertfordshire), co-leads of this project. There is strong support from the UK community, and internationally, the project has engaged scientists and engineers working in Europe, Japan, USA, Canada, and Mexico. A leading role in AtLAST for the UK will capitalise on decades of world-leading science and technology advancement by astronomers and engineers in submm astronomy. The UK has led pioneering projects such as the JCMT and was a key driving force behind ALMA, and more recently contributed innovative instrumentation such as “SCUBA-2” and ALMA’s front-end receivers. The high value of submm sky surveys to the UK community is evidenced by the leading role our astronomers continue to play in the JCMT Legacy Surveys. The JCMT has surveyed less than 10% of the sky, and so AtLAST will take us to new and unprecedented levels of sensitivity, breaking through confusion barriers, and for the first time, the ability to carry out large-scale (“all-sky”) mapping - at least 10^5 times faster than ALMA. This would also be highly complementary to similar upcoming surveys conducted in the Optical/Near-IR (LSST, Euclid) and the radio (SKA).

With an expected total cost of ~£200M, a £100M investment makes the UK a majority stakeholder, ensuring a leading role in science and technology decisions. AtLAST represents a timely convergence of science, technology and opportunity: the science to explore the earliest stages of structure formation in galaxies, stars and planets; the technology to produce a large aperture telescope and “CCD-like” megapixel cameras; and the opportunity to exploit the incomparable Chajnantor plateau to produce the first atlas of the submm sky.

Scientific case: AtLAST's focus on large scale, high resolution (spectroscopic) imaging lends itself to the two example cases below, neither are feasible with current (or upcoming) facilities, while both will create thousands of ALMA follow-up targets.
'A submm SDSS': The Sloan Digital Sky Survey combined wide-field optical imaging with a spectroscopic programme to survey the local extragalactic volume. After 20 years, it continues to deliver impactful science. AtLAST would be capable of a 'submm SDSS' at z=1-10, spanning the peak of galaxy growth and probing into the Epoch of Reionization. This survey will give a complete census of dust-obscured star formation and black hole growth over the first 6 Gyr of cosmic history, determine the evolution of the large-scale structure, and measure cosmology through the detection of baryonic acoustic oscillations and abundances of clusters of galaxies at high-z.
'Galactic Environmental Monitoring': With AtLAST, we can map the ecology of the gas and dust in our Galaxy, explore new regions of star-formation, probe the post-main-sequence evolution of stars, and quantify the nature and abundance of the chemical building blocks of life. Doing so periodically unlocks time domain submm astronomy. A spectroscopic survey of the Galaxy on scales of a few arcsec will enable a spatially and spectrally resolved chemical fingerprint of large scale structures such as long star-forming filaments, quantify low-metallicity star-formation at the edges of our Galaxy, and determine the nature and effects of dust production.

Leadership & potential team members: This project capitalises on the UK's traditional strengths in sub-mm astronomy. Definition of the science case for AtLAST is already being led by from the UK (next meeting in Edinburgh, Sept 2018), and this investment would ensure UK leadership of the entire project. Potential team members who have indicated support include: M. Birkinshaw, A. Blain, D. Clements, J. Dunlop, S. Eales, G. Fuller, J. Greaves, J. Hatchell, W. Holland, S. Longmore S. Lumsden, J. Peacock, D. Rigopoulou, A. Saintonge, S. Serjeant, and M. Thompson.

Societal and Economic Impact: The UK has a long history of providing state-of-the-art technology for telescopes and instrumentation. AtLAST presents an unique opportunity in both high-value manufacturing (e.g. infrastructure) and technology development (e.g. low temperature detectors) as well as to build the skills of a new generation of engineers and scientists. There are substantial opportunities for collaboration with industry, from collaborative R&D to direct procurement contracts. Much of the planned technology, particularly that associated with new instruments and detectors also has potential applications outside of astronomy including: security scanners from THz technology, part of the Global Uncertainties cross Research Council priority area, medical and x-ray imaging scanners and in micro or nano-structures (e.g. MEMS). Through construction, AtLAST would engage in engineering partnerships with major educational establishments to produce greener technologies, and subsequently, the large surveys envisioned for AtLAST require big-data style citizen science, such as data analysis within the 'Zooniverse' framework.

Scale of investment: Investment can be made at various levels with differing associated influence, and science return. A large-scale investment of £100M clearly places the UK as the majority stakeholder. Whilst this is an excellent opportunity for the UK to continue being a world-leader in submm astronomy, a medium-scale investment will still have significant influence; a well-timed £20M investment yields a focused design study, while identifying and advancing one or more key technology area of UK expertise. This would mitigate the risk for all partners and clearly demonstrate leadership in the chosen areas.

Priority projects – summary outline for Advisory Panels

Project Name: Planet Formation Imager
Principal Investigator/Lead Contact: Stefan Kraus, University of Exeter

Project outline

The Planet Formation Imager (PFI, http://www.planetformationimager.org) is a concept for a next-generation ground-based infrared interferometric telescope facility that is optimised for imaging the formation process and early dynamical evolution of exoplanetary systems. Consisting of an array of about twelve 3m-class telescopes spread over an area of 1.2 kilometres, PFI will provide the highest angular resolution of any infrared imaging facility world-wide and enable unique science in the areas of planet formation, exoplanets, and extragalactic astronomy. We ask for funds to conduct a Phase A study (funding personnel at Exeter, Cambridge & Southampton) and to engage industry partners for the development of key technology components.

Scientific case

Planet formation is one of the most fascinating and hotly-debated areas in contemporary astrophysics, linking the field of star formation with exoplanet research and with questions about the origin of our solar system. Although important work is being done both in theory and observation, it is becoming clear that a full understanding of the physics of planet formation will require to open new observational windows that allow us to witness the process in action. The PFI project has crystallized around this challenging goal: to deliver resolved images of Hill-Sphere-sized structures within candidate planet-hosting discs in the nearest star-forming regions. This will allow us to unmask all the major stages of planet formation, from initial dust coagulation, gap formation, evolution of transition discs, mass accretion onto planetary embryos, and eventual disc dispersal. PFI will be able to detect the emission of the cooling, newly-formed planets themselves over the first 100 Myr, opening up spectral investigations for instance in molecular or accretion-tracing lines. Tracing the planet populations in objects at different evolutionary phases will provide unique insights on planet migration, revealing the mechanisms that govern the architecture of exoplanetary systems.

The PFI initiative comprises more than 100 astronomers that are organized in a science and technical working group. Over the last 4 years, we developed the high-level science requirements (Kraus et al. 2016, SPIE 99071K) and a “reference” facility architecture that includes twelve 3m telescopes that are spread over an area of 1.2 kilometres. The architecture enables high-fidelity imaging in the 2-13 μm wavelength range at a resolution of 0.5 milliarcsecond (0.07 astronomical units at the distance of the closest star-forming region), i.e. 50-times higher angular resolution than the diffraction-limited resolution of the upcoming ELTs. So far, the project has resulted in 7 project-level SPIE papers, 17 papers on individual technology aspects, and 1 peer-reviewed paper. We are in the process of defining the key science drivers and to determine feasible technical architectures. Besides the primary science case of detecting protoplanets and imaging circumstellar and circumplanetary dust structures, the concept will enable breakthrough science in a broad range of areas, ranging from stellar astrophysics (e.g. imaging stellar surface structures and mass loss processes), extragalactic science (e.g. imaging AGN broadline regions and dust tori) and calibrating the cosmologic distance ladder with dust parallaxes out to distances of about 1000 Mpc (Hönig et al. 2014, Nature 515, 528).

Leadership & potential team members

UK scientists are taking a leading role in PFI, with the Project Scientist at Exeter and project contributors at Cambridge, Kent, Leeds, Oxford, Southampton, St. Andrews, Warwick, and UCL. Our US and Chilean partners have started securing PFI-related funding on the $2M level and it is timely for the UK to invest in the project in order to maintain leaderships, while also engaging UK industrial partners for technology developments. We note that PFI fits perfectly in the STFC Science Roadmap scheme, where “science missions to understand the processes of planetary formation” are listed as future opportunity. PFI was explicitly supported in the 2015 UK Exoplanet review (https://stfc.ukri.org/files/exoplanet-science-review-2015/).

Societal and Economic Impact

Triggering UK industrial engagement in PFI early on could produce considerable economic benefits, as these companies will gain know-how in innovative technologies, such as mid-infrared fibres / photonics devices and 3D printing of large telescope mirrors. UK companies have expertise in these areas and will be in a good position to transfer the know-how for market applications in the telecommunication, medical imaging and defence sector. A PFI-triggered breakthrough in reducing the cost of 3m class telescope mirrors could also impact other areas of astronomy, e.g. by enabling low-cost telescope arrays for RV exoplanet follow-up surveys or time-domain astronomy. Both the general science case and the technology context are very suitable for public engagement activities.

Scale of investment

For the next 3 years, it will be essential to invest in a comprehensive Phase A study that would include defining and validating the key science goals in planet formation (group Kraus/Exeter) and extra-galactic science (group Hönig/Southampton), simulating the performance and error budget on a system-level (group Cambridge) and engaging with industry partners to demonstrate the performance of key components. Such a formal Phase A study will require an investment of about £3M, where about 50% will be used to fund PhD/PDRAs and administrative support for conducting the science case studies and 50% will be invested to engage industrial partners and to prototype key technology components. We will then use the outcome of the Phase A to secure funding for the deployment of the full PFI array in the mid/late-2020s. With existing technologies, we estimate the cost of building a full-scale PFI array to $250M = £200M (Ireland et al. 2016; Monnier et al. 2018), although the costs could be lowered through pioneering new telescope manufacturing techniques. We also expect that these costs will be shared between several international partners.

Priority projects – summary outline for Advisory Panels

Project Name: 4MOST: megascale wide field multi-object optical spectroscopy in the Southern Hemisphere
Principal Investigator/Lead Contact: Richard McMahon, Cambridge[1]

Project outline

4MOST is a major new wide field (4.1 square degree field of view) high-multiplex (~2400 low and high resolution) spectroscopic survey facility under development, for the ESO VISTA telescope in Chile, by a German led European consortium with significant UK involvement. 4MOST provides a unique opportunity for the UK to fully exploit the next generation Southern Hemisphere observatories from the radio (SKA) to the optical optical (LSST), IceCube neutrino observatory in Antarctica and also Euclid and LIGO/VIRGP sources visible from the south. A UK investment of 2-4M UKP over the period 2020-2027 will permit 4MOST to proceed with two low-resolution spectrographs rather than one, doubling the survey speed and ensure that other hardware and the data management work package can be delivered. STFC previously funded the 4MOST conceptional design phase but in 2013, following a Science Board review, due to limited funding and concerns about technical risk, it did not invite a full proposal to PPRP. Since 2013, these technical risks have been retired, some UK universities have invested in 4MOST and more importantly, the UK has joined the LSST project. It is therefore timely to reconsider STFC funded participation in 4MOST as part of a coherent scientific strategy for astronomy research in the next decade.

Scientific case

4MOST will spectroscopically observe 25 million objects in the first 5 year operation period and has a broad range of science goals ranging from Galactic archaeology, stellar physics, high-energy physics, galaxy evolution, cosmology, dark matter and dark energy. Below we highlight one themes as a exemplar where there is well defined UK leadership;

LSST transients:

LSST will discover a million supernovae, including ~200,000 type Ia (SNe-Ia) in both the wide and deep LSST surveys. To use these SNe for cosmology, we need rapid spectroscopic follow-up of the SN or its host galaxy. Through our leadership, the 4MOST consortium has agreed to make available ~2% of all fibres for such follow-up, and over the first 5 years, we will obtain redshifts for nearly all the bright ($r < 23$) host galaxies of cosmologically-useful LSST SNe-Ia; a 100-fold increase on current samples. Our UK team will lead in the follow-up of other LSST transients and SN types, e.g. superluminous supernovae (SL-SNe) which are ~100 times brighter than SNe-Ia. LSST is predicted to discover 20,000 SL-SNe to z = 2.5, providing a new probe on the distant universe. This science is only possible with two

[1] Submitted on behalf of the proto 4MOST-UK consortium with Institutional representatives; Smartt(Belfast), McMahon (Cambridge), Alexander (Durham), Hook(Lancaster), Nichol (Portsmouth) Sullivan(Southampton), Loveday (Sussex)

low-resolution spectrographs rather than one.

Leadership & potential team members

As the result of investment by STFC and UK universities the UK can expect to have some leadership in the use of 4MOST for transient and other time domain astronomy covering areas of science ranging from the study of dark energy using supernova to multi-messenger follow-up such as gravitational wave electromagnetic counterparts. This proposal will increase this leadership and also has scope for leadership in AGN reverberation based mass estimates of supermassive black holes and X-ray source follow-up leveraging the German eRosita satellite. UK groups would also have an opportunity to lead Gaia follow-up.

UK groups currently involved in 4MOST are: Belfast, Cambridge, Durham, Lancaster, Portsmouth, Southampton, Sussex; See https://www.4most.eu for the current list of 4MOST consortium members. Scientists from the above UK institutes form the core of the UK involvement and have already been involved in the design of the 4MOST consortium survey. Individuals from Hull, Oxford, Warwick, UCL have also indicated interest in becoming involved in the existing 4MOST consortium surveys. Additional investment by STFC could lead to leadership in an ultra-deep optical spectroscopic survey centred on the LSST/Euclid Deep fields. Following the UK DESI model and depending on the level of STFC investment we propose to offer additional UK scientists membership of the 4MOST science team via an open, competitive process.

Societal and Economic Impact

4MOST is obtaining 6k x 6k CCD detectors from Teledyne e2v (UK) and therefore the 4MOST scientific results will highlight UK industrial leadership in detector development to a world wide audience. The broad range of scientific result will highlight the excellence of UK science and technology at a worldwide level. Over a 5 year period, 4MOST will deliver 10's of millions of spectroscopic observations that will have a wide scientific impact which would be complemented by broad public and scientific outreach program that would inspire a new generation of young scientists. The dataset would also be the ideal basis of the development of machine learning algorithms on complex data and hence will inspire and be used to train a new generation of data scientists. 4MOST will be used to take spectra of LSST transients and this would also be enhance the societal value of the UK investment in LSST over that of other countries who do not have access to spectroscopic follow-up capabilities on the scale provided by 4MOST. An exiting possibility is that 4MOST will be able to observe 'live LSST transients' which would open up an exciting opportunity for citizen scientists to get involved in 'real time' next day scientific discovery.

Scale of investment

The proposed level of future STFC investment is 2-4M UKP over the period 2020 to 2027 covering the first 5 years of 4MOST survey operations leveraging previous STFC investment in VISTA and 4MOST and also UK university financial investment in 4MOST. The total cost of the 4MOST instrument is around 45M euro and an investment of 2-4M UKP would make the UK contribution from STFC and Universities reach a level of 10-15% of the total project and make the UK, the second largest contributor after Germany. In Germany, like all the other 4MOST partners, the involvement is institution based with involvement from AIP, MPIA, MPE, Heidelberg University and Hamburg University. The other countries with involvement in 4MOST are Netherlands, France, Sweden, Switzerland, Australia

Priority projects –

summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: Comparative Exoplanetology
Principal Investigator/Lead Contact: Dr Sami Mikhail (University of St Andrews; sm342@st-andrews.ac.uk) and the St Andrews Centre for Exoplanet Science

Project outline

The St Andrews Centre for Exoplanet Science (StACES) was launched in 2016 as a collaborative, multidisciplinary community of geologists, astronomers, astrophysicists, biologists and philosophers focussed on answering two key questions: (I) how does Earth fit within the ensemble of the more than 3500 discovered planets? and (II) how does planetary evolution create environments for life to emerge and survive? These align directly with STFC's Science Challenge: "*How do stars and planetary systems develop and is life unique to our planet?"* The **Comparative Exoplanetology programme** is central to the shared visions of STFC and StACES and merges expertise across planetary geoscience and exoplanet astronomy. The StACES goal is to creat a unified, dynamic research centre of excellence that addresses the key challenge in exoplanetary science: determining exoplanetary habitability and the viability of life elsewhere.

Scientific case

The diversity of exoplanets identified from ground- and space-borne telescopes has offered the scientific community a rich opportunity to revise old and create new ideas about Solar System formation. The cosmos is now known to contain hot Jupiters, super-Earths, mini-Neptunes and small magma planets yet none of these are present in our own Solar System. Ergo, it is now known that there is no such thing as a normal planet, *sensu stricto*. What combination of factors resulted in the make-up of our System and the role those had in the origin of life is a vibrant area of research. The aim of this project is to obtain fundamental new data and create deeper understanding of (exo)planetary formation and the potential such planets hold as a platform for life.

The shared goals of the StACES project is to:

- enhance knowledge of the formation of exoplanets, their masses, densities and atmospheric compositions, to understand their diversity within the cosmos and how Earth fits into this array of worlds;
- determine the role of geological processes in creating the conditions for life in exoplanet systems; and

- undertake meteoritic studies to better constrain the chemical heterogeneities within our Solar System and ground-truth models of Solar System condensation and planetesimal accretion.

This work will provide new, fundamental and underpinning data to use in currently planned missions such as the James-Webb-Space-Telescope, TESS and CHEOPS, and help prepare and guide planning for the upcoming PLATO mission. These insights will form legacy data useful for all future astronomical observations and missions.

Leadership & potential team members

The **Comparative Exoplanetology programme** will fuse the fields of astrophysics and geoscience. St Andrews is one of 5 founding Universities of WASP (Wide Angle Search for Planets), the most successful ground-based search for transiting planets and paving the way in exoplanet characterisation, including cloud-formation models. World-class analytical facilities underpin StACES research enabling simulating planetary interiors, biogeochemical experiments under extreme conditions, and precise and novel isotopic determinations.

Societal and Economic Impact

Knowledge exchange: This project will build a bridge of knowledge between two distinct disciplines: planetary geoscience and exoplanet astrophysics. This is essential for the next stage of exoplanet science, *i.e*. to move beyond discovery and develop deeper understanding of exoplanetary environments and their evolution. Further, StACES will train a new generation of exoplanet scientists competent in integrating research across those two traditionally distinct disciplines.

Industrial partnerships: StACES provides a platform to engage with the burgeoning UK space sector and will enable contributions to the development of robotics and autonomous control, for example ESA ExoMars2020 (Mars surface robotic mission), ARTEMiS (Automated Robotic Terrestrial Exoplanet Microlensing Search), SuperWASP (robotic observatory to search for planets) and human space exploration. Likewise, StACES is well positioned for the UK's first spaceport in Sutherland and will contribute to the UK's growing leadership in space science and exploration.

Public engagement: The search for exoplanets and life elsewhere in the Universe is a matter of public fascination, bridging the realms of science and science fiction. StACES researchers will embark on an extensive programme of public engagement using our established expertise in outreach and educational platforms sanctioned by the Public Engagement team at the University of St Andrews.

Scale of investment

This project requires small-scale (<10M) investment. It will complement St Andrews' recent investments in state-of-the-art laboratory equipment, international telescopes and observational programmes, and new staff in Astronomy and Earth Sciences relevant to the **Comparative Exoplanetology programme**. Investment will ensure StACES' continuing contribution to that programme and its delivery of fundamental research to keep the UK at the forefront of exoplanet investigation.

The **Comparative Exoplanetology programme** at the St Andrews Centre for Exoplanet Science bridges both exoplanet detection and characterisation (astronomy) and planetary geoscience within the Solar System (and beyond). Because of the overlaps between the Astronomy and Solar Systems panels, we have sent this priority project summary outline to both panels, as instructed by email notification on the 3rd July 2018 (sent by Paul O'Brien and Huw Morgan).

Priority projects – summary outline for AdvisoryPanels

Project Name: Blue MUSE
Principal Investigator/Lead Contact: Simon Morris (Durham University) /Roland Bacon (CRAL, Lyon)

Project outline

MUSE on the VLT is a success: it is unique, largely over-subscribed, and has a high publication rate. There is room for a 2nd MUSE type instrument. By 2025-2030 the ELT and JWST instruments will focus on red and infrared wavelengths. The best mid-term solution for the European ground-based community is a complementary MUSE on another UT: The Blue MUSE. As attested by the number of high science impact papers published by the UK community with the current MUSE instrument, UK astronomers will benefit greatly from getting involved in this new instrument.

Scientific case

The current MUSE has demonstrated great flexibility in the range of science cases it can cover. The proposed blue MUSE project would be equally flexible but would offer new advantages in the areas listed below.

Globular clusters: Stellar parameters of 1000s of stars in a single pointing; Intermediate mass black holes; Stellar black holes detected from companions

Stellar nebulae: Resolved physical processes (ionisation parameter, extinction); physics of outflows; Kinematics of nebulae, Herbig-Haro objects (~ 10 km/s)

Dwarf and nearby galaxies: Getting down to < 10^6 M_{sun} BH masses in low mass galactic nuclei; Precise dynamical masses of nearby ultra-faint dwarf galaxies; Velocity dispersion of multiple UCDs in a single pointing

Unresolved stellar populations and kinematics: Galactic cores, bulges: from absorption line indices, kinematic moments; Discs of star-forming galaxies: local vs global star formation history

Low surface brightness sources; Galactic Halos; Thick Disks; Tidal streams; Intra-cluster Light.

Physics of outflows and UV nebular lines at 0.5 < z < 3: Resolved outflows at z > 0.3: from Mg II and Fe II absorptions and line emission; At 1 < z < 3, CIII], CIV, HeII and OIII] nebular emission:

Deep Fields: UV cosmic SFR peaks in this redshift range; MUSE Deep fields (> 10 hrs per pointing) reveal faint emission line galaxies, and in majority; Lyman-alpha emitters (LAEs)

High-redshift galaxies Lyman-α at 2 < z < 4: Lyman-alpha emission can help to probe the diffuse gas in the circum-galactic medium; Blue-MUSE can probe this diffuse gas down to z=2 and benefit from surface brightness dimming (gain x3 between z=3 and z=2) and UV background (x2), in total x6 gain; Higher spectral resolution helps to study Lyman-alpha profiles; Blue wavelength helps to identify Lyman continuum leakers at z=3-4

Lensed galaxies by massive clusters: Magnification allows probing lower mass / luminosity galaxies; Massive clusters have a magnification region extending to 1.5-2 arcmin; 2 < z < 4 is the peak of the redshift distribution for multiply-imaged galaxies

High redshift galaxy clusters: Number counts of galaxy clusters at high redshift is sensitive to sigma_8 and non-gaussianities. Current limits on confirmed clusters at high z; Herschel and Planck have detected many high redshift cluster candidates, and Euclid data will be full of them; Cold (10^4 K) gas and hot (10^7 K) gas seem to coexist in some clusters, as seen with Lyman-alpha and X-ray; Theory predicts that cold flows accretion is needed to maintain the steady state, still to be confirmed in observations.

Uniqueness; Unique combination of large FoV, resolution and wavelength

Leadership & potential team members

The project will be led from France, (CRAL, Lyon), with other major partners being the UK (coordinated through Durham), Germany, Switzerland and Sweden.

Societal and Economic Impact

The previous MUSE project built close links with several industrial partners to manufacture the highly multiplexed and modular components. It is expected that this model would be repeated. The curved detector technology is new and its development in collaboration with Teledyne e2v will have a number of non-astronomical applications.

Scale of investment

Most of the required technology already exists: slicer, spectrograph, etc.
The only new technology needed is the use of 4k x 4k curved detector. In generating a cost estimate the considerations are: it will be slightly more expensive on hardware (larger fore-optics), but less expensive in development, giving a current estimate of 10 Meuros hardware, and 135 FTE. Should the curved detector not be available, then a backup solution would be to drop to a 1x1 $arcmin^2$ field of view, with smaller optics, a 4k x 4k flat detector, but the same spectral range.
The costs would be expected to be shared across the international consortium.

Priority projects – summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: Precision wide-field spectrograph for atmospheric characterisation of exoplanets from the ground
Principal Investigator/Lead Contact: Nikolay Nikolov, University of Exeter

Project outline

Thousands of transiting exoplanets are known today, yet little is known about how exoplanet atmospheric composition links with planet formation and the physical properties of the host stars. Optical and infrared observations of exoplanet atmospheres play a leading role, but no optimised or dedicated multi-object spectrograph exists or has been foreseen to survey the diverse exoplanet population, enabling robust statistical studies. We propose the first large-scale survey with precision, wide field, optical to near-infrared multi-object spectrograph, optimised for characterisation of exoplanet atmospheres. With a wide field of view, the new dedicated instrument will uniquely access bright exoplanets and achieve high precisions unreachable by common user instruments designed around surveying faint galaxies. The new capability would play a transformative role for the field by performing (1) a large-scale statistical survey from super-Earth and warm Neptune to hot Jupiter atmospheres covering key chemical species and (2) reconnaissance spectroscopy of newly discovered super-Earths and hot Neptunes, finding those with H-rich atmospheres and characterizing their features. The spectrograph will also fill the wavelength coverage gap of the upcoming Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) and *James Webb Space Telescope* (*JWST*) by providing highly-complementary simultaneous optical to near-infrared spectra, comparable to HST spectra from the ground and cloud-free atmospheres. With its unique capability and cost of <10M, the proposed project would further increase the leadership of the UK exoplanet and astronomy communities.

Scientific case

Exoplanetary transits and eclipses are key to explore the atmospheric composition and thermal structure of exoplanets. Optical spectroscopy at medium resolution (R=1000) is the most sensitive probe to clouds and hazes; why some exoplanets show cloud and haze opacity, and others do not, is one of the outstanding questions in the field. The optical region is also uniquely suited to determining the cloud top pressure, which provides the critical pressure/altitude baseline necessary for determining absolute molecular abundances from transmission spectra. Large-scale atmospheric surveys with a precision multi-object spectrograph could effectively resolve these fundamental problems from the ground. The new exciting Neptune and super-Earth targets discovered with TESS and PLATO will be much brighter than current ground-based instruments can observe, as they are designed for faint targets and have relatively narrow fields of view, limiting the availability of suitable comparison stars. ***We propose the first wide-field (20') precision (mechanically and thermally stabilised) optical to near-infrared spectrograph for atmospheric characterisation of transiting exoplanets***. All existing spectrographs (ground and space) suffer from systematics at least an order of magnitude larger than the signal of the exoplanet atmosphere and limit the progress of the field. With simultaneous optical and near-infrared capability the new instrument and survey would be highly-complementary to the ARIEL and *JWST*, enabling the first robust steps toward comparative exoplanetology.

Leadership & potential team members

This project is proposed by a UK consortium of institutes, whose major partners are the University of Exeter (home of PI Nikolay Nikolov) and universities of Belfast (N. Gibson & C. Watson), Warwick (P. Wheatley), Keele (C. Hellier), St. Andrew's (Ch. Helling), Cambridge (N. Madhusudhan), Oxford (P. Irwin & F. Clarke), UCL (J. Barstow) & Newcastle (T. Rogers). The team is open to international members.

Societal and Economic Impact

Results from exoplanet research represent an ultimate interest for the general public. Furthering UK lead in a high public profile area of STFC science would offer a big societal impact. This can further increase the potential of expanding instrumentation development within the UK to the broader technology community.

Scale of investment

In 2015 we developed a concept study for a comparable instrument for the 3.5m ESO *NTT* - "ExoMOS". The concept enabled 0.4 - 2.4μm spectroscopy of 2 - 6 targets over a 20' field. The study estimated a hardware cost of ~£7M and a design/build schedule of 4 years. Though not exactly the same this study provides us with an excellent starting point for the new development. Our concept will be proposed as visiting/facility instrument for a 4-8m class telescope, e.g. ESO's *VLT*/ING's *WHT,* to be in the next phase.

Priority projects – summary outline for Advisory Panels

Project Name: Giga-z
Principal Investigator/Lead Contact: Kieran O'Brien

Project outline

We propose to build and operate Giga-Z, a revolutionary new type of Superconducting Multi-Object Spectrograph (Super-MOS). The Giga-Z survey would build on the investment in LSST by providing accurate redshift for 2 billion of the objects detected by LSST. The broad passband of KIDs includes the visible and near-infrared simultaneously leading to much better systematics and fewer 'catastrophic failures' that are an important limitation on current visible-light only surveys.

Scientific case

In 2013, Marsden, Mazin, O'Brien & Hirata (ApJs, 208, 8) described the concept for a revolutionary new multi-object spectrograph, the super-MOS. The instrument employs superconducting Kinetic Inductance Detectors (KIDs) to measure the spectrum of 100,000 objects in a single pointing. Each KID pixel has an energy resolution ($R_{423nm} = E/\Delta E$) of 30 and is sensitive in the 350-1350nm range. The paper models the performance of Giga-z, a SuperMOS designed for wide field imaging follow-up spectroscopy, using simulated observations of the COSMOS mock catalog and compared the results against a simultaneous simulation of LSST observations.

The Giga-z survey, uses the catalogs from large surveys (such as LSST) as an input catalog for target finding. In 3 years on a dedicated 4 m class telescope, Giga-z could observe ≈2 billion galaxies, 1000 times the number measured with any currently proposed LSST spectroscopic follow-up, at a fraction of the cost and time. A 1 deg^2 field of view can be divided among 100,000 detectors, each fed by a macropixel covering 10"×10" of the sky, to be able to cover 20,000 deg2 in a reasonable amount of time. Galaxy number counts ensure that 80% of the macropixels will contain a galaxy at each pointing, with the remainder used for simultaneous sky background measurements. A mask designed using pre-existing LSST (or DES) imaging would permit light from one celestial source per macropixel into a reimaging system that focused the light onto the corresponding large plate scale KID located directly below. This mask could be physically cut, generated from a micro-shutter array, or a liquid crystal spatial light modulator to avoid the need time consuming mask changes.

Giga-z would provide redshifts for galaxies up to $z \approx 6$ with magnitudes $m_i < 25$. From our simulations, we predict redshift estimate accuracies of $\sigma_{\Delta z/(1+z)} \approx 0.03$ for the whole sample, and $\sigma_{\Delta z/(1+z)} \approx 0.007$ for a select subset. We also find catastrophic failure rates and biases that are consistently lower than for LSST. These add constraints on dark energy parameters for WL + CMB (Planck). In particular, for the rate of growth of structure, one of the most important constraints for weak lensing since it cannot be probed by supernovae, adding the Giga-z photometric redshifts would be equivalent to doubling the LSST footprint (e.g., by running a second complete LSST survey in the north). This data could be obtained inexpensively compared with most current and future surveys. Giga-z would immediately be able to use DES catalogs to inform a first pass, and operate in parallel with LSST and other wide field imaging surveys.

Leadership & potential team members

The PI is based at the Centre for Advanced Instrumentation at Durham University and is leading UK efforts to build Optical/IR KID-based instrumentation. As a former group member at UCSB, he has strong ties with the team lead by Mazin who are developing the KID arrays and are (so far) responsible for the only optical/IR KID instruments to go on-sky. Additional UK (Cambridge & Cardiff) and EU (SRON & DIAS) teams have begun promising optical/IR KID array development programs, based on their world-leading sub-mm KID programs and we expect these to strengthen enormously over the time-scale of the project. Much of the technology is transferable and should the proposal be taken to the next stage, we will build a consortium of key people in the field. In 2014, the PI lead a team from Oxford, UCSB, FermiLab and MSSL proposing Mega-z (a smaller instrument) following a call for proposals for the NTT. The feedback from ESO was that this was "*an intriguing new technology that we would like to see developed*", but that it would not be taken further due to other ongoing projects and the technology readiness level. Since then array sizes have increased from 2000 to 30,000 pixels and new instruments, such as DARKNESS, have increased the TRL to the point where we expect to be able to field a 100,000 pixel camera in the next 3-4 years. This would put the UK in a leading role in the development of KID-based instrumentation.

Societal and Economic Impact

The discoveries from astronomy inspire the next generation of STEM students and the existence and understanding of dark matter and dark energy are some of the most fundamental questions in modern astronomy. Giga-Z development includes the areas of superconductivity, cryogenics, radio frequency engineering (read-out system) and data intensive science and will help to train the next generation of researchers in these fields. The development of Giga-z will showcase the technology and enable us to engage with industry. The potential applications for KIDs outside of astronomy are enormous, bringing together the fields of low-light level imaging and hyperspectral imaging. These include the fields of biomedical imaging (advanced fluorescence lifetime imaging), quantum optics (photon number counting), remote sensing (wide passband hyperspectral imaging) and defence (advanced night vision).

Scale of investment

We estimate the construction budget for such an instrument is ~£5M, which includes ~£2.5M in hardware costs. This is based on previous experience with MKID instrumentation. The operating costs are dependent on the telescope, but are expected to be in the range of £5M for a 3year survey. Additional partners will be sought to provide additional funds, especially in the area of operations. Our previous experience of building a consortium for the NTT proposal showed that there are national and international partners interested in such a project.

Priority projects – summary outline for Advisory Panels

Project Name: KIDSPEC
Principal Investigator/Lead Contact: Kieran O'Brien

Project outline

We propose to design and build the first in a new class of instruments based around Kinetic Inductance Detectors. KIDSpec will be a powerful ultraviolet/optical/infra-red (UVOIR), medium spectral resolution (R~10,000), wide pass-band (0.35-1.7micrometer) spectrograph that will maximize the return from large UVOIR telescopes. KIDSpec on the E-ELT, Europe's flagship observatory in the coming decade, would enable the deepest spectroscopic observations ever made. A wide passband, medium spectral resolution instrument, similar to the enormously successful "X-shooter" instrument at the ESO-VLT would fill a clear gap in the currently planned ELT instrument suite, and this demonstrator instrument would enable us to perform unique science and also to showcase the unique capabilities of KIDs to push such an instrument to its limits.

At the heart of KIDSpec (O'Brien, Thatte, & Mazin, 2014) is a KID array that is used as an 'order sorter' for an echelle grating, removing the need for cross-dispersing optics in an echelle spectrograph, as first described by Cropper et al. (2003). The light from each order overlaps onto the linear array, but the orders are sorted using the intrinsic energy resolution of the energy sensitive MKID. The combination of the inherent increase in throughput and the associated reduction in complexity, combined with the zero read-noise and photon-counting properties of KIDs enable observations of the faintest quasars and exotic systems, such as gamma-ray bursts and stellar mass blackholes.

Scientific case

KIDSpec on an 8-10m class telescope, such as ESO's VLT and the South African SALT telescope would enable unique observations in all high-impact areas of STFC-funded astronomy, including (but not limited to) time domain astronomy and high redshift galaxies. It would increase the sensitivity of an equivalent semi-conductor based instrument (such as 'X-shooter') in the same way as doubling the aperture of the telescope due to the increased throughput (simpler optical design), lack of read-noise and cosmic-ray subtraction. Additionally, it would overcome many of the limitations of such instruments, such as allowing time-resolved background subtraction and removing the need for an atmospheric dispersion corrector.

Understanding the nature of compact objects, how they form and evolve relies on challenging observations made in a range of wavelengths. In the UVOIR regime we can study the dynamics of such systems and the evolution of transient (and often cataclysmic) events. Observations of such events often require short integration times (~seconds) to determine the variability of the source and hence its nature. The efficacy of such observations has been demonstrated by the highly successful (and STFC-funded) ULTRACAM instrument (Dhillon, et al. 2007). KIDs would enable us to take these observations to the next level, providing microsecond *spectroscopy* with zero read-noise over a sufficiently large field of view to perform differential measurements. It would enable us to study the dynamical masses of objects such as AMCvn stars, which are thought to be the progenitors of low frequency gravitational wave sources. KIDSpec would enable us to study a range of objects in extreme physical environments, such as Supernovae, GRBs and compact objects spectroscopically and on relevant timescales.

Characterising high redshift objects involves some of the most challenging observations. They are among the faintest object discovered and require observations at optical and IR wavelengths, where detector technology is challenging. KIDSPEC would enable IR sky subtraction from the medium resolution spectroscopy and dynamic rebinning without the penalty of read-noise which currently limits such observations. This would open the door to ELT science on the VLT for single object spectroscopy.

Leadership & potential team members

The PI is based at the Centre for Advanced Instrumentation at Durham University and is leading UK efforts to build Optical/IR KID-based instrumentation. As a former group member at UCSB, he has strong ties with the team lead by Mazin who are developing the KID arrays and are (so far) responsible for the only optical/IR KID instruments to go on-sky. Additional UK (Cambridge & Cardiff) and EU (SRON & DIAS) teams have begun promising optical/IR KID array development programs, based on their world-leading sub-mm KID programs and we expect these to strengthen enormously over the time-scale of the project. Much of the technology is transferable and should the proposal be taken to the next stage, we will build a consortium of key people in the field. This would put the UK in a leading role in the development of KID-based instrumentation.

Societal and Economic Impact

The discoveries from astronomy inspire the next generation of STEM students and the existence and understanding of dark matter and dark energy are some of the most fundamental questions in modern astronomy. KIDSPEC development includes the areas of superconductivity, cryogenics, radio frequency engineering (read-out system) and data intensive science and will help to train the next generation of researchers in these fields. The development of KIDSPEC will showcase the technology and enable us to engage with industry. The potential applications for KIDs outside of astronomy are enormous, bringing together the fields of low-light level imaging and hyperspectral imaging. These include the fields of biomedical imaging (advanced fluorescence lifetime imaging), quantum optics (photon number counting), remote sensing (wide passband hyperspectral imaging) and defence (advanced night vision).

Scale of investment

We estimate the construction budget for such an instrument is ~£5M, which includes ~£2.5M in hardware costs. This is based on previous experience with MKID instrumentation. Additional partners will be sought to provide additional funds, especially in the area of operations.

A 12U CubeSat (SUPERSHARP) for direct imaging of exoplanets

(July 2018 - A proposal in response to the STFC's call for priority projects)

PI: Ian Parry, University of Cambridge, UK. (irp@ast.cam.ac.uk)

Co-Is: G Hawker, M Johnson, M Wyatt, D Queloz, N Madhusudhan, D Buscher (Cambridge), A Triaud (Birmingham), S Hinkley, A Carter, E Matthews (Exeter), B Biller, J Vos, M Bonavita (Edinburgh), S Aigrain, N Thatte, P Irwin, R Garland, J-L Baudino (Oxford), G Kennedy (Warwick), J Eberhardt (UCL).

Project Outline

We propose to build and launch a low-cost 1.5m diffraction-limited space telescope to primarily directly image exoplanets. The mission will also support many other science programs across all of astronomy for the benefit of the UK astronomical community. The telescope will use the SUPERSHARP unfolding, self-aligning technology, which allows a primary mirror with a span of 1.5m to be folded into a 12U CubeSat launch format (12kg, 36cmx23cmx24cm). This gives a spatial resolution of 50mas at a wavelength of 300nm. The primary mirror is unfilled and segmented with a fill factor of ~25%. The telescope will capture images in the wavelength range 250-1000nm and will operate in a low earth orbit (~550km). It will have a coronagraph with a raw contrast of 1×10^{-5} to 1×10^{-6} and will detect exoplanets with a planet-star contrast $>1\times10^{-8}$ via precision subtraction techniques.

Currently, the SUPERSHARP concept (Segmented Unfolding Primary for Exoplanet Research via Spectroscopic High Angular Resolution Photography) is being developed in the lab using funds (~£200k) obtained through STFC and the UKSA. Once we have successfully demonstrated the concept in the lab, we plan to build and launch an in-orbit CubeSat technology demonstrator (either 3U or 6U) in the next 2-3 years. Funding for this (~£2M) could come from STFC but it could also come from sponsors who are primarily interested in Earth Observations (EO) for commercial reasons including UKSA, Innovate UK, and VC funding.

This science proposal will follow on from a successful in-orbit demonstration of the SUPERSHARP technology and so, once it gets to this stage, everything will be at TRL9 and it will have low technical risk. Essentially, our plan decouples the risky technology development program from the science program. The main science objective is to look at 20-50 nearby stars to directly image relatively bright (7-10 earth radii) exoplanets in orbits of 0.3 – 2.0 AU, via their **reflected light**. We will use RV data (amplitude >20m/s, biased to edge-on systems) and GAIA data (biased to face-on systems) to identify stars (M, K, G and F types) that have planets with contrasts in the range 1×10^{-8} to 2×10^{-7}. This search will use ~2.5 of the 5 years of the mission lifetime. The data will help answer questions about planet occurrence rates, planetary system evolution and formation, planetary atmospheres and planetary interiors.

For the remaining time, the telescope will also be available to the whole UK community for general use and all data will be made available to the whole UK community.

Science Case

Most of the >3000 exoplanets known have been indirectly detected (transits or RVs). Direct imaging, transit spectroscopy, and high spectral resolution observations detect photons from the planet itself, enabling direct measurement of atmospheric properties. Crucially, only direct imaging can characterise exoplanets at semi-major axes of 1-10 AU, similar to our own solar system. Ground based direct imaging efforts are limited by atmospheric turbulence and systematic errors -- the ~dozen directly imaged planets to date are all widely separated, young (<100 Myr), hot (~600-100 K) giant planets imaged via their thermal emission in the IR. Young stars are rare, limiting searches to more distant stars (and thus worse physical resolution). Older, cooler planets around nearby stars are too faint in the NIR and must be imaged via reflected light. This requires reaching planet-star contrasts of $>1\times10^{-8}$ and diffraction limited performance at 250nm - 600nm - possible only from space.

JWST will not have the time to study such a large sample and it does not have a coronagraph that operates in the visible part of the spectrum. WFIRST will launch after this project.

The mission proposed here will be a pathfinder for future, bigger missions including searching for bio-signatures (see arXiv:1801.06111). The SUPERSHARP concept is completely scalable.

In general, for all science areas, this will offer high precision photometry and high spatial resolution imaging (compared to ground based telescopes) including the wavelength range 250nm – 600nm, which may become completely inaccessible should HST stop working.

Leadership and potential team members

In this document, Parry is the PI because he is the PI of the SUPERSHARP technology development program including the in-orbit technology demonstrator. The co-I's represent the UK's exoplanet direct-imaging community who are supportive of this proposal at this early stage. A broader team will be set up for the non-exoplanet science and to decide telescope time allocation.

Societal and Economic Impact

The SUPERSHARP concept has tremendous commercial potential because of its applicability to EO. The PI aims to spin-out a company to sell SUPERSHARP telescope systems.

SUPERSHARP's unique selling point is that it provides 10× better resolution for a given launch cost. This has the potential to be a disruptive technology. The commercial products generated will be unfolding telescopes as both satellite sub-systems and complete satellites. We expect to be able to sell hundreds of units at price points ranging from hundreds of thousands to millions of pounds per unit and we estimate the Specific Addressable Market to be >£100 million.

The End users will be: 1) Large aerospace/EO companies such as Airbus (including SSTL) , Maxar (formerly MDA-DigitalGlobe), and Thales who sell imaging platforms at £1M to £100M per unit, and/or imagery via brokers such as Earth-I and LandInfo.com with archive/new tasking imagery selling from \$312.50/\$537.5 per 25km^2 unit. 2) EO small satellite start-ups that have received >\$150 million in venture capital such as Planet and Spire. 3) Large science projects such as the one described here. 4) Industrial partners working with us to develop custom platforms incorporating standard and larger scale SUPERSHARP technology on a consultancy basis.

An important capability development follows from the machine-learning and deep-learning techniques that will be applied to the large datasets that SUPERSHARP will produce.

We will actively seek opportunities to support technology transfer to business partners (including SMEs and enterprising students) and demonstrate the benefits of the project to policy makers in government and elsewhere. A small percentage of telescope time will be reserved for "student" projects to help train the next generation of astronomers. We also intend to make time available to the general public and media to support engagement activities for large groups and audiences.

Scale of investment

This will be a small-scale (<£10M) project (compare for example with the "Skyhopper" 12U Australian CubeSat project – PI: Trente, Univ. Melbourne). Our ROM cost estimates are £2M for the in-orbit technology demonstrator and £7M for the 12U science mission.

These very low costs may seem too good to be true but they absolutely are not. They are a direct result of the "New Space Revolution" whereby the commercial sector has now become the dominant investor in what was, until 5 years ago, a field dominated by government agencies. Our costs are based on comparisons to other CubeSat missions and published prices for CubeSat components and launch services. There is now a tremendous opportunity to have high impact space-based science missions at much reduced costs compared to traditional NASA/ESA missions (see for example "On the verge of an astronomy CubeSat revolution" by Evgenya Shkolnik, Nature Astronomy, Vol 2, May 2018, 374–378). Currently, the UK is lagging behind and it is crucial that the UK does not miss out on this opportunity. The SUPERSHARP technology has the potential to make the UK a world-leader in this field. Also, with these low-costs it is possible to have several space telescopes serving different science areas and communities.

Priority projects – summary outline for Advisory Panels

Project Name: The Far-Infrared Spectroscopic Explorer (FIRSPEX)
Principal Investigator/Lead Contact: Prof. Dimitra Rigopoulou (Univ. of Oxford)

Project outline: The Far Infrared Spectroscopic Explorer (FIRSPEX) is a novel UK-led astronomy mission concept developed to enable large area ultra-high spectroscopic resolution surveys in the THz regime. FIRSPEX taps on a relatively unexplored spectral and spatial parameter domain that will produce an enormously significant scientific legacy by focusing on the complex physics of the interstellar medium, the assembly of molecular clouds in our Galaxy and the onset of star formation; topics which are fundamental to our understanding of galaxy evolution. FIRSPEX science has great synergistic values with both ALMA and SKA where the UK has already made strategic investments. Through wide area spectral maps of the gaseous component of the interstellar medium FIRSPEX will unveil the complex physics that regulates the conversion of gas into stars and eventually the formation of planets. FIRSPEX comprises a ~1m lightweight telescope (SiC) operating from low earth orbit (LEO). At the heart of the FIRSPEX mission is world-class terahertz technology realised in the form of ultra-high spectral resolution space-born heterodyne receivers. The FIRSPEX Consortium is led from the UK and involves European teams (France, Germany) as well as Chinese (PMO, CAS) and eventually participation of the Indian Space Research organization (ISRO). The UK is strategically placed to control the research agenda of the mission and deliver cutting edge science whist the technical leadership and contribution of specific payload components ensures that the UK will remain at the forefront of THz technologies and applications. While a number of exciting space and ground-based facilities will emerge in the next 10 years, FIRSPEX has a unique place on the world scene and the ability to turn the narrative of the star formation potential of galaxies into quantitative theory by providing answers to many outstanding questions from the formation of planets to the evolution of galaxies and the origin of heavy elements in the Universe. The UK should seize this opportunity.

Scientific case: Star formation and the ultimate destruction of molecular clouds are fundamental processes at the heart of galaxy evolution. The interstellar medium (ISM) of galaxies is the reservoir out of which star forming cores condense and the repository of gas ejected by stars at the end of their evolution. The cycling of baryonic matter between different reservoirs drives the evolution of galaxies. Understanding the coupling between the mass in stars and the various components of the ISM is essential for a complete model of the formation and evolution of galaxies. Previous IR missions (IRAS, ISO, Spitzer, AKARI, Herschel and Planck) have made great strides in elucidating the properties of the coldest and densest components of the ISM and, the mechanisms that lead to the formation of stars and planets, the building blocks of galaxies. However, all of these missions have had limited ability to probe the components of the ISM and especially its velocity structure which is key to unlocking its 3D structure. FIRSPEX targets the properties of the ISM through spatially resolved observations of its key components. By scanning the entire sky in four discrete spectral lines FIRSPEX will unravel the complex kinematic signatures of the ISM components and study the onset of star formation. The FIRSPEX spectral bands are centred on the following key lines: CI (809 GHz), CII (1.9 THz), NII(1.4 THz) and OI(4.7 THz). Each spectral line has been carefully chosen to allow FIRSPEX to probe a different phase of the ISM: from cold neutral material (CII) to dense gas (OI). The key questions of the FIRSPEX mission are:

1) How do molecular clouds form and collapse to form stars and planets?

2) What is the life-cycle of matter across cosmic time?
3) What fraction of the baryonic matter is in CO-dark gas?
4) What regulates star formation in galaxies?

The FIRSPEX science team has designed a suite of observations to tackle these questions. The flagship program of FIRSPEX is a wide area survey of the Galactic Plane (+/-5 degrees above and below) in unprecedented sensitivity. The survey will resolve (in velocity-space) individual clouds and allow us to study the interfaces between ISM components, the feedback of massive stars on their environment and the conditions for the formation of stars. In addition, FIRSPEX will map a large sample of nearby galaxies to try and elucidate the properties of the ISM in different environments. The FIRSPEX sicence themes align perfectly with the STFC Science Board Strategy and are at the forefront of modern astrophysical research.

Leadership & potential team members: The FIRSPEX concept is led by Prof. D. Rigopoulou from the University of Oxford. UK Consortium team members include: Prof. B. Ellison (technical lead), Dr. C. Pearson (RAL-STFC), Prof. S. Viti, Dr. G. Savini (UCL), Prof. E. Linfield, Dr. A Valavanis (U Leeds), Prof. G. Yassin, Dr. B. K. Tan (U Oxford), Prof. G. Fuller (U Manchester), Dr. H. Fraser (Open U).

Societal and Economic Impact: FIRSPEX probes the fundamental building blocks of the Universe: how do stars form? When and where did the Carbon we have in our body and the Oxygen we breathe first formed? Extensive spectral mapping of large areas of the IR sky in the terahertz frequency range is an essential methodology for understanding the formation and subsequent evolution of the Universe. Terahertz observation of the ISM gives astronomers a unique observational window that directly enhances scientific knowledge of our Universe. The FIRSPEX THz high-spectral resolution instrument will widen the frequency range observed from space to limits within the terahertz region never before attempted. Through this advancement a new imaging capability will be made available. Scientifically, added value will be achieved through the mission data output complementing current and planned ground-based instruments in which the UK is heavily involved, i.e. ALMA and the SKA, respectively. Moreover, it will build upon the science and technical output and developments of past space missions, e.g. Herschel and Planck, that have provided very substantial science return and with which the UK has also had significant involvement. Having gained significant traction within the UK and wider European and international communities, the FIRSPEX mission thus brings together leading scientific and technical groups in the form of a UK led consortium that proposes a new and novel mission that will substantially advance science and technology. Through its project leadership, scientific and technical skills, cross-flow of information and knowledge between partners, and use of new space facilities, the UK will build upon and demonstrate its considerable strength in key and related areas of scientific and technical endeavour, and further raise its standing in respective fields on the world-stage. The technology development on the FIRSPEX receivers has application (and indeed is ongoing work) for an Earth Observing mission to help quantify different molecular species in the lower thermosphere which are believed to play an important role in regulating the heat exchange in the upper atmosphere and thus impact climate change.

Scale of investment: A medium-size investment from STFC of £10Mi -£20Mi will enable the development of the FIRSPEX payload. The cost of the spacecraft is pursued through a collaborative project with industry and deployment through developments of a privately owned platform (One-Web) while the cost of the launch could be borne by one of our consortium partners.

***Priority projects* – UK participation in SDSS-V.** This project will support a large and diverse group of UK scientists as participants, with data rights, in SDSS-V[1] (Sloan Digital Sky Survey). In 2020-2025, SDSS-V will conduct the first optical and infrared all-sky, multi-epoch spectroscopic survey of $6{\times}10^6$ objects. UK participation in SDSS-V is crucial to maintain leadership in the growing area of multi-object spectroscopy. All Co-Is are international leaders across the SDSS-V science remit.

Project Name: Pioneering Panoptic Spectroscopy -- UK participation in SDSS-V
Principal Investigator/Lead Contact: Dr Francesco Shankar, U. of Southampton

Project outline

SDSS-V will decode the history of the Milky Way Galaxy (MW), reveal the inner workings of stars, and the origin of planets. It will create a contiguous spectroscopic map of the interstellar gas in the MW and Local Group 10^3 times larger than the state of the art and at high enough spatial resolution to reveal the self-regulation mechanisms of galactic ecosystems. SDSS-V will pioneer all-sky spectroscopic monitoring, revealing time variations from 20 minutes to 20 years, detecting down to the flickers of massive black holes, and identifying ~$4{\times}10^5$ *eROSITA* sources.

Scientific case

SDSS-V will take advantage of 2.5m telescopes in *both* hemispheres, each equipped with a 300-fibre R~22,000 infrared spectrograph and a 500-fibre R ~2000 optical spectrograph, to conduct the first multi-epoch spectroscopic survey of the whole sky. It is the ideal complement to *Gaia*, *TESS*, *eROSITA*, *LSST*, *PLATO*.
The SDSS-V Milky Way Mapper will generate the most detailed yet extensive map of the structure of the MW disc and bulge in multi-dimensional (age-chemistry-kinematics) space. It will reveal the MW star formation, mass assembly history and initial mass function, generate unprecedented binary star statistics, and provide a robust characterization of exoplanet hosts and their planets. SDSS-V will also investigate the structure of white dwarfs and their role as progenitors of Type Ia supernovae. An all-sky coverage of low latitude, makes SDSS-V a perfect complement to other (partly) UK-funded MW programmes, e.g. *WEAVE*, *MOONS*.
The SDSS-V Local Volume Mapper, with contiguous optical spectroscopy (3600-10000Å, R~4000) over thousands of square degrees, will map entire galaxies (e.g., MW, M31, M33) with unprecedented spatial resolution (down to 0.1-1 pc) and coverage. Connecting pc (sub-GMC) to kpc (galaxy-wide) scales will reveal the physics governing star formation, the structure and energetics of the interstellar

[1] https://www.sdss.org/future/

medium, the baryon cycle, and, ultimately, the evolution of galaxies.

The SDSS-V Black Hole Mapper will obtain redshifts and spectroscopic classifications of 4×10^5 sources from the *eROSITA* experiment, predominantly quasars and Active Galactic Nuclei (AGN). SDSS-V will also carry out reverberation mapping (~150 epochs) of 1500 quasars and coarser time-domain spectroscopy (~10 epochs) of 25,000 quasars. This will generate vast data on black hole masses, clustering, energy distributions, and quasar variability, which probe from the very inner to the largest scales around massive black holes, providing the most accurate tests to black hole-galaxy co-evolution models to date.

Leadership & potential team members

With its strong emphasis on time-domain (repeat) spectroscopy, MW archeology, and AGN demography, SDSS-V will provide a wealth of exciting and unique data to be readily used by UK-based astronomers who are world-leading experts in: 1) high-speed astronomy, with the STFC-supported ULTRACAM and HiPERCAM high-speed cameras; 2) asteroseismic data, chrono-chemo-dynamical maps of the MW, exoplanets hosts (*TESS*, *Kepler*, *K2*); 3) cutting-edge models of black holes. The PI, Francesco Shankar, has co-led numerous SDSS-based studies of galaxy-black-hole co-evolution. Other team members include the Survey Scientist of the SDSS-III APOGEE survey (R. Schiavon, LJMU), the MaNGA lead observer and SDSS-IV data co-lead (A. Weijmans, St. Andrews), a co-lead of the APOGEE-*Kepler* collaboration (B. Chaplin, Birmingham), and leading players in SDSS white dwarfs (B. Gaensicke, Warwick) and quasar reverberation mapping (K. Horne, St. Andrews) studies. Other participants, many of them former SDSS collaborators, are: D. Alexander (Durham), A. Aragon-Salamanca (Nottingham), G. Davies (Birmingham), A. Lawrence (Edinburgh), M. Martig (LJMU), A. Miglio (Birmingham), S. Parsons (Sheffield), N. Reindl (Leicester), C. Villforth (Bath), V. Wild (St Andrews). With participation in SDSS-V, UK scientists should continue maintaining leadership positions within the SDSS collaboration.

Societal and Economic Impact

UK participation in SDSS-V would link the community to one of the most influential ground-based astronomy projects of the last quarter-century. UK participants will develop novel data-driven algorithms in, e.g., time-domain modelling and data mining, in high demand in the private sector. With in-house outreach officers they will lead outstanding public engagement activities (e.g., art-projects, mobile planetariums) to bring the newest discoveries of SDSS-V to the broader audience.

Scale of investment

Membership to this ground-breaking survey for ~20 faculty-level participants (and their postdocs and graduate students) would cost ~£3.5M, well within the “small” category. Membership entails proprietary access to pre-publication SDSS-V data. Leveraging ~£40M of investments by other institutions around the world and the Sloan foundation, the scientific return on this investment is extraordinarily high.

Science & Technology Facilities Council

Priority projects – summary outline for Advisory Panels

Project Name: PRISTINE-UK
Principal Investigator/Lead Contact:
Lead Contact UCL – Giorgio Savini (g.savini@ucl.ac.uk)
Lead Contact Manchester – Jens Chluba (jens.chluba@manchester.ac.uk)

Project outline

PRISTINE is a small satellite concept with a two-telescope nulling polarized Fourier Transform Spectrometer with a wide spectral coverage (90 GHz – 2 THz). PRISTINE will make the first major leap beyond the original Nobel prize-winning COBE-FIRAS measurements of the cosmic microwave background (CMB) frequency spectrum, providing all-sky polarisation measurements with detailed spectral information (including lines) at high-frequency. With full spectral coverage achievable only from space, and using current state-of-the-art and readily available (high TRL) technology, PRISTINE is in a unique position to open a new frontier in CMB cosmology and complement ongoing searches for primordial gravitational waves from the ground. PRISTINE is currently undergoing Phase-0 study in France (Lead country) with UK contributions (UCL, Manchester, Oxford).

Scientific case

Since the 1992 COBE/FIRAS measurements, the CMB frequency spectrum is known to be extremely close to a perfect blackbody, with deviations limited to $\Delta I/I \sim 10^{-5} - 10^{-4}$. These distortions are of two main types: Compton y distortions from energy releases (optically thin; low redshift) and chemical potential μ distortions (optically thick; high redshift). Measuring guaranteed spectral distortions from the primordial universe, such as the cosmological recombination lines originating at redshift z~1000 or due to the Silk damping of small-scale acoustic modes created during inflation, requires between 3-4 orders of magnitudes' improvement on the COBE measurements. Other distortions from the primordial universe yield probes of new physics, such as dark matter (DM) interactions with the standard sector or non-standard physics (e.g. DM annihilation, decaying gravitinos or axions, primordial black holes, super-conducting strings). Spectral distortions from late-time cosmology such as reionisation and large-scale structure formation and evolution (e.g., the Sunyaev-Zeldovich (SZ) effect of galaxy clusters and the cosmic web, cosmic infrared background, first galaxies) are attainable within a realistic improvement on COBE (between 1-2 orders of magnitude). They are part of the standard cosmological model and represent guaranteed signals bearing very high scientific return. In combination with the E-mode polarisation, spectral distortions will enable us to differentiate between reionisation scenarios based on first stars or galaxies. Compton y distortions will reveal the gas content of the cosmic web, representing much of the baryonic component of the cosmos, and allow us to measure its temperature using relativistic corrections to the SZ spectrum.

Currently PRISTINE is the only proposed experiment on the horizon focusing on CMB spectral distortion measurements, opening up this rich and novel science case. In addition it will strongly complement the broader international CMB cosmology programme by measuring the Thomson optical depth, as well as exquisite measurements of the large-angle foreground components. The latter will allow improved foreground correction to both ground- and space-based CMB experiments with limited frequency coverage, which are targeting primordial gravitational wave signals from inflation.

Leadership & potential team members

PRISTINE is currently led by the IAS, France (Aghanim and Maffei) and a CNES study on the preliminary mission design is ongoing in relation to ESA's F-class mission call released 16/07/2018. The mission concept stems from a previously proposed US design (PIXIE) led by Kogut (Princeton) and Fixsen (NASA-Goddard, PI of DIRBE on COBE), with whom an agreement is currently being sought for US participation. This is an ideal time for the UK to invest in this unique mission to secure leadership both in the instrumentation and scientific exploitation. The PRISTINE-UK Consortium plans to contribute equally to instrumentation (design and build), the cosmology theory and data analysis. Instrument lead Savini is currently actively engaged in the first PRISTINE concept designs triggered by mission requirements, and has extensive experience from the calibration and testing of the Planck HFI experiment as well as work on the (unpolarised) Herschel SPIRE-FTS data analysis. Science lead Chluba is an international expert in CMB recombination physics. He has been at the forefront of the resurgent international interest in developing CMB spectral distortions as a powerful new cosmological probe. The potential team members include world leaders in CMB instrumentation, cosmological theory and data analysis.

Instrumentation Team: G. Savini (lead), B. Winter (UCL); P.A.R. Ade, G. Pisano, C. Tucker (Cardiff); M. Crook (RAL).

Science Team: J. Chluba (lead), R. Battye, M. Remazeilles (U. Manchester); H. Peiris, A. Pontzen, J. McEwen, T. Kitching (UCL), M. Abitbol (Oxford).

Societal and Economic Impact

The new frontier represented by CMB spectral distortions will shape *future cosmological models* (as the Nobel-winning COBE measurements did in the past), and could shed light on the *nature of dark matter* as well as the *origin of our Universe*, yielding strong societal impact. As in most cases, technology advancement in the build of new experiments is tensioned against "readiness" and risk aversion from space agencies. We aim to capitalize on the previous technological success achieved through STFC on Planck HFI and the Herschel SPIRE-FTS in order to maximize chances of selection of PRISTINE.

Scale of investment

This project fits on the high-end of the small-scale definition provided, with hardware and support costs through the development and exploitation phases totalling to close to 10M (this depends on the selection of the coolers and the involvement of RAL Space). Theoretical studies are expected to be supported through standard routes (including Consolidated Grants). The UK is expected to participate in PRISTINE at Co-I level, with contributions to the hardware of the instrument payload (quasi-optical components and potentially coolers from RAL) as well as support for science activities running up to launch, in case of selection in the new F-class mission call (for reference, the F-Class Phase 1 proposal deadline 25/10/2018; launch readiness is expected Dec 2027).

Science & Technology Facilities Council

Priority projects –

summary outline for Advisory Panels

Project Name: Gravitational-wave Optical Transient Observer (GOTO)
Principal Investigator/Lead Contact: Danny Steeghs (Warwick)

Project outline

The UK's key role in the development of sufficiently sensitive gravitational wave detectors has firmly paid off with a string of highly significant detections during the first two science runs of the advanced GW detector arrays. The first binary neutron star merger signal (August 2017) led to an unprecedented global follow-up campaign featuring facilities across the EM & astro-particle spectrum. Key for this to be possible was the early localisation of the source so that our fleet of sensitive facilities could be pointed at it. Generally, the GW signal by itself only provides loose constraints on the source location, typically in the form of a wide arc of the sky spanning hundreds of square degrees. This challenge will remain till well into the 2020s when additional detector arrays may become available that will improve the typical localisation by GW alone. The ability to survey such regions quickly and isolate viable source candidates is not easy to achieve with our existing infra-structure. We have developed a cost effective design using an array of autonomous robotic telescopes optimized for this specific challenge. It offers to fill a critical gap in our infra-structure at a pivotal point in this emerging field of gravitational wave astrophysics.

Scientific case

The Gravitational-wave Optical Transient Observer (GOTO) was envisaged as a rapid response system targeting the early localisation of gravitational wave sources. The design centres on using arrays of wide-field optical telescopes in order to survey the sky regularly in anticipation of detections. Immediately following a detection, the region of the sky consistent with the source location is searched intensively and compared with very recent passes over the same area of sky. The prototype phase of the project has been deployed at the La Palma Observatory, a premier observing site that also offers a variety of follow-up facilities. The prototype is able to reach 20th magnitude in a few minutes and can push deeper if required. This makes it a very competitive facility on the global scene and thanks to our design principles, it can be scaled up quickly and cost-effectively. The exotic sources that power these events offer unprecedented insights into fundamental questions, such as the origin of heavy elements, their possible use as cosmological beacons, luminous relativistic outflows and fundamental physics concerning our understanding of gravity and the formation and structure of compact objects. But for gravitational astrophysics to deliver, we need not only sensitive GW detectors and powerful follow-up telescopes. The hunt and rapid localisation of viable sources is key and without it our facilities cannot be properly exploited. The vision of the project is to scale the La Palma prototype into a full node consisting of 16 unit telescopes that can capture 80 sqr deg of sky and deploy a 2nd identical system in the Southern hemisphere. With 16 units at each hemisphere, a high cadence survey of the optical sky is possible. All GW detections would then be in reach and such a facility would also probe unexplored parameter space for a variety of other transient phenomena.

Leadership & potential team members

The GOTO project is a partnership consisting of the Universities of Warwick, Monash (Australia), Leicester, Sheffield, Armagh Observatory and the National Observatory of Thailand. Additional partners are interested in joining, including the University of Turku (Finland) and several UK groups. We thus see it as a UK-led project that operates on the global scene of gravitational wave follow-up, competing with US facilities such as ZTF and upcoming projects such as BlackGEM (NL). In addition to cementing a key role for our community in gravitational wave astrophysics, GOTO will also be able to study and discover a variety of other exotic sources, linking with other UK investments such as CTA, neutrino experiments, the LSST and SKA and its pathfinders.

Societal and Economic Impact

Gravitational waves have captured the imagination of the public, and media interest during the early years has been intense. It offers inspiring science, an excellent example of collaborative science achieving what seemed impossible till recently. The facility will also generate vast amounts of data and exploiting the cutting edge of data mining tools such as machine learning is key. The related data mining infra-structure and expertise will offer good impact opportunities. We currently are using a Newton Fund grant with Thailand to explore some of these issues, which involves not just astronomers but also computer scientists and database experts. We also see strong opportunities for citizen science given the vast amount of imaging data the project will produce.

Scale of investment

GOTO has thus far been funded by the consortium partners, amounting to a capital investment of £750k as well as significant human resources. We are now in an ideal position to use our experience with the prototype hardware and deploy the envisaged array of telescopes. The capital cost to complete the La Palma node is £700k. A Southern node would require a capital investment of approx. £1.5 million, dependent on site. Site operating costs amount to £200k/year (for two sites & dataflow). A final key component is operational support covering 3 FTE noting that managing the dataflow is a key aspect to ensure that the science products can be delivered and served. The proposed GOTO deployment is thus classed as a small project, consisting of £2.2 million of capital investment and a combined operational cost of approximately £350k/year.

Science & Technology Facilities Council

Priority projects – summary for Advisory Panels

Project Name: New Robotic Telescope (NRT)
Principal Investigator/Lead Contact: Iain Steele, Liverpool JMU

Project outline

We propose a contribution to the construction (£15M) and operation (£10M over 20 years) of a new 4m robotic telescope (provisionally 'NRT') on La Palma and its instrumentation. This will guarantee UK leadership with a 60% time share. It will maintain and grow traditional UK strengths in time domain and solar system physics and exploit considerable STFC investment being made in projects such as LSST, aLIGO, CTA & PLATO. It addresses Science Roadmap Challenges: A:3. Dark matter and dark energy; B:1. Extrasolar planetary systems; B:2 Dynamic influence of the Sun on Solar System bodies; D:1. Extreme physics; D:2. High energy particles and gravitational waves; D:3. Ultra-compact objects, extreme gravity and the impact on environment. The case has recently become even stronger with the discoveries of EM counterparts to gravitational wave (aLIGO/Virgo) and neutrino (IceCube) sources, a greater role for the UK in LSST and the planned repurposing of INT and WHT.

Scientific case

The next decade will see the commissioning of many major new international projects that will open windows on the time variable universe. They will search wider areas of the sky than has ever before been possible and find new classes of transient and time variable sources using techniques such as radio waves, high-energy gamma rays, particles and gravitational waves. These 'discovery' facilities are often massive ~£1bn scale projects involving the collaboration of many countries. We identify a critical need (https://arxiv.org/abs/1410.1731) for 'a new 4.0m follow-up' facility which can rapidly respond to such discoveries and make detailed photometric, spectroscopic and polarimetric studies. We highlight examples such as (i) ultra-rapid (<30s) spectroscopic and polarimetric follow-up of EM counterparts of GW (aLIGO/Virgo) and neutrino (IceCUBE/ANTARES) sources and new radio (e.g. LOFAR/SUPERB) and high energy (e.g. SVOM, Fermi, Einstein Probe) transients, (ii) rapid (<1 hr) spectroscopy and polarimetry of (e.g. LSST/ZTF) SNe to explore the shock-breakout phase and find spectral signatures of the progenitor, and of recurrent Novae which are the supposed progenitors of SNe-1a, (iii) timely (<24 hrs) and time resolved spectroscopy of the evolution of the previously mentioned sources, plus galactic transients such as outbursting binary X-ray transients and eruptive YSOs detected by VISTA/Pan-STARRS/LSST, and (iv) simultaneous spectroscopic and polarimetric monitoring of sources such as Blazars (e.g. with Fermi, CTA) and changing look AGN.

Satellite surveys (e.g. TESS, PLATO) will find a zoo of new exoplanets which will need ground-based characterization via time variable signatures (e.g. transit spectroscopy and polarization, detection of debris disks) and preparatory observations to select ARIEL targets. And within our solar system, science is naturally dominated by the time domain. NRT will contribute to understanding the physics of individual Solar System objects (e.g. YORP effect in asteroids, simultaneous spectroscopy and polarimetry of small bodies in conjunction with rendezvous missions (e.g. Psyche, Lucy) for gas and dust composition and dynamics, and monitoring the post New Horizons encounter evolution of the surface chemistry of Pluto). It will also support population studies where fast non-sidereal tracking will enable spectroscopic observations of moving targets, an important tool for taxonomy. The robotic operations model will allow rapid follow-up of new discoveries (e.g. LSST, ZTF, Pan-STARRS) to extend the orbit arc and studies of transient events such as asteroid collisions and interstellar visitors.

The La Palma location will be complementary to the specialized observing roles being adopted by the ING telescopes with WEAVE delivering statistically complete catalogues of object populations and NRT delivering follow-up of variable and the rare objects not well suited to the massively multiplexed

WEAVE model. It will ensure UK astronomers retain and improve access to the Northern transient sky (many sources of transients are all sky e.g. Gaia, GWs, GRBs or Northern e.g., ZTF, CTA-N, IceCUBE etc.). La Palma is also sufficiently equatorial that many LSST targets will be visible for ~4-6 hours per night. Co-location with the GOTO GW counterpart finder and the current LT (which we plan to transition to a wide field survey/transient detection machine) also adds value. The La Palma site therefore offers considerable scientific synergies and opportunities, combined with its logistical and cost advantages due to its relatively nearby location and well developed existing infrastructure.

Leadership & potential team members

This proposal gives UK leadership in many of the highest priority science topics of the coming decades. It is led by LJMU (who have committed £1m in new project office staff) with international partners (Spain, Thailand). Interest in participation (https://goo.gl/AJowwd) has been received from individuals and groups at Bath, Birmingham Cambridge, Durham, Edinburgh, Exeter, Hertfordshire, Kent, Leicester, Liverpool, OU, Oxford, QUB, Southampton, Surrey, St Andrews and Warwick.

Societal and Economic Impact

NRT will significantly enhance the activities of the hugely successful National Schools' Observatory (NSO) which provides educational resources and allows schools to make observations on the telescope. A 2013 independent review by Sheffield Hallam University concluded "...this initiative has unprecedented reach and is one of the most significant educational initiatives in the STEM field linked to an HEI". The NSO website receives 1.5 million visits per year, and to date there have been over 120,000 requests for data from more than 2,500 schools. NRT serves NSO in two ways. It will release more observing time for NSO activity on the existing LT and it will be used by the most motivated students, leading ambitious projects contributing to the scientific research programme of the telescope. There will also be the opportunity to engage with the public and schools during the development of the telescope reaching students in other STEM areas such as engineering and computer science. The latter is of particular interest since 'big data' and 'AI' challenges are a key aspect of NRT. Such challenges are also well matched to 'crowdsourced' solutions and a citizen-science programme would be a natural way to take these aspects outside of the classroom.

The proposed optical design is conventional (4m f/7.5 RC). However there is considerable technical novelty in the proposed implementation to ensure we can deliver the rapid slewing capability (<30s on target for any source) needed for the science case. We are exploring the option of using a segmented primary mirror to reduce the total mass of the system. Our baseline is to adapt the GTC mirror support, handling and re-aluminizing model as part of a 6-segment design. This reduces development and operations costs and represents the first time segmented technology will be scaled down to a 4-m class telescope. We will deliver significant industrial/economic impact by developing a UK supply chain for key components, including mirrors (e.g. Glyndwr Innovations who manufactured E-ELT prototype segments), high precision structures for harsh environments (e.g. Cammell Laird) and lightweight structures for precision scientific instruments (e.g. UKSpace SME members). The new telescope will also be an ideal testbed for new technologies in astronomical instrumentation and detectors, for example the MKIDS optical detectors and associated spectrograph currently under development at Durham University. We also note that working with IAC we are exploring a model for commercialization by UK and European partners of the NRT design into an "off the shelf" solution for worldwide markets in astronomy, space tracking and asteroid defence applications. This may also provide the opportunity to develop a southern hemisphere twin of NRT at a later date. Finally, there is considerable potential to develop strong international (ODA) impact (GCRF and Newton), building on already successful collaborative activity with Thailand in telescope control and archive software.

Scale of investment

The project is well established with a LJMU funded project office leading conceptual design and signed international MOUs. It is "ready to go" on receipt of funding. The STFC contribution request is of "medium" scale. Total capital cost (including a first light imager/spectrograph and contingency) is estimated at £22M. Operating costs over 20 years are estimated at 20*£1M/year = £20M. We seek an STFC contribution of £15M to capital costs in the period 2019-2023 plus £500k/year over 20 years in 2023-2043 for operations. This would yield a UK time share of 60%. Other time shares based on their contributions would be Spain (~30%) and Thailand (~10%). We note neither LJMU or any other partners are seeking to have exclusive access to particular science areas or operating modes.

Priority projects – summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: Twinkle – a mission to unravel the story of planets in our galaxy
Principal Investigator/Lead Contact: Marcell Tessenyi, Giovanna Tinetti and Jonathan Tennyson (UCL/BSSL)

Project outline

The Twinkle Space Mission is a small (45 cm telescope), low-cost mission that will use spectroscopy in the optical and infrared to analyse exoplanets and solar system objects. The mission is designed to address two cutting edge areas of science with currently limited access to data: spectroscopy of exoplanets and solar system objects. Twinkle will be able to reveal the chemical composition, weather and history of worlds orbiting distant stars. In addition, the satellite design is compatible with other science areas including solar system spectroscopy (asteroids, NEOs, moons, planets, comets). The Twinkle satellite will be built in the UK and launched into a low-Earth orbit within 3 to 4 years.

Twinkle offers spectroscopic capabilities from the visible to the infrared (0.4 to 4.5 μm). The provision of this visible-IR coverage from space is a highly sought after capacity (e.g. oversubscription of HST, Spitzer). Some observational targets can be viewed from ground-based telescopes at certain wavelengths (e.g. visible) but significant issues are encountered in other bands due to atmospheric absorption, particularly if observing at IR or UV wavelengths. Additionally, ground observations can be affected by weather and atmospheric distortion. Space telescopes avoid these issues and thus are fundamental to increasing our knowledge of the Universe.

Twinkle is a new mission concept that aims to exploit the off-the-shelf capabilities developed by the earth observation community to launch a low-cost, quick (3 years to launch) mission. Twinkle is entering its mission definition phase (Phase B) funded through PPPs (public-private-partnerships); and is on course for launch in 2021/22.

Scientific case

Exoplanet science: Nearly 4000 exoplanets have been discovered and many more will be found in the next 5 years with upcoming surveys from space (e.g. TESS and CHEOPS) and the ground (WASP, NGTS, RV surveys). Twinkle will be able to probe a large number of planets at low spectral resolution, useful to refine planetary, stellar and orbital parameters, search for transit time variations (TTVs), refine the ephemerides and monitor stellar activity through time. For planets orbiting bright stars, Twinkle observations at higher spectral resolution will probe atmospheric chemical and thermal properties, with the potential to revisit them many times over the mission lifetime to detect variations such as non-uniform cloud cover. Existing and upcoming surveys mentioned above will reveal thousands of new exoplanets, many of which will be located within

Twinkle's field of regard. The James Webb Space Telescope (JWST) is expected to launch in 2021. Although a good fraction of JWST observation time is likely to be allocated for exoplanet science (e.g. Cowan et al. (2015)), for a space observatory of this scale, oversubscription is likely to be an issue and not all interesting science cases will necessarily require the sensitivity and accuracy of JWST. By 2028, the UK-led ESA ARIEL mission will be launched with a focus on characterising 1000 exoplanets to reveal the bigger picture of planetary formation through a statistical sampling of planets of many types. Twinkle's observations will be able to flag optimal targets for further analysis by the larger facilities, and will allow Twinkle to be available as a precursor facility.

Solar system science: Spacecraft studies of Solar System bodies have increasingly contributed to our knowledge of these objects over recent years. Whilst in-situ measurements provide the best means of understanding a target, dedicated lander, orbiting or fly-by missions are rare and thus remote sensing missions offer a great chance to observe objects of interest. Solar System targets, for which Twinkle's capabilities allow for the acquisition of high quality, high-resolution spectroscopic data within a single observation is found to incorporate planets and some larger moons. The potential also exists for observations of smaller moons and large asteroids at a lower resolution whilst photometric observations should be possible for a vast number of objects. The targets vary with spectral band; for instance, absorption features of water and OH of primitive asteroids (0.7, 3μm), as well as organic material on asteroid surfaces (3.2 to 3.6 μm) can be studied with Twinkle. In addition, spectral features at 2.7-3 μm make Twinkle especially well suited to surveying the larger objects in the asteroid belt.

Leadership & potential team members

MT, GT and JT are founding co-directors of the UCL start-up Blue Skies Space Ltd (BSSL) that is managing Twinkle. The Phase A technical feasibility studies were carried out by a number of UK research institutes, government organisations and space companies including Airbus-Surrey Satellite Technology Ltd, Selex/Leonardo, RAL Space, UKATC, UCL MSSL, Open University, Cardiff University. The satellite benefits from a high-heritage design: we will use a flight-proven low-Earth orbit satellite platform and will reuse existing components for the science instruments (e.g. UVIS spectrometer from the ExoMars NOMAD instrument).

Societal and Economic Impact

This model has the scope to dramatically changing the provision of space science satellites to the scientific community, by introducing a parallel stream of small, quickly launched satellites to address near-term science requirements.

Scale of investment

The total cost of the Twinkle Space Mission is estimated at £30M (excluding launch & operations) – "medium". BSSL is currently contacting the international scientific community, obtaining a very positive response. Twinkle is accessible to all scientists worldwide, interesting in buying telescope time to perform their science. The data will be provided encrypted to users. The UK community could have access to Twinkle via STFC or university funds/grants.

Project Name: Extending the search for nearby Earth-like worlds to the Northern Hemisphere **Principal Investigator/Lead Contact:** Amaury Triaud (U. Birmingham)

Project outline

The SPECULOOS consortium is currently finalising the construction of four robotic 1m telescopes at Cerro Paranal in Chile. This facility will monitor nearby very-low-mass stars seeking the photometric signals of planets the size of the Earth transiting their host. A pilot programme made in preparation for SPECULOOS discovered the highly celebrated TRAPPIST-1 planetary system (www.trappist.one; Gillon, Triaud et al. 2017). SPECULOOS can only observe targets in the South and most low-mass stars are in the Northern skies (due to an incomplete Southern census). This proposal aims to extend SPECULOOS to the North, by building at least one robotic telescope in Tenerife.

Scientific case

The search for life elsewhere has been debated about in writing for nearly two and a half millennia. Thanks to our recent discovery of suitable exoplanets, and thanks to the construction of facilities like the *James Webb*, or ESO's E-ELT, we will soon have the capability to remotely probe the atmospheric chemical composition of terrestrial exoplanets. Indeed, **within 10 years**, we expect to have collected data able to inform us on how the atmospheres of the TRAPPIST-1 planets compare to Venus, and Earth (Morley et al. 2017). The detection of multiple systems such as TRAPPIST-1 is key to understand the diversity of terrestrial climates, and how they are affected by stellar activity, how they relate to the inner composition and geology of the planet, to the presence of comets, and of course, to the existence of active biology.
There is a race on to rapidly identify which of the hundreds of very-low-mass stars exhibit transiting Earth-size planets. This is a race against time, since the *JWST* has a limited life expectancy, but also a race against various teams. Fortunately the SPECULOOS consortium has taken an important lead with the discovery of TRAPPIST-1, and the construction of our telescopes in Chile. We have however heard about several efforts attempting to replicate what we do in the South, in the North. The stakes are high; this is not a time to be overtaken.

Once the search for planets orbiting very-low-mass stars is completed, the facility will prove invaluable to follow up all know transiting exoplanets, found to date, but also those of *TESS* and *PLATO*. Atmospheric investigations require up-to-date ephemerides, which will need verifying. A ground-based facility can perform this task efficiently and save precious observing time on expensive infrastructure (*JWST*, *Ariel*, ELT). It will provide support for two ESA missions with important UK involvement (*PLATO* & *Ariel*).

Leadership & potential team members

The UK has a very distinct leadership in the discovery of exoplanets, and the remote exploration of their atmospheres. SPECULOOS can keep both these advantageous positions, and retain/attract highly talented individuals to our shores. The extension of SPECULOOS-North will ensure we have a competitive edge in the discovery of high-value planets, while our tightly knit British community will benefit from the study of dozens of terrestrial planets. SPECULOOS already involves Cambridge and Birmingham. Within the collaboration I occupy a leading position (2^{nd} author on the TRAPPIST-1 discovery, 1^{st} author on our first discovery paper, which is in preparation). I also have an intellectual leadership within the team, having defined several of our science rationales for the past seven years. On account of the very short notice for this call, and due to some important personal events, I was not able to reach out to other institutes and make arrangements, which will be done should we be allowed to advance on this project. Regardless, we expect to work with our colleagues across the country (e.g. Exeter, Oxford, Cambridge, Warwick, Imperial, UCL, Queen Mary …) to infer the internal compositions of the planets, to better understand planet formation at the bottom of the Main sequence, and interpret correctly the atmospheric signals of those far removed worlds. With SPECULOOS, the UK can lead this century's most exciting scientific quest.

Societal and Economic Impact

The discovery of TRAPPIST-1 led to enormous public attention. For instance, twenty million people visited our website in the week following the discovery. This showcases the important interest our society bears to progress in the search for life elsewhere. Our discovery has inspired many artists as well, and provides a formidable example to help teach STEM, and to improve our society's science literacy and interest.

Scale of investment

This is a small-scale project, aiming to purchase one or two telescopes. (~ 0.9M£ each). This will be a significant contribution on a par with our international colleagues: Liège, Bern, Cambridge and MIT. An STFC-supported extension of SPECULOOS will provide a strong UK leadership within the collaboration. We will attempt to raise funds within the University to help support the construction costs.

Priority projects – summary outline for Advisory Panels

Project Name: CASTOR
Principal Investigator/Lead Contact: Rubén Sánchez-Janssen (UK ATC)

Project outline
We propose leading UK roles in CASTOR, the Cosmological Advanced Survey Telescope for Optical and uv Research. This 1m space telescope will provide panoramic, near-diffraction-limited imaging (FWHM=0.15”) in the ultraviolet (UV) and blue-optical (0.15-0.55μm, in three simultaneous bands) and UV multi-object spectroscopy (R~1000 over a field of view up to 0.2deg). CASTOR has been developed as a powerful contribution to the international portfolio of wide-field imagers in the 2020s. With a field of view nearly a hundred times that of the Hubble Space Telescope (HST) but comparable spatial resolution, it will have excellent synergies with facilities with significant UK investment (e.g. Euclid, LSST). There is emerging worldwide recognition that such a mission is an urgent follow-on to HST given its limited lifetime.

CASTOR is led by the Canadian Space Agency (CSA), who as part of an ongoing Science Maturation Study are actively seeking international partners to refine the science case and develop the technical design. NASA-JPL (USA) and IIA (India) are actively working with CSA to develop the project, and this is a timely opportunity for the UK to establish both scientific and technical leadership roles.

Scientific case
CASTOR's combination of UV sensitivity, high angular resolution and wide field make it a unique facility to tackle a broad range of scientific questions that cannot be realised with any other existing or planned facility, including: characterisation of small bodies in the solar system; studies of resolved stellar populations, from the Galaxy to the Local Universe; the evolution of galaxies and their supermassive black holes; cosmology and the nature of dark energy and dark matter; and the transient universe, from exoplanets to the broad class of exploding sources (gamma-ray bursts, supernovae, tidal disruption events, and gravitational wave sources). As such, CASTOR will address the four key Science Challenges identified by STFC, and will provide immense legacy value in all areas of astrophysics.

A key science goal for the UK community is the study of *Star Formation in Galaxies over Cosmic Time*. UV emission from galaxies is primarily from hot, short-lived stars, and thus traces the instantaneous star-formation rate (SFR). The UV holds critical information for galaxy spectral energy distributions and, importantly, can greatly improve photometric redshifts both at low and high redshift. The GALEX mission had a huge impact on this field (>12,000 citations to GALEX papers within this context). With a 30-fold improvement in angular resolution and a tenfold gain in sensitivity, CASTOR will be transformational for studies of galaxy evolution. CASTOR will be ideal to measure the rest-frame UV flux of galaxies out to z~1.5, enabling definitive measurement of the SFR on short (~100Myr) timescales. Its wide field will enable large, homogeneous samples from which we can measure the stellar mass function and clustering (hence, halo mass) of galaxies with varied SFRs. Combined with optical and near-IR data from LSST and Euclid, this will allow us to connect the growth of stellar mass to the assembly of dark haloes, over two-thirds of the age of the Universe. NUV-optical colours also provide a powerful means to distinguish star-forming galaxies from quiescent systems, thus tracing the growth of the passively-evolving populations that seem to be the end-point of galaxy evolution in most cases. Access to the UV is essential to break the well-known degeneracies between age, metallicity and dust that plague stellar population studies, and CASTOR's excellent angular resolution will allow detailed mapping of these quantities. Finally, a very exciting prospect is the possibility of directly imaging the diffuse filamentary structure of the Universe--a key prediction of galaxy formation models. Such observations would provide an exquisite new view of the Universe and a much better understanding of the intergalactic medium within which galaxies form.

Leadership & potential team members

We have identified two areas where, in close collaboration with NASA, the UK can play a significant role in CASTOR:

Science: The UK and NASA will co-lead the *Galaxy Evolution* science case, building on the enormous synergies with LSST and Euclid. UK participation would be led by Sánchez-Janssen (UKATC), in collaboration with Baldry (LJMU), Fumagalli (Durham), Ferguson and Heymans (Edinburgh), Kaviraj (Hertfordshire), Mundell (Bath), Popescu (UCLan), Sobral (Lancaster), Tojeiro and Wild (St Andrews).

Technology: The UK will lead the design and construction of the focal-plane array in collaboration with NASA, who are experts in the delta-doping technology required for extreme sensitivity. There is initial interest from the groups at UKATC and Leicester (Barstow), who both have significant experience working with Teledyne e2v.

Societal and Economic Impact

Knowledge exchange / capability & skills development: The Government's National Space Policy set-out an ambition to grow the UK space sector from £11.8bn in 2014 to £40bn in 2030. The international collaborations within CASTOR will provide excellent opportunities to help with this agenda, establishing new partnerships with Canadian and US groups, while the proposed UK work will contribute to the skills pipeline required to support the burgeoning UK space sector.

Industrial partnerships: Teledyne e2v manufactures state-of-the-art detectors with superb UV sensitivity and are well placed for a substantial contract for the focal-plane array. UK participation in the mission would ensure close collaboration with e2v in the specification and development of the arrays, as well as opening-up other opportunities for UK industry.

Scale of investment

The CSA is the major partner and the planned UK participation would be a medium-scale investment (£25M), comparable to the expected level of NASA. This would ensure: (i) UK leadership of one the most prominent science cases (giving influence on both the mission design and plans for exploitation); (ii) a significant hardware contribution in development of the telescope focal-plane array.

Priority projects – summary outline for Advisory Panels

Project Name: GravityCam
Principal Investigator/Lead Contact: Colin Snodgrass (The Open University / University of Edinburgh)

Project outline

We propose to construct and operate an entirely novel survey instrument ("GravityCam") for a 4m class telescope. It will, for the first time, combine wide-field (30'), high angular resolution (0.25'') and high time resolution (40 ms) in the visible. The development of GravityCam has been welcomed by ESO, following our initial proposal to their 2013 Call for Ideas for Scientific Projects for the 3.6m NTT at La Silla Observatory (Chile), which ultimately led to the selection of the SoXS spectrograph. GravityCam complements SoXS, and could be installed at the other focus of the NTT, and contributed as a common user ESO instrument by the UK-led consortium in return for time to conduct a variety of survey observations, which would lead to advances in the fields of extrasolar planets, extragalactic astronomy and Solar System science. GravityCam uses an array of about 100 high-speed CMOS array detectors for fast full frame imaging (20-30 Hz). CMOS detectors are rapidly replacing CCDs for most scientific imaging applications. This will be the first major use of such a detector system for a wide range of astronomy programs. GravityCam uses already widely-used re-alignment techniques to correct for atmospheric disturbances, giving a 2.5-3 fold improvement on the resolution over natural seeing. In addition to ESO, key stakeholders are a number of UK universities, reflecting the broad scientific interest in the instrument, and UK industry, especially Teledyne-E2V, whose world-leading next generation CMOS detector technology enables this advanced instrument to be built. GravityCam builds on "Lucky Imaging" techniques pioneered in the UK by Craig Mackay (Cambridge) and colleagues. There is considerable expertise in Edinburgh/UKATC having delivered many major instruments for astronomy. The OU will lead on the detector arrays using their close links with Teledyne-E2V. Other groups will be involved on a variety of roles involving hardware, software and the broad scientific programme, which includes UK areas of excellence in exoplanets and observational cosmology.

Scientific case

GravityCam will enable uniquely detailed studies of the demographics of cool low-mass planets and satellites throughout the Milky Way down to the mass of the Moon, accessible through a microlensing survey towards the Galactic bulge.

While the better spatial resolution improves photometry in the crowded galactic bulge fields (as already demonstrated by using Lucky Imaging for current microlensing follow-up campaigns), the ability to carry out a wide-field survey with a 4m-class telescope delivers comparable statistics for stellar companions that are 100 times less massive than current limits with OGLE, for example.

GravityCam will moreover improve our knowledge of the optical variability of stars and compact objects, tight binaries and photometry of stars in galactic clusters, Dark Matter in the universe through the distortion of distant galaxies, as well as binary asteroids and objects in the Kuiper Belt and Oort Cloud through stellar occultations, enabled by high-speed photometry of many stars at once.

The GravityCam concept has been developed by an international consortium, led by the UK, with contributions from groups of researchers in France, Germany, Denmark, Italy, Brazil, and ESO staff. It will be a unique instrument internationally; highly competitive with current and planned wide-field spacecraft surveys costing orders-of-magnitude more. The project involves constructing the hardware (relatively simple optics and a detector array), developing the software to process the data in real time on-site, and providing high-performance PCs per detector for parallel processing to handle the data rate of ~150Tb/night.[1]

Leadership & potential team members

This bid is now led by C. Snodgrass (formerly ESO, the Open University and now Edinburgh). He will be supported by C. Mackay (IoA, Cambridge). UK team members: M. Dominik (St Andrews); J. Skottfelt, K. Stefanov, S. Serjeant (OU); I. Steele (Liverpool JM); P. Gandhi (Southampton); C. Evans (UKATC); N. Hambly, R. Mann (Edinburgh). A meeting at the OU in 2017 showed significant interest from the UK community. This will be pursued at an RAS meeting in Feb.

Societal and Economic Impact

In almost all imaging applications CCDs are being replaced by CMOS detectors. Teledyne E2V have already delivered a wide-field imaging CMOS array camera for astronomy. Their detectors, already very high spec, are being developed further for this project, strengthening their international lead in scientific imaging based in future on CMOS detectors that have now many advantages over CCDs.

Scale of investment

GravityCam is a medium-scale project, although expected to be at the cheaper end of this scale, at around £10-15m. As the instrument is proposed for an ESO telescope, there are international partners (with a minor TBD contribution) and it is expected that ESO will provide a contribution in kind (guaranteed telescope time) in return for making the instrument available to the wider community (to be negotiated). The project is UK-led and the majority of the funding will come from the UK, with these funds to be spent in the UK. The project should take about three years to first light.

[1] C. Mackay et al., “GravityCam: Wide-Field High-Resolution High-Cadence Imaging Surveys in the Visible from the Ground”, arXiv:1709.00244

Priority projects –

summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: ExoMet
Principal Investigator/Lead Contact: Nathan Mayne, University of Exeter.

Project outline

The detections of planets outside our solar system (exoplanets), and continually improving observational constraints present an excellent opportunity for combining several UK-based, internationally leading, theoretical research efforts. Not only can these exoplanets be used to expand our knowledge of how planets form, evolve, and their potential to host life, but also to aid our understanding of our own (and neighbouring) planets. However, the parameter space is immense, and planetary climates multi-faceted and complex, pushing our understanding of fundamental physics & chemistry to extremes. Therefore, a concerted and large scale theoretical project is required to maximise the scientific return from investment in observational facilities, e.g., TESS, JWST, etc.. ExoMet is a multi-institute, cross-discipline, large-scale, theoretical framework, built on areas where the UK is at the forefront, to develop tools with which to understand current and future observations. Observations of the atmospheres of potentially Earth-like exoplanets will become achievable in a decade or so, and only if the UK invests now, can we ensure we are at the forefront of determining whether these planets can, and do, host life. A question that can't be answered without theoretical models. This proposal is to form a flagship, distributed UK framework supporting an exoplanet theory community, facilitating scientific excellence, and training the next generation of scientists.

Scientific case

The nascent field of exoplanets is a vital component to STFC's key science challenge of determining how planetary systems develop and whether life on Earth is unique. ExoMet science will cover development of a range of atmospheric models, combining existing frameworks within the UK studying objects from gas giants to terrestrial planets. This suite of models, will be developed across disciplines, with an associated, concerted, inter-comparison and validation programme to provide a leap forward in our understanding of how planetary climates work. The UK is already leading the field of exoplanet modelling for both terrestrial and gas giant exoplanets. The ExoMet network will hinge on sharing of developments, and expertise, between centres of excellence, initially: Exeter, Oxford, St Andrews, Edinburgh, UCL & Cambridge.

Leadership & potential team members

Several nodes will be connected via shared postdoc and PhD positions to combine centres of excellence. Each node will have a primary focus, with the resulting model components, and knowledge, shared across the network. A good early example, is the recent integration of the SOCRATES open-source radiative transfer code in several climate model frameworks (e.g., UM: Exeter, ROCK3DE: US, exo-FMS: Oxford, ISCA: Exeter). More recently microphysical cloud models developed at St Andrews have also been "ported" to several model frameworks. *Exeter:* Led by Nathan Mayne a strong, and real-time link in development with the University and the Met Office has been facilitating knowledge transfer. Current Exeter collaborators include Eric Hebrard, Geoff Vallis, Isabelle Baraffe, Hugo Lambert & Tim Lenton. *Oxford:* Led by Ray Pierrehumbert and Vivien Parmentier, treatments of convection in terrestrial atmospheres alongside the modelling of very high temperature hot Jupiters are being developed. Additionally, Pat Irwin provides expertise in retrieval, connecting observations with model outputs. *St Andrews:* Christiane Helling & Peter Woitke, have developed the most sophisticated microphysical cloud scheme, with Helling pioneering a hierarchical, modular modelling approach and convening the educational `Cloud Academy'. *Edinburgh:* Paul Palmer leads a programme focusing on atmospheric chemistry of, chiefly, Earth-like exoplanets. *Cambridge & UCL*: Retrieval techniques have been developed along complementary lines, by Ingo Waldmann and Jo Barstow Eberhardt (UCL), and Nikku Madhusudhan (Cambridge).

Societal and Economic Impact

Developing climate models requires a high level of computer literacy, an ability to handle, visualise and interpret large volumes of data and a cross-disciplinary approach. The development of flexible planetary climate/evolutionary models is a very challenging undertaking and will require investment in computational techniques. These developments will feed back into climate and weather modelling of Earth, but also provide a flow of highly skilled researchers vital to the UK economy. Additionally, this is an area primed for interaction with both industry and the wider public. Successful projects already exist combining exoplanet research with visual effects (e.g., VR animation with 5M+ views: https:/tinyurl.com/y.y2pdzr3).

Scale of investment

The UK Met Office leads the world in climate research, in ExoMet we are proposing a smaller and institutionally distributed version of such a facility, built on the strength of our centres of excellence. The prime aim is cross-institute projects, therefore, the dominant cost will be that of hiring postdoctoral researchers (PDRA), PhD students, support staff (admin, computational software/hardware) and staff time for secondments. A budget of ~£15Million, will allow us to employ 10 PDRAs for terms of 6 years (£5Million), an administrator, and two computational support staff (~£1.25Million), 10 PhD students (two batches of 5, ~£0.75Million) with ~£5Million allocated to staff FeC equivalent to ~10 FTE for 6 years. Finally, a budget for travel, and hosting international visitors at our centre of excellence will be required, alongside investment in a small number of computational servers (~£3Million).

Priority projects – summary for Advisory Panels

Project Name: A Dedicated Wide-Field Spectroscopic Survey Telescope
Principal Investigator/Lead Contact: Professor Richard S Ellis (UCL)

Project outline

We propose the detailed design and construction of an international 8-10m class optical and near-infrared spectroscopic survey telescope with a field of view comparable to that of LSST. Such a facility will enable transformational progress in many areas of astrophysics for decades. Deep imaging from LSST and Euclid will provide accurate photometry for a range of Galactic and extragalactic targets and transients beyond reach of 4m class instruments. The international community has shown considerable interest in such a facility through several conceptual studies which have highlighted novel technical opportunities in fibre positioning robotics, fast spectroscopic cameras and a new generation of detectors. Through its rich heritage in survey spectroscopy and associated instrument development, the UK can play a lead role in enabling such a facility.

Scientific case

Spectroscopy will always be a primary tool of astronomy yielding unique astrophysical insight into the chemical composition and radial velocities of stars in the Milky Way and nearby galaxies, and accurate redshifts, measures of internal motions, stellar populations, non-thermal sources and the ionising radiation field in extragalactic sources over cosmic time. The last decade has seen a huge investment in imaging at optical and near-infrared (OIR) wavelengths through surveys undertaken with 4m-class facilities (VST, VISTA and DES). More ambitious imaging surveys are planned with LSST, Euclid and WFIRST. Collectively these will provide spectroscopic targets beyond reach of current or upcoming 4m spectroscopic instruments (4MOST, WEAVE and DESI) ensuring a leadership role in upcoming facilities such as LSST and SKA.

As a result there is considerable community interest in developing a 8-10m class spectroscopic telescope with a wide field and large multiplexing capability for exploiting such data. A user poll in the ESO community indicated that a dedicated OIR spectroscopic 10-m class telescope was the most requested facility not yet under construction[1]. The US community has promoted such a facility to fully exploit LSST[2]. The CFHT community[3] has completed a concept study for the Mauna Kea Spectroscopic Explorer (MSE), a 11.25m telescope designed to replace the CFHT 3.6m. These initiatives have provided detailed documentation on the science justification for such a facility (e.g. McConnachie et al 2016[4], Ellis et al 2017[5]). It would have wide-ranging applications in at least three broad areas as illustrated below:

Galactic archaeology: The Milky Way is the only galaxy whose history can be studied using the full distribution of stars from white dwarfs to supergiants. These stars and those in the Local Group can be surveyed at high spectral resolution with a large aperture telescope providing kinematic and chemical information leading to new insight into the Galactic gravitational potential and properties of dark matter, assembly histories via unprecedented accuracy in `chemical tagging' techniques, as well as probing fundamental aspects of stellar physics and the origin of the heavy elements. A typical multi-year programme could provide R~40,000 spectra

---

[1] ESO Messenger **161**, September 2015
[2] Najita, J et al 2016 *Maximizing Science in the Era of LSST*, https:/ arXiv 1610.01661
[3] Including Australia, China & India with US observers
[4] McConachie, A et al 2016 *The Detailed Science Case for the Maunakea Spectroscopic Explorer*, https://arxiv.org/abs/1606.00043
[5] Ellis, R et al 2017 *The Future of Multi-Object Spectroscopy: a ESO Working Group Report*, https://arxiv.org/abs/1701.01976

from 360-950nm at a s/n~80 for ~50M accessible stars to V~17. Together with Gaia, this would yield 6D phase-space kinematics, stellar parameters and a rich array of chemical abundances.

Galaxy Assembly and the Cosmic Web: Ultimately we seek to understand how galaxies assembled in the context of surrounding dark matter structures. This occurs within an evolving network of halos, filaments and voids accreting matter from it and ejecting baryons into it. Nearby datasets (SDSS, 2dF) have provided a comprehensive view in the local Universe but no current facility can provide such detail at z~2 where star formation and AGN activity was at its peak. The new capabilities required include high density sampling (so small-scale processes can be examined), adequate spectral resolution (to reveal stellar and interstellar absorption lines as probes of chemistry and in-/out-flowing gas), a wide field with massive multiplexing (to ensure the full range of web environments) and a wavelength range extending to 1.3 microns (to ensure access to nebular emission lines over $1<z<4$). As an example, the proposed facility could undertake a high quality survey of several million galaxies per Gpc^3 in redshift volumes to z~4.

Transient Science: This major growth area in astrophysics is driven by exciting new facilities such as PanSTARRS and the Zwicky Transient Facility; LSST will find more than a million transients in its first 5 years. The range of targets is expanding from classical supernovae to superluminous examples, tidal disruption events, gravitational wave counterparts and kilonova with the exciting potential for new discoveries. Spectroscopic follow-up of such a wide range of sources is pivotal to the full exploitation of LSST and the UK has the potential to take the lead. The studies mentioned above have proposed a coherent strategy distinguishing, for example between *live* events (requiring immediate follow-up) and *transpired* events (where a host galaxy is the target).

The detailed science cases have defined the requirements for such a facility. A **8-10m aperture** is essential to secure adequate resolution spectra, a **wide field** of >2 deg^2 enables the **multiplex gain** of ~5000 and a **wavelength range** from 370nm to 1.3 microns is required to provide access to key diagnostic spectral lines.

Leadership & potential team members

At this early stage, several options are envisaged. The UK could take leadership of a detailed design of the facility proposed to ESO (Ellis et al 2017). The project is of great interest to the ESO community and the UK can provide the necessary initial momentum while the ELT is completed. Members of the community willing to lead such a technical study include Evans (UK ATC), Doel (UCL) and Sharples (Durham). Scientific management would include Bremer (Bristol), Nichol (Portsmouth), Gaensicke (Warwick) and Sullivan (Southampton). In addition the UK has the potential to be a major partner in MSE. Durham, Oxford, Belfast, St Andrews, Sussex, UCL, Herts & Warwick are each involved in science planning for MSE's planned Preliminary Design Phase. Further international options are also possible. A key feature of this proposal is that the UK can now play a prominent or leading role in initiating a detailed design phase.

Societal and Economic Impact

The proposed facility will transform our understanding of cosmic evolution adding a new dimension to earlier work done by smaller telescopes and complementing the UK's investment in ELT. Through its heritage in survey spectroscopy (2dF, WEAVE, 4MOST, DESI and MOONS) and its formal involvement in LSST, the UK is a strong leadership position, scientifically and technically. There is great scope for technical innovation through new developments in robotic fibre positioning, large-format IFUs as well as in fast camera optics, curved CCD detectors and possible use of cheaper CMOS devices, areas with strong UK industrial links.

Scale of investment

A detailed design for the proposed facility would represent a small-scale investment whether conducted solely by the UK (£10M estimate) or if it chose to be a 30% partner in MSE (£5M). The construction would represent a large project. Both MSE and the ESO facility are estimated at £300M with the UK share being at least 20%.

Priority projects –

summary outline for Advisory Panels

Page limit - 2 sides A4

Project Name: Virtual Centres of Excellence (ViCE) Programme
Principal Investigator/Lead Contact: Dr. Jonathan Eastwood, Imperial College London (jonathan.eastwood@imperial.ac.uk)

Project outline

Please briefly describe the Project, including objectives, scope, key stakeholders and the scientific drivers and areas of excellence.

In the remit of STFC science, the UK is world leading in many areas. However, this excellence is often fragmentary, largely as a consequence of the AGP process which does not foster long term alignments in research areas except at the highest level. To increase the impact and visibility of STFC science, I propose the formation of a Virtual Centres of Excellence (ViCE) programme – a vehicle to consolidate expertise in different STFC science areas to strategically address challenges relevant to STFC's science roadmap that require a large-scale, coordinated approach. Further notes:

- **The ViCE programme is deliberately envisaged as being flexible and applicable across the STFC remit.**
- **The focus of the Centres would be challenge-led.**
- **These could be directed by STFC (e.g. selected via a panel process) or proposed from the community (a combination may be advisable).**
- **Consequently, whereas the grants line is 'blue sky', the ViCE programme would be more applied in nature.**
- **Cross-cutting initiatives should also be encouraged.**

Scientific case

Describe the scientific relevance of the Project, and of the unique science to be carried out, in an international context as well as any international activities in this area and how competitive the Project will be in comparison with others in the field. Summarise access to, and level of, computing infrastructure or any other relevant enabling infrastructure, required to exploit the project.

As explained above, the goal of each ViCE would be to consolidate and translate STFC science to maximise impact. Each ViCE would be a multi-institution network, (5 year initial lifetime), consisting of academic, STFC and industrial/government/end-user stakeholders. To reach critical mass, a typical budget per Centre might be £1m p.a., funding a network of 5-10 institutes at the order of 1 FTE p.a. and associated equipment/facilities.

Leadership & potential team members

Describe the expected UK leadership of the project, as well as possible participation by other individuals or groups.

There are a number of application areas that would be well served by the ViCE programme: e.g. detector technology, data science, healthcare, natural hazards, etc. If it is preferred to have a more science-challenge-oriented approach, Centres could be based around e.g. the ESA science programme and specific areas with major UK investment via UKSA.

Societal and Economic Impact

Describe the potential Societal and Economic impact of the Project in terms of knowledge exchange, capability/skills development, industrial partnerships and public engagement. Outline any key technologies and technology development associated with your Project. Please explain the technical importance of the Project and the scope for wider application of any technologies to be developed.

The ViCE programme is envisaged as including stakeholders from the start as a mandatory element. The success of the programme would be defined in terms of the creation of a critical mass of knowledge in a particular area, and demonstrated translation of knowledge towards solution of the headline challenge. A vigorous programme of public outreach would also be a mandatory element of the ViCE programme.

Scale of investment

State whether your project will be large (>50M), medium (10-50M) or small-scale (<10M). Identify any expected contributions from sources other than STFC. For international Projects, please describe the relative scale and significance of the UK contribution.

The ViCE programme is of the order of a medium scale project.