Near Universe Advisory Panel (NUAP) Strategy Document (@16th November 2009)

Introduction

This strategy document covers those areas of STFC's astronomy and space science program concerned with the Sun, our Solar System and the properties of objects within our Galaxy. Members of NUAP, their affiliations, areas of expertise and information revealing any vested interests are listed below:

- Michele Dougherty (Imperial College London) Chair - planetary magnetospheres; Cassini magnetometer PI, EJSM (ESA Co-Lead), BepiColombo
- Emma Bunce (Leicester University) – space physics; Cassini, EJSM (ESA JGO Deputy Lead), BepiColombo, AGP - Planetary sub-panel
- Paolo D'Arrigo (Astrium)- space technology; future space science missions
- Ian Franchi (Open University)- Solar System & planet formation; Marco Polo, UKCAN, AGP - Planetary sub-panel
- Boris Gaensicke (Warwick University) – stellar astrophysics; Gemini, NTAC
- Tom Hartquist (Leeds University)- star formation and diffuse matter; Theory, HPC
- Sarah Matthews (MSSL) – solar physics and Sun-Earth connection; Solar Orbiter, STEREO, EST, Solar C, Hinode
- Don Pollacco (Queens Belfast) – exoplanets; PI SuperWASP-N, Chair LT Oversight Committee, Chair ING Science Advisory Committee, PI PLATO-Science, Astronomy representative on PPRP

This document has resulted from an iterative consultation process with the community, which will continue in the months and years to come and will lead to the document's further evolution. In it, we address five over-arching questions central to the study of the Near Universe, and within each of these several more detailed sub-questions (of which there are seventeen in total).

NUAP Science Challenges over the next 10-15 years

1. *What controls the properties and evolution of stars including the Sun?*

   1.1. What are the processes that lead to convection and the generation of stellar magnetic fields, how do they evolve and what is their role in controlling activity?

   1.2. What are the stellar content and stellar distribution in the Milky Way?

   1.3. How do low mass, intermediate mass and massive stars evolve?

   1.4. How do binary and multiple systems, including those that emit gravitational radiation or become Type IA supernovae, evolve?

2. *How do the Sun and other stars affect their environments?*

   2.1. How does solar activity affect the near-Earth space environment as well as those of other planets, and how does the Sun affect civilization?

2.2. How do evolved stars lose mass and what is the history of stellar ejecta present in young stars and planetary systems?

2.3. How do star formation triggering and feedback work and affect the Galaxy locally and globally?

3. *How are stars born and how do planetary systems, including our own Solar System, form and evolve?*

3.1. What processes, including those leading to prebiotic molecules, are important in the evolution of molecular clouds to form stars and planets?

3.2. What are the physical characteristics of exoplanetary systems (including different types of host stars) and how do they evolve?

3.3. How did the Solar System form and what can it tell us about other planetary systems?

3.4. Is there a universal model of magnetospheres and atmospheres?

3.5. How do planetary bodies evolve and what can they tell us about the history and climate of Earth?

4. *What is the extent of habitable environments and life in the Universe?*

4.1. What are the limits for life, past and present, in the Solar System?

4.2. What is the frequency of habitable planets in the Universe and can we detect bio-markers in their atmospheres?

5. *What fundamental processes operate in astrophysical sources, including the Solar System?*

5.1. What are the fundamental laws of physics under extreme conditions?

5.2. What are the fundamental processes that transport, convert and release energy in plasmas?

5.3. How and where are particles accelerated in nature?

For each of these sub-questions we present a description of its scope; comment on some related UK strengths, involvement and opportunities; as well as list relevant current and potential facilities. Of course, the scope of any of these questions is richer than a short description can indicate. Similarly, our comments on the UK strengths and involvement are indicative rather than comprehensive.

The various sub-questions are related to one another in many ways. We have emphasised some of those ways in the text of the individual questions and by recognising the relationship of each of the seventeen sub-questions to one of five more general or overarching questions. During the construction of this document we encountered some issues and constraints. We mention the most important of these below and start with the most significant.

Issues and Constraints:

a) Grants and fellowships - the highest priority

Feedback from the community has revealed widespread concern about the balance between expenditure on grants and fellowships and investment in facilities. Even before the first wide public consultation, one scientist wrote, "There is going to be a lost generation ... and one must have serious concerns as to who will be around in 15 years time to provide core expertise and leadership in UK astrophysics." At the same stage, another wrote, "The loss of grants (and people from the UK astro-community) will have a long term detrimental impact and should be addressed immediately." During the consultation process, many wrote of the uselessness of facilities in the absence of sufficient support for people to exploit them, as well as of how the UK's most valuable assets for research and for society in general are the researchers and the young people whom they train. One respondent wrote, "The science program can (and should) be broader than the science program which UK facilities can address... UK astronomers can do leading science ... on other people's telescopes. This kind of science ... should be ... funded by the grants line if it is of high enough quality." Indeed, this operational mode can be extremely cost effective. Six galactic, stellar, and Solar System theorists from five universities wrote, "... UK astronomy theory is consistently ranked as world-leading in international surveys and costs STFC very little by comparison ...observational astronomy is supported through facilities and projects ... cuts to the grants and fellowship lines therefore hit theory far harder ..... 'Tensioning' theory funding against grant support for observational and instrumentation programmes, as now, does not ... constitute a fair or profitable use of the resources ..., given that these areas have other funding streams which are not so tensioned. Ideally we would like to see the success rate for all grants maintained ... [at the level anticipated by the community in June 2007]. However, if this is impossible, we believe that maintaining the ... rate for theory grants alone should be the highest priority."

b) Other prioritisation

We are very aware that part of our remit is to serve as a two-way conduit for information from and to the community. We want the community to know that its views are being communicated, taken seriously, and influencing the process and decisions. Hence, we now address prioritisation, about which the community expressed strong views, particularly at our Town Meeting. The absence or inactivity of advisory panels from the time when PPARC was undergoing absorption by STFC until several months ago combined with the redrawing of boundaries between the advisory panels have caused a huge discontinuity and discontent. Consequently, many in the NUAP community have said that STFC has requested that NUAP do too much on too short a timescale and that the NUAP panel membership is too small to cover all the relevant areas. Thus, we have not attempted to fully prioritise facilities yet, and we, like many in the community, are very uneasy about the task that faces us. However, others have recognised the need for us to prioritise facilities on a short timescale due to looming deadlines, when recommendations that will inform STFC and government decisions must be provided. Though NUAP members cannot change the history of the advisory process over the past few years, we wish to assure the community that each NUAP member has at multiple times solicited, through direct emails and phone calls, advice from a number of the community's members. Typically each of us has been in contact with 12 to 20 or more scientists in communication outside the more public calls for input and the Town Meeting. Within these constraints, including those that time imposes, we are doing our best to present a strategy that is as consistent internally and with as much of the community input as possible.

We are grateful for all of the community's comments received this far and will require and greatly appreciate the community’s continued assistance when we further prioritise science questions and facilities and continue to develop this strategy document.

c) The size of the NUAP community and the breadth of its scientific activity

We have some data on applications made to STFC. They were described as being for "all applications regardless of whether they are large rolling grants or small applications for telescope time, fellowships, etc." Analysis of them suggests that the NUAP community is 1.7 - 2.3 larger than the FUAP community. Neither community is dominated by a small number of monolithic projects. Thus, we suspect that each of the NUAP and FUAP remits is amongst the broadest that any of the advisory panels has and that the ratio of the breadths of the scientific programs of the NUAP and FUAP panels is also between 1.7 and 2.3. The breadth of the science that NUAP must consider therefore makes its job particularly challenging. This accounts for this report exceeding the 20 pages mentioned in guidelines provided to the various panels.

d) The boundary between NUAP and FUAP remits

This is another issue about which strong feelings were expressed by the community, particularly at our Town Meeting. We wish all to realise that we take what was said very seriously and have tried to act accordingly. Many galactic and stellar astronomers have expressed great displeasure and concern that their science is being considered with Solar System science rather than with the science which FUAP is addressing. An important ground for their concern is that much of their research requires observations of stars and clusters and star forming and diffuse regions in other galaxies, especially those in the Local Group but in some cases those out to distances up to 10 Mpc. In order to attempt to mitigate some of these concerns relevant NUAP members have had telecons and exhanged emails and draft documents with FUAP members. They have also attended the FUAP town meeting, just as some FUAP members attended the NUAP town meeting. Through the maintenance of such interaction, we will aim to ensure appropriate coverage of extragalactic astronomy vital to NUAP science and galactic and stellar astronomy important for FUAP science. We draw attention to parts of the text in the sections concerning various questions (e. g. Qs 1.2, 1.3, 1.4, 2.2, 2.3, 5.1) that explicitly mention extragalactic studies.

In contrast, some galactic and stellar astronomers and many Solar System scientists are enthusiastic about how future interactions between the galactic and Solar System communities will benefit both. In fact, the NUAP process has stimulated efforts by a galactic astronomer and a meteoriticist to organise a workshop to be attended by scientists working on evolved stars, molecular astrophysics, cosmo-chemistry, and exoplanets.

e) Overlap of NUAP and PAAP remits

Sources of gravitational waves and TeV gamma rays include both galactic and extragalactic objects. The gravitational wave and TeV gamma ray communities have requested that we consider their science and facilities as part of the NUAP process. We are happy to do so. However, we note that three panels will be reviewing some of the particle astrophysics facilities. We wish to stress to PPAN that that should not in any way give those facilities priority over facilities being considered only by NUAP. For example, although NUAP, FUAP, and PAAP all address particle acceleration, in situ measurements of the properties of acceleration regions and the supporting theoretical investigations fall only within the NUAP remit. Such Solar System studies are absolutely vital for understanding the universal mechanisms that give rise to particle acceleration. In contrast, observations of radiation emitted by astrophysical energetic particles primarily reveal the sites of shocks where acceleration occurs rather than provide detailed diagnostics of the acceleration physics.

f) Omission of facilities not funded and unlikely to be funded by STFC, ESA, or ESO

As mentioned above, supporting the exploitation of non-STFC facilities through the grants line can be a cost effective way for the UK to produce high quality research. However, we do not mention a number of such facilities (e. g. e-VLA, Kepler and Plateau de Bure). We strongly emphasise that this choice should in no way disadvantage grant applications to support high quality science to be done with such facilities.

g) High Performance Computing

Community input indicates that HPC is relevant for many NUAP areas. In May one computational astrophysicist wrote to a NUAP member of the necessity for a facility much larger than those to be managed by existing UK astronomy HPC consortia. However, NUAP had some input favouring investment in a number of more modest HPC facilities rather than one Hector-like facility, and NUAP believes this to be the more widely supported view. Rather the main issue, other than the delay in the release of funds by DIUS to support HPC, concerns ensuring that those who are not members of HPC consortia have sufficient access to HPC facilities. The UKAFF model is a relevant one, but such access can also be achieved if consortia are required to make some of their CPU time open access. HPC provision based on the latter model is likely to work effectively and serve the community's needs provided that the availability of open access is properly managed and monitored. Such availability should be made a strict condition placed on funding awarded to HPC consortia.

h) Support for data storage and handling infrastructure

The UK has been leading and will continue to lead a number of large-scale survey projects, and several groups have developed world-renowned expertise in the processing, archiving, and serving of terabyte-scale data sets. The UK community would fail to fully capitalise on its observational efforts if specific aspects of the existing expertise were lost. We recommend continued support, after an appropriate review, for large-scale data processing and storage in areas in which the UK leads and is not duplicating international efforts.

i) Support for generic technology development infrastructure

The responses from the community indicated that support of basic technology and instrumentation should form an important part of STFC plans for the next 10-15 years. The investment in technology activities plays a major part in delivering high scientific return to the UK as well as often providing the broadest and strongest economic impact to society. The UK has established a significant leading position in Europe (and sometimes in the world) in a number of technology areas that are crucial to delivering STFC science. From the survey, the prominent areas include detectors (focal plane arrays across a broad range of wavelengths and cryogenics in particular), ground and space-based instrumentation (focal plane array imagers, spectroscopy and MEMS instrumentation being particularly strong), optical technologies (including adaptive optics), radio interferometry & telescopes, data processing & computing, planetary science technology (robotics, cosmochemical laboratories, sample curation in particular). STFC continued funding of technology research, both within academia and industry, is considered crucial to answering the key scientific challenges that NUAP has identified and also to UK leadership at international level (technology know-how is often the best basis for achieving key roles for UK scientists and industries).

j) Astrobiology

Astobiology is the study of how life formed and developed on the Earth, the conditions that made this possible and whether these conditions can exist elsewhere in the Universe. With such a broad range, it is not surprising that astrobiological research is associated with investigations mentioned in many of the sections (including sub-questions 2.1, 2.2, 3.1, 3.2, 3.3, 3.4, 3.5, 4.1 and 4.2). Astrobiology is a rich and diverse field which is clearly a very central theme in NUAP science.

Prioritisation of Science Areas:

Though many in the community stated at our Town Meeting that they did not want NUAP identifying priorities at this stage, STFC placed enormous pressure on NUAP and all other panels to do so. Hence, with difficulty, each scientific member of NUAP identified for the September version of the report what he or she personally saw as the highest priority sub-question. They are listed below. Following on from the community feedback exercise which was run at PPAN's request in October/November 2009, these sub-questions are being retained. Detailed information gleaned from the community feedback is described in the next section. Also listed below is an initial prioritisation of facilities for each of these sub-questions (as described in the September presentation to PPAN and retained following the recent community feedback). Underlined current facilities indicate they continue beyond the immediate 5 year horizon.

Q1.4 How do binary, and multiple systems, including those that emit gravitational radiation or become Type IA supernovae, evolve?

Current facilities: 4-8m telescopes (WHT, ESO/NTT & ESO/VLT), survey telescope (INT, UKIRT), ultraviolet telescopes (HST), X-ray telescopes (Swift, XMM), Geo600, LT

Next 5 years: Gaia, survey telescopes (ESO/VST, ESO/VISTA), Advanced Ligo

> 5 years: Future X-ray (IXO) and ultraviolet (e.g. ATLAST) telscopes, LISA, Einstein

Q2.1 How does solar activity affect the near-Earth space environment as well as those of other planets, and how does the Sun influence our civilization?

Current facilities: Solar Physics: Hinode, STEREO, SOHO, BiSON & ROSA

Non-solar: Cluster & Cassini, ground-based STP, VeX, MeX

Cross-cutting: theory & modelling/HPC

Next 5 years: Solar Physics: PROBA-3, LoFAR

Non-solar: KuaFu*

> 5 years: Solar Physics: Solar Orbiter*, Solar C & ATST , HiRISE, EST

Non- solar: Cross-Scale & EJSM, BepiColombo

*Solar and Space Physics

Q3.1 What processes, including those leading to prebiotic molecules, are important in the evolution of molecular clouds to form stars and planets?

Current facilities: HPC, JCMT (through at least 2012), Herschel, ESO VLT/VLTI, labs, EVN

Next 5 years: ALMA, e-MERLIN, MROI, JWST

> 5 years: ELT, SKA and SPICA, C-CAT, FIRI

Q3.2 What are the physical characteristics of exoplanetary systems (including different types of host stars) and how do they evolve?

Current facilities: WASP, UKIRT (WYFCAM), LT, WHT, ESO

Next 5 years: UKIRT (UPF), JWST, Gaia, Gemini

> 5 years: PLATO, e-ELT

Q3.3 How did the Solar System form and what can it tell us about other planetary systems?

Current facilities: Analytical facilities, Laboratory simulation facilities, Cassini, UKIRT, ING, Nullarbor Fireball Camera Network

Next 5 years: Rosetta, GAIA

> 5 years: Marco Polo, SR Curation Facility, EJSM/Aurora to MSR/BepiColombo

Q3.4 Is there a universal model of magnetospheres and atmospheres?

Current facilities: Cluster & Cassini, Theory/HPC & ground based STP, Venus Express,Mars Express, ground based observations of planets (e.g. HST), Double Star

Next 5 years: Rosetta, KuaFu, LOFAR

> 5 years: Cross-scale & EJSM, BepiColombo

Q5.2 What are the fundamental processes that transport, convert and release energy in plasmas?

Current facilities: Space Physics - Cluster & Cassini, Theory/HPC & ground basedSTP,

Venus Express, Mars Express

Solar Physics - Hinode & ROSA, STEREO, SOHO

Next 5 years: KuaFu*, LOFAR

> 5 years: Space Physics - Cross-scale & EJSM, BepiColombo

Solar Physics - Solar Orbiter*, Solar-C & ATST, HiRISE, EST

*Solar and Space Physics

We have made no attempt to prioritise these sub-questions relative to one another. Difficulties have been compounded by the unusual breadth of science covered by NUAP. We visualise this strategy document as a living document which will evolve with continued community feedback and input.

Supplementary Information following Community Feedback in November 2009

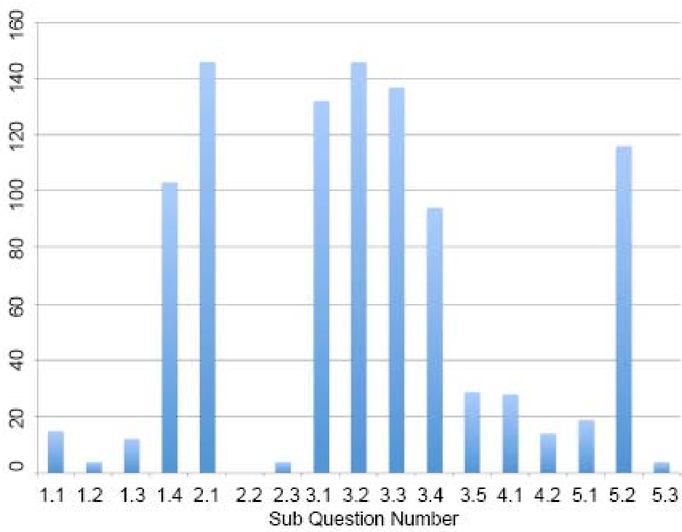
This sub-section contains a summary of the 310 responses from the NUAP community to questions put to them concerning the NUAP prioritisation process, as described in the slides of the 28 September NUAP presentation to PPAN. The questions asked of the community are reproduced at the end of this section.

1. <u>NUAP's prioritisation process</u>

147 of the 310 respondents (or 47.4%), answered "Yes" to the question concerning whether, given NUAP's broad remit, the seven sub-questions identified by NUAP as of highest priority form the basis of a coherent and cohesive program. Others, some of whom have been counted below as disagreeing with all seven sub-questions, wrote statements like:

- "No : Overall these highest priority sub-questions are excellent, ... However, I would like to raise a few minor points ..."
- "No: My answer is Yes, but I want to comment ..."
- "No : Q3.1 is too all-embracing as compared to the others ..."

We conclude that half of the community is in general agreement with the 7 priority questions described in our report. A couple of trends, which we address below, emerged in the negative responses. However, we consider agreement with our selection to be sufficiently high, and the suggested changes in sufficiently contradictory directions, to retain our initial 7 highest priority sub-questions. The bar chart below reveals, for each sub-question, the difference between the number of respondents who approved of it or wanted it added and, in the case of each initial high priority sub-question, the number of people who either wanted it removed or who were counted as opposing all of the initial sub-questions.



2. <u>The Balance of the NUAP Community</u>

Some negative responses, including many concerning gravitational waves and compact objects, contained criticisms of the balance of the seven sub-questions since four of them concern the Solar System. Many astrophysicists working in NUAP areas other than Solar System science seem to not to be fully aware of the volume of UK Solar System activity. We analysed the submission rates of proposals for grants and fellowships and the fractions of time that applicants reveal they spend on different areas. The analysis yielded a 60: 22: 18 percentage split between those doing Solar System science, stellar astrophysics, and galactic astronomy.

One should bear in mind that galactic astronomy concerning the overall nature of the Galaxy is in the FUAP remit. Aware of concerns of many astrophysicists that some science would fall between the NUAP and FUAP gap, we did address science associated with the global evolution of the Galaxy (cf. parts of Q2.2 and Q2.3). Some NUAP members feel that these sub-questions are very important for one of FUAP's highest priority questions. However, the responses from the NUAP community do not indicate that either of these sub-questions should be substituted for any of the previously identified seven.

3. Gravitational Waves

Due to an obviously coordinated campaign, we received 48 responses, most of which followed a template, from gravitational wave scientists in Birmingham, Cardiff, Glasgow, and Southampton. Though the responses primarily concern the promotion of gravitational wave science, they also imply that NUAP generally has neglected studies of compact sources outside the Solar System. Given that the words "gravitational waves" appear in our high priority question Q1.4, the tone of much of the gravitational wave community's input surprised us. We note that many other respondents, who described themselves as stellar astrophysicists but who are not members of the gravitational wave community, replied that Q1.4 is not the highest priority stellar astrophysics sub-question. However, we included it as a high priority sub-question to ensure that the study of compact sources by a number of methods, including the detection of gravitational waves, would be associated with such a sub-question.

There is considerable overlap between aspects of the studies associated with Q1.4 and Q5.1. Thus, in addition to seeing no compelling grounds based on the statistical analysis of the 310 responses to replace Q5.2 with Q5.1, we feel that that overlap reduces the strength of any scientific case for replacing Q5.2 with Q5.1. A much more thorough understanding of the fundamental non-linear processes that Q5.2 concerns is necessary for a great deal of astrophysical theory to advance to rigorous, quantitative, and predictive stages. Such theory includes that of:

a) solar, stellar, compact object, and AGN activity;

b) the viscosity in, evolution of, and launching of jets by accretion disks;

c) the radio and gamma-ray emissions of galactic and extragalactic compact objects;

d) AGN and supernova induced feedback in star and galaxy formation.

We do appreciate the input on facilities and have added Advanced Ligo, Geo600, and Einstein to the facilities list for Q1.4. We have added Geo600 and Einstein to the list for

Q5.1. We note that gravitational wave and some other facilities are being considered by PAAP, a panel with a much narrower remit than ours and representing a very much smaller community than we are. Their area is also being considered by FUAP. We repeat here that excellent science that falls within the remit of only one panel should not be disadvantaged. Some such science has relevance for a broad range of astrophysics but can be conducted only with in situ observations.

4. Life and Aurora

The issue of whether Q4.1 and/or Q4.2 should replace previously identified high priority questions is another that deserves comment. Approximately 40% of "Planetary Interiors, Surfaces and Atmospheres" (PISA) respondents requested that Q4.1 be identified as being of high priority. Q3.4 and Q5.2 are sub-questions that were downgraded by many of those respondents favoring the inclusion of Q4.1 and/or Q4.2.

NUAP recognises the importance of astrobiology and, in particular, those aspects that concern the processes that lead to life and its continuation. These processes include those that:

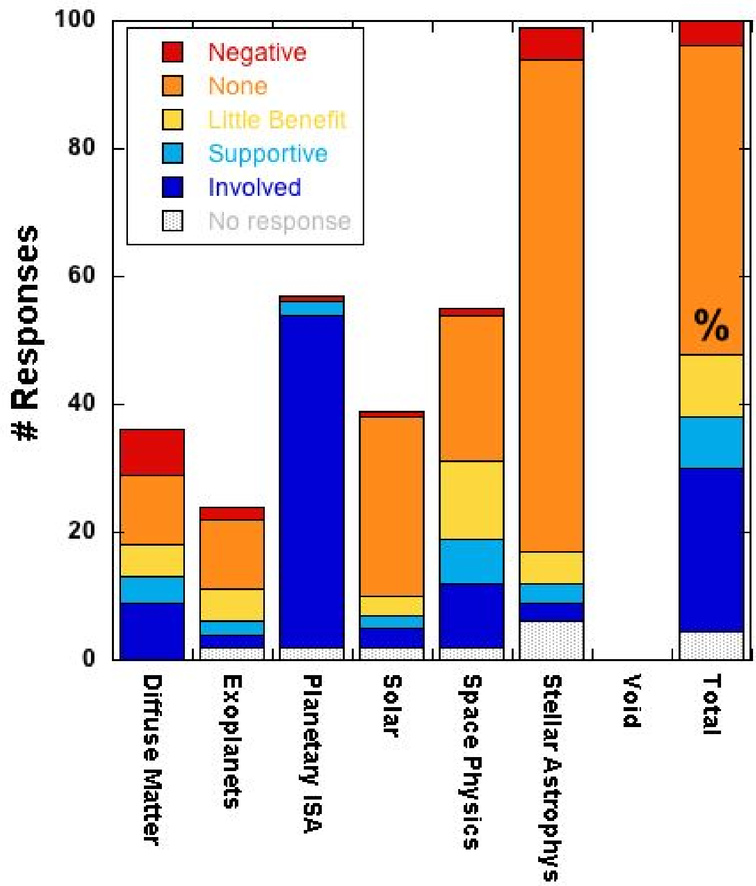
a) result in the formation of planets in habitable zones;

b) lead to and deliver complex chemical precursors to life;

c) regulate the atmospheres of planets and protect life from the activity of the nearest star.

A great deal of astrobiology is associated with questions other than Q4.1 and Q4.2. Some members of NUAP feel Q4.2 should be integrated with Q3.2, as it was in early NUAP documents. This would create a single high priority sub-question. However, NUAP members, like the NUAP community, are divided on Q4.1. The division is associated in part with a corresponding division on Aurora. PPAN requested the NUAP Chair to organise a survey of the NUAP community in which Aurora would be addressed. The statistical results of the responses on Aurora are shown in the figure below. One third of all respondents indicated involvement in Aurora or its science or were supportive of its overall aims, with 80% of this category from the PISA community (where 95% were involved or supportive).

Many of the PISA respondents highlighted the scientific objectives of the Aurora programme. The aims of Aurora are described elsewhere in the sub-questions sections, however, if it is to achieve those aims it must be viewed as a long-term programme involving multiple missions. The number of PISA respondents agreeing with NUAP's prioritisation (with Q3.3 as a top priority) was similar to those who requested Q4.1 becoming a top priority, although only 2 PISA respondents did so in preference of Q3.3. NUAP feels that there is no compelling reason based on any of the statistics to alter the seven top priority sub-questions. PPAN can draw its own conclusions on Aurora from the results.



5. Facilities

The community has made clear to NUAP that grants and fellowships are of the very highest priority. However, as the statistics below show, people are reluctant to name facilities in their own areas to be cut. Obviously, the community cannot have it both ways unless the government provides unexpected levels of funding. We encourage PPAN to take seriously the message that the community's highest priority is healthy funding for grants and fellowships, but not to the point that our expertise and leadership in international projects is diminished such that a balanced programme for the future ceases to exist.

Some community input, that is not necessarily representative and in some cases is provocative, as approaches for the way forward include:

- In difficult financial times, it is essential to ensure the survival of the community as a whole rather than investing heavily in flagship projects that support relatively few scientist for a comparatively low scientific return.
- (I would give up) All of them. We can always get time on telescopes (I do ...) through collaboration if not by direct access. But without postdocs and fellows, our science activity and credibility will collapse.

- You need to get a grip on ground-based astronomy. [The] condition for joining ESO was to exit JCMT, UKIRT, WHT etc on a 10 year scale ... Ground-based has become bloated (ESO + all the others + Gemini + Merlin). Are we in ESO or not? Is it the priority? Need to get ESA thinking small again. Vast projects, vast cost overruns (Herschel-Planck*). You can do excellent, small and European space science if you try (VEX, MEX and Eddington would have been). There is NO purely European mission after GAIA. That loses the purpose of ESA. *note added by NUAP: also Lisa Pathfinder, ExoMars, Bepi-Colombo.

- After Herschel, the ESA programme provides no benefit to my field. I would pull out of ESA - 2012, and just buy into missions with other international agencies (e. g. NASA, Japan).

- I would be prepared to lose upcoming bilaterals ... It is vital to support whatever is selected for Cosmic Vision ...

- [We must be] addressing the big subscriptions ...

- Participation in the ESA Science Programme and the Exploration Programme are important to the health of the space industry. These Programmes work at the limits of feasibility and as such drive the development of technologies and skills – an essential input to the innovation required for a healthy science-based industry such as ours. These Programmes are catalysts in knowledge transfer between industry and academia and as such a key part of the knowledge economy. UK participation is so important that it is often taken for granted….membership of ESA (and in the current context, particularly of the Science Programme, the ExoMars programme, the MREP, and the supporting Technology Programmes) is fundamental to the economic benefits to the UK generated by the UK space industry.

6. Detailed Feedback regarding Facilities

Below is given some detailed information regarding feedback for facilities in the various science areas covered by NUAP.

Diffuse Matter and Star and Planet Formation:

For this area, we had 36 responses and we include a facility in a list if it was mentioned by at least two repondents in ways that its inclusion would be appropriate. The lists require little comment. A bit of support for placing Herschel just above the JCMT until 2012 was expressed. We did not have full confidence in the priority list for Q2.2 given in the 28 September presentation to PPAN and had expected considerable comment on it. In particular, we had expected to hear support for IR spectroscopy with 8m class telescopes. We received one comment advocating that method of observing the ejecta of evolved stars. Two people mentioned EVN/VLBI in various contexts. One of the specific comments that is not reflected due to the threshold imposed for inclusion in a list in this summary of DMSPF responses is that EVN/VLBI is potentially relevant for tracking Solar System space probes.

The number of people commenting positively about facilities were:

Q1.2 - UKIRT (3); VISTA (2)

Q1.4 - e-Merlin (2); EVN (2)

Q3.2 - UKIRT (3)

no specific question - ALMA (3); Herschel (3); JCMT (2); C-CAT (2)

The number of people who named various facilities as ones that they would be prepared to lose were: Gemini (8); MROI (3); UKIRT (3); e-MERLIN (2); EVN (2); ING which includes WHT (2); Labs (2); Liverpool Telescope (2); LOFAR (2); Lunar Sample Return (2); XMM (2)

Exoplanets:

There were 17 responses in the extrasolar planet area (there were a number of others mixed into the Stellar Astrophysics area but these will be looked at within that context). Of these there were more than 60% agreement with the sub question selected as of greatest importance. A few submissions thought that Q4.2 should be given more emphasis.

In general there was also good agreement (13 responses) with the selected facilities prioritisation for Q3.2. Of these >8 responses requested that access should be maintained to small facilities even in the era of the e-ELT/SKA (4 of these felt so strongly about this that they stated that a lower share of these large facilities should be negotiated in order to keep smaller facilities in operation). The facilities felt as least useful were Gemini (7), UKIRT/LT (3), LOFAR (2). We must admit to being somewhat surprised by some of these results. For example, early withdrawal from UKIRT seems at odds with the overwhelming support given to the IR spectrograph – the UKIRT Planet Finder (post 2012).

Planetary Interiors, Surfaces and Atmospheres:

There were 57 responses in the PISA category – which covers Q3.3 (solar system formation), Q3.5 (planetary evolution) and Q4.1 (life and habitats in the solar system). This included one institutional response. In the following summary - all percentages shown refer to percentage of respondents to PISA.

Prioritisation of sub-questions: 44% of those responding in this area agreed with the prioritisation of sub-questions – i.e. Q3.3 as highest priority. Of the 56% who disagreed, only 2 individuals (4%) disagreed with Q3.3 as the highest priority sub-question in this area. Instead, the majority of those disagreeing targeted one or more sub-questions from across the NUAP remit – in particular Q3.4 (30%), Q3.1 (18%), Q1.4 (16%) and Q5.2 (9%). Those disagreeing were evenly split in their request for alternative high priority sub-question(s) –the vast majority proposing Q3.5 (40%) or Q4.1 (40%), with 30% of the respondents requesting that both these questions be high priority. With 44% agreeing with Q3.3 as the highest priority – there is almost an even split between solar system formation (Q3.3), planetary evolution (Q3.5) and Life and habitats (Q4.1). On the basis of these responses it was not clear that there was a strong argument to change the priority sub-question.

Facilities Prioritisation: Almost 80% of those responding in the PISA area agreed with the proposed Facilities priority lists. Only one respondent commented on the facilities for the highest priority sub-question Q3.3. Of the remaining respondents disagreeing with the facilities for Q3.5 and 4.1 there were no common suggestions. Responses included inclusion of missions unlikely to receive significant direct STFC support (Phobos-Grunt and Mars Science Laboratory) or missions ahead of their scheduled availability. The diversity and high levels of agreement with the facilities order indicates that any changes in the priority list are not warranted. However, a couple of omissions were noted that should be rectified - PDS data mining (from NASA missions such as MRO, Odyssey and the MERs) to Q3.5 facilities. These resources were identified in Q4.1 – and given the high degree of overlap between these two sub-questions it would seem appropriate to incorporate this change. Another respondent highlighted the omission of HPC for hydrocode modeling of impacts for Q3.5.

Facilities to lose: There was not so much input here - some comments along the lines that everything too valuable or there were very few missions in this area already…. A number of facilities were identified - BepiColumbo (9%); Ground based telescopes (5%); Lab simulation, Lunar sample return Marco Polo (all 4%) and one comment each for ExoMars, comet SR, Cluster, Mars SR, Cassini and one comment to delay MoonLite and another to reduce access to facilities such as Diamond and Isis. The levels of response give little steer to the way forward.

Solar Physics:

In general, feedback from the questionnaire indicated that the community largely agreed with the facilities prioritization in the original presentation given to PPAN and the clear priorities that emerged were support for Hinode, STEREO, Solar Orbiter and theory/HPC. In terms of the prioritization of the sub-questions, there was no disagreement with the selection of Q2.1 and Q5.2, but 20% felt that Q1.1 should be added at the expense of either Q1.4 or one of Q3.2, 3.3 or 3.4. Most people refused to be drawn on the question of what they would be prepared to give up, but SOHO and LoFAR were the most frequently identified in this category. There was mixed support for BiSON, ATST, EST, and HiRISE, and as has been consistent throughout this most people identified grants and fellowships as their highest priority. Clearly, there is considerable variation in the size of the investment in projects and the most important goal for the community is to achieve a balance that allows us to maintain our international leadership by participating in international projects and their exploitation, as well as capitalising on our world-leading expertise in MHD and dynamo theory and helisoseimology. So, while support for BiSON was mixed, people recognised the intrinsic value of supporting long-term monitoring of this kind and the high science return and international leadership it provides in this area. Similarly, ROSA offers high return for a small investment and positions the UK well in this area. Given that decisions about international projects are largely at the mercy of changes in the political landscape, the requirement to maintain some flexibility by providing resources in a couple of areas until selections have been made was also identified. Solar Orbiter, Solar C and HiRISE fall into this category.

Of 49 respondents, 69% agreed with our initial prioritisation; 10% felt that HPC/theory should carry equal weight to the top facilities and 14% requested a slight re-ordering of the top ranked facilities. The remaining disagreement was over the inclusion of non-STFC supported facilities.

The following percentages of respondents indicated that they would be willing to lose facililties:

ATST (12%), EST (14%), ROSA (16%), HiRISE (12%), Proba-3 (4%), LoFar (18%), KuaFu (8%), Solar C (6%), Solar Orbiter (0%), BiSON (12%), SOHO (22%), STEREO (8%), Hinode (0%)

Space Physics:

In the area of Space Physics there were a total of 54 responses to the questionnaire. From this number just 9 disagreed with the priority sub-questions chosen by NUAP. Those who disagreed mentioned replacing 5.2 with 5.1, and most notably the possibility of merging sub-questions 3.2 and 3.3 was mentioned a number of times. Beyond this though, the community are mainly happy with the 7 sub-questions chosen.

Facilities Feedback: Overall 42 people agreed with the prioritised list of facilities and 12 disagreed. In general it was highlighted that Cluster and Double Star should be written as one facility, which should be underlined as a facility whose funding would continue beyond “current”. Beyond this it was clear that the Space Physics community are comfortable with the priorities set in these areas.

Facilities respondents are prepared to lose (total of 54 responses – therefore all responses at the ~10 % level or less):

KuaFu (5), Ground based STP facilities (1), Cassini (1), Theory/HPC (3), Double Star (4), Ground based obs. of planets (2), ROSA (1), Mars Express (7), Venus Express (7), STEREO (1), XMM (1), Cluster (2), LoFar (5), Rosetta (2), EST (2), Solar C (3), BepiColombo (6), Bison (2), MoonLite (1), SOHO (1), Aurora Programme (4)

Stellar astrophysics:

There were 100 responses in this area, about half of those (48) were from the gravitational wave community. A significant number of those submissions were clearly orchestrated both in content and style. All of them call for higher priorities on the GWR detectors (Geo600, [Advanced] LIGO, LISA, ET), and about 20 of them include SKA and LoFAR on their wishlist. A few people (2-4) outside the GWR community voted against some of the GWR facilities. On going through the other half of the responses: very few people associated specific facilities to specific sub-questions, and for quite a few, one had to decipher what they really meant (e.g. telling us in Q4 which facilities could be axed, and in Q5 which are most important). This is summarised below as a simple count of which facilities were considered not to be sufficiently highly ranked/praised in our report (+++), and which ones are not important/could go (---).

+++

ELT (3), ING (7), Gemini-N (3), Gemini-S (0), Gemini-both (0), e-Merlin (3), XMM (4), Swift (4), Gaia (5), LT (5), WASP (3), JCMT (0), IXO (3), ESO (5), UKIRT (2), SKA (2), LoFar (2)

ELT (2), ING (4), Gemini-N (0), Gemini-S (5), Gemini-both (10), e-Merlin (7), XMM (2), Swift (0), Gaia (0), LT (6), WASP (0), JCMT (2), IXO (2), ESO (0), UKIRT (8), SKA (4), LoFar (3)

Single +++ responses were given for: JWST, HST, VLBI, RXTE replacement, EVN, Corot, Kepler, Plato, MROI. Single --- responses were given for: BiSon, ALMA, post-launch support for high-energy missions, ESO/La Silla 2m telescopes, survey telescopes, "proprietary" facilities, Lovell Telescope, VISTA, C-CAT, MROI, ESA membership. Two responses said that the solar system missions were too expensive, and two explicitly targeted BepiColombo as ---.

7. NUAP Second Questionnaire to the Community 15th October – 4th November 2009

The questionnaire sent to the community after the September 2009 PPAN meeting is copied below:

1. In which of the six main areas (Diffuse Matter and Star and Planet Formation, Stellar astrophysics, Exoplanetary Systems, Space Physics, Planetary Interiors, Surfaces & Atmospheres, and Solar Physics) covered by NUAP do you work most?

2. What is the scientific significance of the Aurora programme in your research area?"

3. Given the broad remit of NUAP and the importance of a cohesive and coherent science strategy, are the seven sub-questions identified by NUAP as being of highest priority the most appropriate? (Please see the NUAP consultation document for details of the scope of each question http://www.scitech.ac.uk/Resources/PDF/NUAP_PPANReport_210909.pdf)

    a. Answer Yes or No
    b. If your answer is No; identify which one (or at most two) sub-questions you would remove from the highest priority category. Please suggest a replacement sub-question for each. At least one of these replacement sub-

questions must be in the same general area as one of the initial priority questions.

4. In the presentation made to PPAN in September (http://www.scitech.ac.uk/About/Strat/Council/AdCom/nuap.aspx) an initial prioritization list of facilities under each sub-question was given. For those sub-questions in your area of expertise, do you agree or disagree with this prioritization:

    a. Agree
    b. If you disagree with our prioritization please provide your take on what it should be in three specific timeframes:
        i. Present
        ii. within the next 5 years
        iii. more than 5 years from now

5. In order to protect the Grants & Fellowships round - what facilities in your area of expertise would you be prepared to lose involvement in?

6. Any Other Comments?

1.1 What are the processes that lead to convection and the generation of stellar magnetic fields, how do they evolve and what is their role in controlling activity?

Scope of the question

Magnetic dynamos operate in all stars at some time, impacting the formation of planetary systems and the near space environments around them. This impact has potential consequences for the systems' habitability. Dynamos also operate in planets themselves, accretion disks, and AGNe, making the understanding of them broadly relevant throughout astrophysics. Although internal flows and convection are clearly essential for the dynamo mechanism, no current dynamo theory accounts for the strength, patterns, or temporal variation of stellar magnetic fields. For example, current models of the solar dynamo are incapable of reliably predicting whether the next solar cycle will be stronger or weaker than the current one, or of explaining the current unexpectedly extended solar minimum. The goal in this area of research is thus to develop a successful theory, through the combination of numerical and MHD modelling with observations that provide long-term monitoring of solar and stellar dynamos and seismic observations of solar and stellar interiors. In particular we must:

a) Understand the nature and evolution of flows in the solar interior, formation and evolution of the tachocline and its role in the solar dynamo, and subsequent impacts on the Earth’s environment. This includes understanding the evolution of magnetic activity from the interior out into the heliosphere, including the links between the interior and the atmosphere.

b) Understand the chemical evolution of the solar interior, including mixing, settling, and convective overshoot and whether analogous processes operate in stars, and what their impact is on stellar evolution and population models.

c) Understand the angular momentum evolution of the Sun, the rotation of the deep interior and how this can inform our studies of the angular momentum evolution of stellar populations.

d) Understanding the internal mass distribution of stars and its effect on stellar evolution.

UK involvements and strengths, and opportunities

Dynamo theory: UK scientists are world leading in astrophysical turbulent dynamo theory, including the underlying physics of the generations of small and large-scale cosmic fields. They have provided critical insights into the role of radial shear in controlling magnetic buoyancy in mean-field models; producing dynamo solutions that show strong amplitude modulation consistent with grand minima and the simulation of small-scale dynamo action by turbulent convection in the solar photosphere.

MHD theory and modelling: The UK is internationally acclaimed for its work on simulations of magnetic flux emergence and the global solar magnetic field (as well as in coronal seismology and 3-D magnetic reconnection, see Q5.2). Recent 2.5-D numerical simulations of the interaction of a pair of twisted, buoyant magnetic flux tubes rising from the solar interior into the outer atmosphere of the Sun can now reproduce some of the dynamic solar phenomena in a self-consistent manner. This is an exciting and important step forward in understanding the links between the solar interior and the atmosphere and what triggers active phenomena.

Helio- and astro-seismology: UK scientists hold a world-leading role in helioseismology observation, data analysis and theory, including the collection of ground-based Sun-as-a-star data from the BiSON network and analysis of resolved global seismology and local seismology data, and have developed unique high-precision astroseismic techniques for diagnosing the internal structure and rotation of the sun and stars, and 2 and 3D models of dynamos, convection and rotating stars. Scientists in the UK have been responsible for mapping the rotation of the solar interior, establishing the role of magnetic fields in the amplitude and frequency modulations of the solar p-modes, and providing evidence (both observational and modelling) for the direct dynamic effects of photospheric wave leakage (e.g. p-modes) on atmospheric fine-scale structure formation. They have also led the way on constraining the structure of the deep interior and the internal chemical composition. The UK is well represented in the CoRoT asteroseismology project and chairs two of the working groups of the Kepler Astroseismic Science Consortium.

The UK is well placed to combine these strengths to make significant big advances over the coming decades for a relatively modest financial investment. Investment in theory and modelling will enable us the provide the necessary predictive framework for understanding how magnetic fields originate and evolve in the Sun and stars, but must be complemented by observations to constrain the theory. Access to the required observations should include both the collection and analysis of primary data, as well as resources to exploit data collected from non-UK funded facilities such as Solar Dynamics Observatory, Kepler, CoRoT, and SONG that are critically important for achieving the science goals. Primary data collection from BiSON and the unique ROSA instrument represent relatively small investments through the grants line, as does support for existing facilities such as HINODE through the PLS line. Solar Orbiter addresses several key science areas for the UK, and is a mission whose challenging orbit will make detailed planning for the science encounters critical. In order for the UK to achieve all of its science goals in this area it must have the power to make decisions about observing strategies that are only afforded to major contributors to the project. There has been substantial investment in Solar Orbiter within the UK to date and subsequent juste retour for UK industry. Investment in Solar C, now likely to also include ESA co-operation, represents a complementary opportunity to that afforded by Solar Orbiter, which builds on a now long-term and fruitful relationship with JAXA. Solar C Plan A would afford more continuous coverage of the solar poles and is planned to coincide with the predicted time of solar polarity reversal, greatly enhancing the observations that will be made by Solar Orbiter in the latter parts of its mission. Solar C Plan B would provide key high-resolution measurements of the emergence and evolution magnetic flux at the photosphere and its evolution throughout the outer atmosphere, important for quantifying local dynamo processes.

In the longer term, in the exoplanet and astroseismology areas the UK is extremely well placed for a leading role in PLATO.

Summary List of relevant facilities and resources

Current

Grants and Fellowships, Theory and modelling (inc. High Performance Computing), BiSON, HINODE, SOHO, CoRoT, Kepler, ROSA

Becoming available in the next 5 years

Becoming available after 5 years or more

Solar Orbiter*, Solar C, PLATO*

*Depends on ESA selection

1.2 What are the stellar content and stellar distribution in the Milky Way?

Scope of the question

The Milky Way Galaxy has always been one of the laboratories of astrophysics. The proximity of objects allows detailed studies of individual objects in a way that is not possible for extragalactic systems. Traditionally this has underpinned our basic knowledge of areas such as star formation and stellar evolution. With the launch of the Gaia mission in 2012 this area will enter a new era when astrometric positions will be determined with unprecedented accuracy over the whole sky. Gaia will also obtain velocity information for these objects and hence a 6 dimensional map of the Galaxy could be constructed. Many of our fundamental beliefs in astrophysics will be challenged by this new data.

Some of the exciting areas that will be impacted are:

a) Spatial distributions of low luminosity populations such as white dwarfs, brown dwarfs and high mass exoplanetary objects. These objects tie up the bulk of the baryonic mass but are only visible in the local environment. There exists a real need to identify large samples of these objects to understand the basic global population properties which could also impact on our knowledge of other areas. For example, there is some evidence to suggest that there exists a significant population of white dwarfs in the local environment that are actually halo objects. Gaia will be crucial in determining the initial and final mass function for white dwarfs and be able to probe the high mass exoplanet regime (see Q3.2)

b) Star clusters as astrophysical laboratories and tests of stellar evolution, binary stars and black hole formation theory. With the recent confirmation that black holes could exist in globular clusters it is important to try to understand the internal constitution of these objects (e.g. the mass function of black hole systems) as well as their internal dynamics (are they merged bodies?). Studies of the stellar populations in these systems will also give binary fractions etc and other parameters that will help constraint their formation.

c) The spatial distribution of stellar populations in the Galaxy. The positions and motions of stars and other objects are of importance to many fundamental questions, e.g. was the galaxy formed over a single epoch or is there evidence for multiple populations (indicative of mergers)? This topic lies at the interface between the advisory panels and will no doubt be covered by FUAP. However, it is of such importance that we are also highlighting it here.

UK involvements and strengths, and opportunities

While the UK is traditionally strong in survey astronomy we should recognize that studies of individual objects (especially rare objects) are important. This topic is unusual as it combines both approaches needing surveys to find, what are, rare objects. Historically, the UK has been strong in these areas and even now some 40-50% of the astronomical community would describe themselves as stellar or Galactic astronomers. Given this there are groups in many institutes with demonstrable leading expertise that places them ideally to take advantage of GAIA data:

1) Some have extensive experience in studies of the Galaxy's structure (and also local group objects) as well as star clusters etc. Leading theoretical and observational programmes on tidal streams, dark matter, etc. are in progress.

2) The UK has good expertise in stellar populations in globular clusters etc.

3) The IPHAS/VPHAS Consortium is a large UK led group of researchers from 20 institutes, (somewhat more than half of which are in the UK) that has been conducting surveys of the galactic plane from both hemispheres. The scientific aims are to map the global stellar populations and also extinction, etc.

The above list is not exhaustive.

Summary List of relevant facilities and resources

Current

Grants and Fellowships, ESO Facilities, 8m Telescope (Northern Hemisphere), ING (WHT+INT)

Becoming available in the next 5 years

GAIA, High spectral resolution MOS spectrograph (Both Hemispheres), VISTA and VST (ESO)

Becoming available after 5 years or more

LSST, e-ELT

1.3 How do low-mass, intermediate mass, and massive stars evolve?

Scope of the question

Our knowledge about the structure and evolution of stars at both ends of the stellar mass spectrum is fragmentary. At very low masses, the sub-stellar population bridges into the mass range of planets, with a strong overlap in physical properties, such as the internal structure of partially degenerate objects and complex, cool atmospheres. Within the intermediate mass range lies the dividing boundary between those stars that peacefully fade away, leaving behind white dwarfs, and stars collapsing into neutron stars or black holes. Among the most massive stars are the likely progenitors of long gamma-ray bursts (GRBs), the most powerful explosions in the Universe. The UK community is involved in a plethora of research lines, addressing questions such as:

a) What is the stellar mass function of low-mass stars, and where is its lower bound?

Practically all work on the stellar mass function of low-mass stars is based on very local samples, simply because these objects are intrinsically very faint. Current understanding is that the luminosity function decreases for stars below ≈0.2 Solar masses, but the form of the mass function below ≈0.1 Solar masses is very uncertain. A significant problem in the observational characterisation of low-mass stars is the degeneracy between age and mass, which prohibits the determination of a mass-luminosity relation. In addition, there are no reliable age-calibrators for sub-stellar objects.

b) What are the progenitors of core-collapse supernovae and of GBRs, and what other types of explosive stellar deaths exist?

Recent supernova surveys have uncovered a rich variety in the light curve morphologies and spectral properties of core-collapse supernovae, linking this diverse population of supernovae to stellar progenitors is still in its infancy. Time-series surveys have also uncovered a number of very unusual cataclysmic events, whose nature is very uncertain - it can be expected that the number of such events will steeply increase with the large-scale time-domain surveys coming online between now and the middle of the next decade. Finally, the study of the detailed nature of GRBs, and their relation to supernovae, remains a very active area.

Scope of the question cont'd

c) What is the galactic population of stellar remnants?

White dwarfs are by far the most numerous stellar remnants, but their exact contribution to the baryonic mass of the Galaxy is still controversial, depending on the initial mass function in the early days of the Galaxy. Mapping out the white dwarf population in the Galaxy will provide some direct insight into its star formation history. Only a small fraction of the neutron stars in the Galaxy are known, the vast majority being young radio pulsars. The evolutionary link to other neutron star populations, such as magnetars, or X-ray dim isolated neutron stars is yet unclear. Only a handful of stellar black holes, the most massive remnants of stellar evolution, are known so far; all of which are in binary stars.

Overlap: massive stars lose large fractions of their mass into the interstellar medium, feeding back into star formation (Q2.2); sub-stellar stars share many physical properties with exoplanets (Q3.2); massive stars can be studied as resolved populations in external galaxies (FUAP); supernovae and GRBs probe star formation in the far Universe (FUAP); stellar remnants represent astrophysical laboratories for extreme physics (Q5.1).

UK involvements and strengths, and opportunities

The UK is at the forefront of observational studies of sub-stellar populations. The exploitation of UKIDSS through vigorous follow-up programmes on the WHT and Gemini will be a major driver for UK's internationally leading activities. In the imminent future, ESO/VISTA will add to the UK's strength in large-scale near-infrared surveys, increasing the population of low-mass stars available for characterisation. Continued access to 4-8m facilities in both hemispheres is crucial to fully reap the investments made into the survey infrastructure. A crucial step will be the exploration of ultra-cool sub-stellar objects in the previously unexplored temperature range 200-600K, corresponding to masses near the fragmentation limit 1-12M_{JUP}. UK astronomers are also strongly involved in establishing gravity and age indicators for sub-stellar objects, either in the form of particular atmospheric features, or using common-proper motion companions with well established ages.

The UK hosts some of the world-leading groups working on the identification of core-collapse supernova progenitors, based on deep pre-explosion imaging. A recent result is the determination of a lower limit of ≈ 8 Solar masses for a star ending its life in a type II-p core-collapse. Other work underway is the identification of large numbers of Wolf-Rayet stars in local-group galaxies, with the aim to provide pre-explosion information for future type Ib/c supernovae in some of these galaxies. The UK is also a key player in the field of GRBs observations, with the most recent highlight being the discovery of the highest-redshift GRB at Z ≈ 8.3. All of these projects clearly require long-term efforts, and rely on continued long-term access to large-aperture telescopes. Access to both hemispheres is essential as nearby supernovae or extreme redshift GRBs are rare events, and losing access to the north will further decrease the chances of using one of these few opportunities. A future ELT will dramatically push the limits of this type of research. The UK also hosts some of the world-leading groups working on stellar evolution models of massive stars; the continued impact of their work relies on maintaining a healthy grants line and investing into high-performance computing. This whole complex of research is a fine example of the close links between the study of supernovae, resolved populations in external galaxies, and the theory of stellar evolution.

The UK has a long-standing track-record in white dwarf research, a recent example of strong UK involvement in white dwarf research is substantial work on the initial-final mass relation. ESA's GAIA mission offers the potential of a quantum leap, identifying an expected 200 000 white dwarfs. This will allow the determination of the white dwarf luminosity function for the galactic disk and halo, and thereby provide insight into the star formation history of the Milky Way. Continued access to 4-8m telescopes is essential to follow-up GAIA discoveries; among the 4m class telescopes the WHT is particularly important due to its superior instrumentation compared to the ESO/NTT. Similarly, new surveys are underway to establish the complete local population of pulsars, using the Lovell telescope and eventually LOFAR. A recent example of the current incompleteness of the pulsar population has been the discovery of the subclass of Rotating Radio Transients (RRATs). These surveys are expected to uncover rare objects, such as relativistic binaries, also. The future study of the galactic pulsar population with the SKA and LOFAR will address the nature of gravitational wave radiation. Before these new radio facilities come online, the UK will continue with the world's most ambitious programme of pulsar timing, which is aimed at making both astrometric measurements (positions and proper motions) as well as studying the evolution and stability of the rotation of the pulsars themselves.

Summary List of relevant facilities and resources

Current

UKIRT, Gemini, WHT, ESO/VLT, Swift, Grants and Fellowships, Lovell Telescope, e-MERLIN/VLBI

Becoming available in the next 5 years

ESO/VISTA, ESO/VST, GAIA, LoFAR, JWST

Becoming available after 5 years or more

ESO/ELT, SKA

1.4 How do binary and multiple systems, including those that emit gravitational radiation or become type Ia supernovae, evolve?

Scope of the question

A large fraction of all stars in the Galaxy are part of binary or multiple stellar systems, and a significant fraction of them will interact at some point in their lives. Many of the most extreme environments and exotic objects, such as stellar black hole binaries or milli-second pulsars, are descendants of binary stars, and binary evolution leads to some of the most powerful explosions in the Universe. The detailed physics of these interactions and their impact upon the evolution of the stellar components is poorly understood. Major open questions at the level of physical processes are: What is the efficiency of common envelope evolution?; At what rate does magnetic braking drive angular momentum loss from the binary orbit; How does binarity affect the evolution of the individual stellar components?

These questions are fundamental for our understanding of binary and multiple star evolution. Higher-level questions layered on top of these fundamental mechanisms bridge into many areas of modern (astro)physics. One example of such broad themes is “what are the progenitors of type Ia supernovae (SNIa) and (short) gamma ray bursts (GRBs), and do they evolve with time?”. While most of us agree that SNIa are exploding Chandrasekhar mass white dwarfs, the debate whether they descend from single-degenerate or double-degenerate progenitors, or both, is entirely open. Astronomers think about new costly space missions to use SNIa to measure even the time evolution of the equation of state of the Universe. However, as of today, our understanding of the very nature of SNIa, and their evolution as a function of e.g. metalicity is unknown, and without significant progress in developing this understanding human and financial resources may be wasted. A second example is “what sources of gravitational wave radiation are there in the sky?” The (astro)physics community is working on and planning experiments to detect gravitational wave radiation (GWR) - galactic short-period binaries containing stellar remnants are expected to be a substantial source of the continuous GWR signal that those experiments will detect, mergers of such binaries will be detectable in external galaxies. Again, interpretation of the GWR results has to go hand-in-hand with observational and theoretical population studies of compact binaries. Answering all these low-level and high-level questions needs simultaneous progress along several research lines.

Scope of the question cont'd

From the observational side constraints on the evolution of binary systems come from two lines. Large-scale surveys are necessary to produce homogenous and unbiased populations of binary stars. Large surveys are also required to identify sufficient numbers of intrinsically rare objects holding key information on the outcome of binary evolution. Beyond the mere identification, detailed follow-up studies of individual key objects as well as entire sub-samples are necessary to provide accurate physical parameters. This empirical information can then be used to infer observational constraints on their evolution to test and guide theoretical developments. A number of such surveys are currently being carried out in the time domain and in multi-colour space, and several more will begin throughout the coming decade. A clear lack is the provision of large spectroscopic surveys, but modest investment in existing facilities can overcome this issue.

On the theoretical side, progress needs to be made both in the area of detailed models of stellar evolution in binaries, as well as in population syntheses assembling those models to predict total numbers specific types of objects, such as e.g. the rate of SNIa. Stellar models need to be further developed to account for all the complex physical processes affecting the evolution of binary stars, e.g. angular momentum exchange, rotation, magnetic fields, or mass loss through stellar winds. Binary population models suffer currently from uncertainties in the energy and angular momentum balance during the common envelope phase. High-resolution three-dimensional hydrodynamical models of this phase, calibrated by observational constraints on the common envelope efficiency, will have to supersede current parameterised approximations.

Overlap: A wealth of astronomical laboratories for extreme physics descend from binary evolution (Q5.1), and provide insight into the nature of accretion inflows/outflows (Q5.2 & 5.3) as well. GRBs and SNIa are essential beacons for observational cosmology-i.e. within FUAPs remit.

UK involvements and strengths, and opportunities

The UK has an excellent long-standing track record in observational studies of binary populations, with several research groups that regularly win significant amounts of observing time on current ground-based (ESO/VLT, ESO/NTT, ING/WHT, Gemini) and space-based (XMM, HST, Swift) facilities. Major achievements under UK leadership include: very successful programmes to identify double-degenerate white dwarf binaries, which represent one possible type of SNI progenitors; the realisation of a binary origin of most hot subdwarfs, which are contributing to the UV excess in elliptical galaxies; and the identification and detailed characterisation of X-ray binaries in the Milky Way and local group galaxies, including precise dynamical mass measurements of neutron stars and stellar black holes.

The UK is also leading a number of large-scale surveys that are instrumental to identifying the binary population, including the ongoing UKIRT/UKIDSS and INT/IPHAS. In the near future, the ESO/VISTA and ESO/VST will initiate large photometric surveys under UK PI status. The launch of the ESA cornerstone mission GAIA will lead into an entirely new era, providing distances and optical spectral energy distributions for a billion stars down to V=20. All this data becoming available from the middle of the next decade will represent an unprecedented resource for establishing the census of the galactic population of binary stars. A full exploitation of the UK's investments into ESO and ESA will require that we maintain a sufficiently large stake in ground-based facilities to enable efficient and timely follow up of the forthcoming surveys. With limiting survey magnitudes in the range V ≤ 20-22, VST/VISTA/GAIA follow-up will require not only large amounts of observing time on 4-8m telescopes, but also adequate instrumentation. A clear lack in the currently available instrumentation is efficient wide-field multi-object spectroscopy on a medium-sized telescope, and steps to provide such a facility should be taken now to ensure its timely availability. Given that many products of binary evolution are sources of high-energy emission, panchromatic follow-up of binary populations relies on continued access to the ultraviolet and X-ray regime. In X-rays, a potential replacement for XMM exists in the form of the ESA/NASA IXO mission. However, the UK currently has no involvement in any of the potential future ultraviolet missions, and participation (through ESA) in NASA's ATLAST would be highly desirable.

The UK hosts several world-leading groups working on stellar evolution, with particular focus on the evolution of binary stars, as well as binary population synthesis. We are now in a position to evolve 1-D models through some of the most complex stages of evolution such as core carbon ignition followed by second and third dredge up in super-AGB stars, as well as calculating reliably much of the complex nucleosynthesis in these stars. Though steady mass transfer in a binary system can be modelled with some confidence, important dynamical phases of mass transfer such as the common envelope phase of evolution, required to generate many of the exotic close binaries we observe is still modelled with intuitive guesswork. The next ten years can potentially change all of this, and the challenge is to make 3-D models that can evolve on the stellar thermal and nuclear timescales over which significant changes occur. Any progress in our understanding of the evolution of binary populations relies on continued support in terms of human resources and high-performance computing facilities.

Summary List of relevant facilities and resources

Current Grants and Fellowships, 4-8m telescopes (WHT, ESO/NTT, ESO/VLT), survey telescopes (INT, UKIRT), high-performance computing, ultraviolet telescopes (HST), X-ray telescopes (Swift, XMM), LT
Becoming available in the next 5 years GAIA, survey telescopes(ESO/VST, ESO/VISTA).
Becoming available after 5 years or more future X-ray(e.g. IXO*) and ultraviolet (e.g. ATLAST) telescopes, LISA*

*Depends on ESA selection

2.1 How does solar activity affect the near-Earth space environment, as well as those of other planets, and how does the Sun affect civilization?

Scope of the question

The existence of life on Earth depends on the Sun; its output and activity define the space environment in which we live - we effectively live within the Sun’s outer atmosphere (the Heliosphere). In an increasingly technologically reliant society, the influence of the Sun on our direct space environment can have severe consequences, for example, on satellite, communication and power technologies, and therefore is important for the functioning of our modern society. Another important aspect of the Sun’s impact on our lives is the as yet unclear influence of the Sun on changes in the Earth’s climate. The contribution of solar energetic particles (SEPs) and galactic cosmic rays (modulated by the solar magnetic field), and changes in EUV and UV irradiance and their effects on atmospheric chemistry are currently lacking in climate models.

The magnetic fields that thread the solar surface fill and structure the solar atmosphere. This interaction of the plasma and magnetic field produces a number of dynamic phenomena whose size and lifetime evolve over a wide range of length and time scales. Many of these phenomena such as coronal mass ejections (CME’s), solar flares and open flux may directly affect the Earth and thus understanding and eventually predicting these phenomena is of great importance. Key questions include:

a)Understanding the nature and evolution of flows in the solar interior, the solar dynamo, and the evolution of magnetic activity, including the links between the interior and the atmosphere (see Q1.1).

b)What role do small and large scale flows observed at the level of the photosphere play in the build up of energy and the reorganisation of atmospheric magnetic fields into complex energy releasing structures? How do these processes produce long-term variations in solar activity?

c)What mechanisms result in the release (transfer) of energy both over small (few metres) and large (solar radii) length scales leading to solar flares and CMEs? How do CMEs propagate into the heliosphere? How do small and large-scale flows transport the open flux across the solar surface? What causes the variations in the level of open flux over short (days-weeks) and long (solar cycle) time scales? How does the Sun so efficiently accelerate particles into the heliosphere?

As a persistent material outflow from the Sun that carries with it the solar magnetic field, the solar wind and its interactions with bodies within the heliosphere can have a profound influence on their evolution. It is thus critical that both the origins at the Sun, and the evolution of the wind, are fully understood in order that we can understand the variations that we see in situ and their subsequent impact on the planets. Key questions include: What is the global structure of the solar corona and the near-Sun solar wind? What are the sources and acceleration mechanisms of the fast and slow solar wind? What are the drivers and effects of solar wind turbulence, and how and where are shocks formed? A key element in understanding these phenomena is the marriage of observational data and theoretical models to reproduce the characteristics of these complex systems and then to predict them.

Magnetospheric activity is governed by the solar wind and solar variability, especially for slowly rotating planets in the inner Solar System: this dominates at Mercury and Earth, is important at Saturn, and has an influence at Jupiter. In the case of non-magnetized planets, e.g. Venus and Mars, solar wind activity also controls the outer plasma environment; at Mars, interaction of the interplanetary magnetic field with remnant crustal fields could lead to low altitude intrusion of solar wind plasma. Concentrating on the Earth, several key questions remain unanswered, which all relate to coupling with solar activity and the changing solar wind: how is energy, mass and momentum coupled from the solar wind into the magnetosphere, esp. via magnetic reconnection; why is magnetic reconnection episodic in nature (flux transfer events and substorms); what leads to the acceleration of particles (including “killer electrons”) in the radiation belts; what leads to the enhancement of the ring current (geomagnetic storms), and what is the feedback between the ring current/inner magnetosphere with the solar wind coupling processes; what determines the “geoeffectiveness” – the level of geomagnetic activity induced in the magnetosphere – of solar wind structures such as ICMEs and CIRs, and the solar cycle dependence of these structures; what is the impact of geomagnetic activity on the ionosphere and the impact on positioning, communications, detection, and power systems; what is the influence of geomagnetic activity on atmospheric chemistry, and pathways to tropospheric control.

UK involvements, strengths, and opportunities

UK scientists have internationally recognised expertise in the use and analysis of the many disparate datasets required to address these questions, with excellent track records in the use of UK-led and non-UK-led instrumentation. Many novel techniques developed for this purpose are widely used internationally. In particular, the emergence, evolution and eruption of magnetic fields and the tracking of the associated disturbances through the heliosphere to their impact at Earth are growing UK strengths. These include the developing field of Heliospheric Imaging, in which the UK has played a leading role, with SMEI and STEREO; the UK STEREO HI instruments for the first time allow CMEs to be tracked from their solar origin to the Earth. The UK has also made pioneering contributions to our understanding of flare and CME initiation and connections between the solar source region and ICMEs. Hinode has played a key role in this area in highlighting the structure of outflows from CME source regions.

The UK also has complementary expertise in the area of the solar wind and interplanetary scintillations. The UK involvement in Ulysses and Cluster in particular, together with supporting theory, has produced groundbreaking advances in our understanding of the solar wind and its interactions within the heliosphere. Similarly expertise in the area of interplanetary scintillation has led to a key role for the UK in this area within the LOFAR consortium. New results from Hinode from within the UK are for the first time providing concrete evidence of the origins of the solar wind in the low corona, enabling us to begin to make reliable connections between processes occurring on the Sun and signatures observed in situ.

The UK plays a leading role in understanding solar wind/magnetosphere coupling, the resulting magnetospheric behaviour, including extreme events such as geomagnetic storms, the impact on man-made systems, and the influence on the lower atmosphere. Advances in these fields require a multi-point, multi-instrument, multi-technique, ground- and space-based approach that is unique in the STFC portfolio, and in which the UK excels: the assimilation, analysis, and synthesis of disparate datasets to study solar effects from cradle-to-grave. The solar wind/magnetosphere/atmosphere system is highly complex, with many interacting subsystems occurring on a wide variety of temporal and spatial scales. The UK is a world-leader in studying the influence of solar variability on the Earth from a “system-level” perspective.

These growing strengths place the UK well in this area for the coming decades, and it is a topic that has clear implications for the quality of life on Earth, and thus an area that deserves investment. We must combine theory and observation, including both the collection of primary data that will allow us to observe the processes on the relevant temporal and spatial scales (such as Hinode, STEREO, BiSON, SDO, Solar Orbiter (2017), ATST (2014) or EST (2020), ROSA and Solar C (2015)), in which we currently hold leading or strong science positions), and the resources to exploit the datasets from other missions that are so critical for diagnosing complex, coupled systems (e.g. SDO, RHESSI, TRACE, NoRH, LOFAR, IRIS). Solar Orbiter in particular offers a unique opportunity to bring together the solar, heliospheric and space plasma communities within the UK to achieve groundbreaking science that capitalizes on our ESA subscription. The UK has been instrumental in the development of Solar Orbiter since its conception, and stands to gain considerably scientifically and internationally from a continuing leading role in the payload. Solar C is still in the definition phase, but will provide unique and complementary observations in the period leading up to the launch of Orbiter, that will build on our existing strong relationship with JAXA and exploit internationally recognized hardware strengths. Continuing grant support and PLS support for Hinode, STEREO and ROSA during the preparation for Orbiter are critical to allow the community to continue to develop its expertise in this area. PLS funding for these current missions represents a small investment. Supporting investment in theory and modelling of the solar interior and a coupled Sun-Earth system will greatly enhance our capability to predict the impact of solar variability on our own environment.

Summary Lists of Facilities and Resources (including size of investment and importance)

Current

Grants and Fellowships (includes exploitation of non-primary data-sets), Hinode, STEREO, BiSON, ROSA, SOHO, Cluster/Double Star, Ground based STP, theory and modelling, Cassini, Venus Express, Mars Express

Becoming available in the next 5 years

LoFAR, PROBA-3, BepiColombo

Becoming available after 5 years or more

Solar Orbiter*, Solar C, Cross-Scale*, KuaFu, EJSM*, ATST/EST, HiRISE

*Depends on ESA Cosmic Vision selection

2.2 How do evolved stars lose mass and what is the history of stellar ejecta present in young stars and planetary systems?

Scope of the question

All heavy elements and dust in the interstellar medium (ISM) originated in evolved stars, and were ejected by supernovae (SNe) or stellar (AGB, LBV, WR) superwinds. The abundances of those elements and of the various types of dust control the ISM's cooling and opacity. Thus, they regulate star formation. The heavy element abundances also affect stellar evolution, the efficiencies of superwinds, and the SN rate and mass return. Consequently, galaxy evolution is driven by processes which enrich and deplete the ISM. ISM dust becomes an integral part of protoplanetary discs. The solids are processed and grow within the discs, dominating the dynamics and initiating planet formation. The compositions of meteorites and other Solar System solid bodies reflect the histories of the ejecta incorporated in them.

a) The processes causing the superwinds of stars, from asymptotic giant branch (AGB) to massive stars (RSG, LBV, WR), can cause the ejection of 20-80 percent of a star's mass. Superwinds determine the lower mass limit of core-collapse SNe. The elemental and isotopic composition of ejecta and dust is governed by a combination of nuclear reactions, dredge-up efficiency, and mass loss mechanisms. These stars are the chief sources of carbon and nitrogen; the s-process in the helium-burning shells of low- and intermediate- mass stars (LIMS), which produce half of all nuclei heavier than iron, is also important.

b) SNe may have produced the Universe's first dust, but LIMS dust became important for $Z \leq 6$. When dust became sufficiently abundant, the types of stars forming changed. Shocks at SN ejecta - ISM interfaces destroy dust. The evolving balance between SN dust formation and destruction was key to the Galaxy's early evolution. SN remnants (SNRs) and protostellar outflows drive shocks that modify the Galaxy's dust content. Surviving ISM particles include large aromatic and aliphatic carbon molecules.

c) Dust surfaces catalyze ISM and disc chemistry leading to prebiotic molecules (cf. Q3.1 section).

d) Laboratory studies of meteorites, interplanetary dust, and samples from asteroids, comets, and other Solar System objects reveal the astrophysical sources of Solar System solids, and signatures of ISM and disc processing. The isotopic compositions show that different nuclei in the solids formed in different stars, and conglomerated within the disc. They indicate that a SN triggered the Solar System's birth.

UK involvement and strengths, and opportunities

a) Superwinds are major sources of heavy elements and dust. UK-led projects to study dusty mass loss over a wide range of stellar masses, ages, and metallicities were awarded over 1000 hours of NASA's Spitzer

Space Telescope time. This led to the identification of a dual trigger mechanism for superwinds. Direct evidence has been found for efficient dust formation at extremely low metallicity. The development of a new self-consistent approach for solving for the velocity fields and mass-loss rates of high mass stars, constitutes another recent important contribution to the UK's strong legacy in studying mass loss from stars. The approach opens the possibility of performing reliable mass loss calculations for stars which have major effects on their galaxies but for which empirical constraints are unavailable. Mass-loss rates of high mass stars can now be inferred from X-ray studies of wind-wind collisions in binary systems, and binarity influences the morphology of many superwinds and nebulae.

The UK's construction of 3-D Monte Carlo radiative transfer codes and use of them in the analysis of optical and infrared data for mass loss outflows, nebulae, and SN ejecta are leading to unprecedentedly reliable determinations of the elemental and dust contents of such sources. For instance, UK groups have made major contributions to measurements of the dust in the ejecta of SNe with high mass stellar progenitors. These results bear significantly on the origin of the first dust in the Universe. From studies of the dust forming around a star in a nearby, very metal poor galaxy, UK researchers have concluded that carbon rich stars were potential alternative sources of early dust. The key to recent and future advances is access to telescopes that can reach luminous stars in galaxies up to 10 Mpc away.

The UK is well positioned to use ALMA, ELT, e-MERLIN, EVN, Gemini, Herschel, HST, IXO, JCMT, JWST, MROI, SKA, SPICA, VLT, WHT, and XMM in leading research on stellar mass loss and dust formation.

b) SN ejecta drive a shock into the progenitor star's wind and then the ISM. An inner, reverse shock decelerates the ejecta. Recent UK studies with Gemini and Spitzer of SN2008S show that the SN destroyed a negligible fraction of the pre-SN wind's dust. Though SN ejecta are clumpy, theorists investigating dust sputtering in them, as they pass through a reverse shock, have assumed that they are distributed smoothly.
UK researchers have applied innovative techniques, including a k-ε treatment of turbulence, in simulations of shock interactions with clumps. Shocks driven by protostellar jets and outflows into surrounding material, the study of which is a UK strength, induce sputtering and affect the gas phase molecular composition and emission, to be observed with ALMA and Herschel to diagnose the shocks. UK researchers have developed the first relevant fully time-dependent multifluid models of oblique hydromagnetic shocks with self-consistent descriptions of the effects of dust grains on the dynamics. HPC is required for the modelling of shocks in clumpy media or having complicated geometries.

The ISM dust population results from shocks processing the ejecta and is observed primarily from the submm through the FUV. Dust and nanoparticles contain much of the interstellar carbon. Some of it may be in fullerenes, nanotubes, or graphene, all materials only recently accessible in the laboratory. The history of this carbon is important from the perspective of its possible role in the production of prebiotic molecules. UK scientists conduct laboratory, theoretical, and observational investigations aimed at identifying the nature of the interstellar carbon nanoparticles and grains from their spectra.

c) Surface chemistry in star and planet formation is addressed in the section on Q3.1.

d) The refractory nature of most presolar grains permits the laboratory analysis of them to provide information about isotopic abundances that cannot be measured with purely astronomical observations and, consequently, about physical properties in stellar atmospheres, galactic chemical evolution, and mixing of ejecta during SN explosions. UK researchers are now leading a large survey of the abundances in and distributions of primitive materials. A UK group has developed a technique to isolate the rare presolar grains in meteorites without destroying the nonrefractory mantles or altered surfaces.
At least 15 individual stars are responsible for distinct contributions to the presolar grain population. Most presolar SiC grains came from AGB stars. However, a significant number are SN ejecta, and isotopic data for a few suggest ONe novae as probable sources. Presolar graphite, oxides, and silicates are due to a range of stellar sources. Recent UK work on SiC grains revealed the first evidence of high energy implantation processes affecting them. Signatures of the implanted components provide insight into the planetary nebular

phase and ISM shock processing. Samples of more pristine early Solar System material returned from primitive asteroids or comets (e. g. with Marco Polo) will provide new presolar grain populations and better understanding of the presolar grain inventory at the Solar System's birth.

The analysis of cometary material returned by NASA's Stardust mission has been one of the UK's major contributions to the investigation of the processing of solids in the Solar System. As discussed in the section on Q3.3, the study of processed solids yields insight into the dynamics of the protosolar nebula. It will inform research on the formation of exoplanets and the systems where they are found.

The cosmochemistry laboratory provision, recently augmented by the establishment of the UK Cosmochemical Analysis Network (UKCAN), is vital for UK studies of presolar grains and processed extraterrestrial solids. Continued investment will be essential to maintain UK leadership.

Summary Lists of Relevant Facilities and Resources

Current

Grants and Fellowships, EVN/Global VLBI, Gemini, Herschel, High Performance Computing, JCMT, laboratory facilities, UKIRT, VLT, VLTI, XMM, WHT

Becoming available in the next 5 years

ALMA (full array 2012), e-MERLIN (2010), JWST (2013), MROI (2014), VISTA (2010), VST (2010)

Becoming available after 5 years or more

ELT (2018+), IXO* (2020), Marco Polo* (2017), SKA (2018+), SPICA* (2017)

*Depends on ESA selection

2.3 How do star formation triggering and feedback work and affect the Galaxy locally and globally?

Scope of the question

The goal of much of diffuse matter and star formation research is to obtain an understanding of the relationship between the diverse range of star forming environments, the physical processes involved, and the stars that are produced. Q 3.1 also concerns issues related to this goal.

Triggering of and feedback in the formation of stars, especially high mass stars, control global, as well as local, properties of galaxies. Feedback must have been negative during the births of spiral galaxies for sufficient dissipation to have occurred for discs to develop. However, the stellar age dependence on location in some star clusters demonstrates that feedback is sometimes positive. We do not even know why feedback can have such contrasting effects in different regions or why star formation sometimes occurs quiescently. Hence, no prescription for the star formation rate used in models of the formation and evolution of galaxies, including the Milky Way, is reliable. Therefore, we do not understand why galaxies have the properties that they do or how the stars that trace galactic structure formed.

a) The use of computational hydrodynamic and magnetohydrodynamic simulations, including a wide range of physics, from radiative transfer to cosmic ray advection and diffusion, are required to identify how a multiphase interstellar medium (ISM) is regulated and its properties affect triggering and feedback.

Scope of the question cont'd

b) The enrichment of the ISM with heavy elements and dust ejected by stars affects star formation and galactic evolution, as mentioned in the Q2.2 section.

c) Multiwavelength studies of extragalactic starbursts and superwinds complement research on triggering and feedback in the Milky Way. Some multiwavelength surveys will be completed, while others will be initiated, to probe the diverse natures of and provide unbiased samples of Milky Way star forming regions.

d) Detailed high spatial and spectral resolution radio, millimeter, submillimeter, and infrared studies to follow up the surveys and probe the structures and kinematics of star forming regions are necessary to understand the physics of triggering and feedback.

UK involvement and strengths, and opportunities

a) Triggering and feedback involve scales ranging from kpc (spiral arms) and 100 pc (Giant Molecular Clouds - GMCs) to pc (translucent CO clumps in GMCs) and 0.1 pc (dense cores in which stars form).

UK scientists have developed numerical hydromagnetic models that give insight into the triggering of GMC formation by galactic spiral arms. Other UK groups have shown how fast- and slow- mode shocks driven into regions that are initially only marginally thermally stable generate GMCs containing magnetically dominated substuctures as well as high density shells. Computational studies performed in the UK indicate that the efficiency of feedback in star formation may depend on the ratio of the sound crossing time in clouds to the flow time between clouds of a hotter, more diffuse embedding medium. This result provides hope that reliable prescriptions for the feedback efficiency can be developed. It also indicates that on 100s - 1000s pc (as well as smaller) scales, triggering and feedback depend on the cloudy, multiphase nature of the global ISM, which is regulated by supernova remnants (SNRs) and the winds and radiation of high mass stars (stars of more than eight solar masses). In the ISM, the cosmic ray (CR) pressure is comparable to the thermal pressure. World leading theoretical and computational efforts in the UK on CR acceleration and magnetic field amplification in SNR shocks will prove key to understanding SNR evolution and how global ISM properties are established.

Other UK scientists have made important computational contributions to the understanding of triggering on GMC- and smaller scales. Several UK groups are elucidating theoretically and computationally how dense cores form, and some of them have incorporated continuum radiative transfer in hydrodynamic models to study radiative feedback in the formation of star clusters High Performance Computing (HPC)is vital for the type of work described in this and the previous paragraph.

b) The impact on stellar birth of ISM enrichment by stellar ejecta is treated in the Q2.2 section.

c) Star formation occurs under very diverse conditions. The achievement of an understanding of triggering and feedback requires observations of similarly diverse environments. UK scientists have conducted important radio interferometric, X-ray, and optical studies of extragalactic SNRs, the hot phase and its interaction with embedded clouds, and the distribution of star clusters in starburst galaxies. Two UK groups collaborate with Penn State colleagues on the interpretation of X-ray data for young Milky Way stellar clusters to study wind-induced feedback. Facilities relevant to such extragalactic and galactic observations include EVN, e-MERLIN, Gemini, IXO, SKA, VLT, and XMM.

Extensive surveys of large areas and numbers of objects are essential for understanding the relationship between the great variety of star forming environments, the dominant processes, and the stars that are born. They are necessary for the capture of intrinsically rare but important objects and events, such as the births of the most massive stars in a system. The $> 10^6$ factor difference between the linear sizes of a dense core where a star forms and of a star also demands complementary work at the highest angular resolution to study the physical processes of star formation. The UK leads the world in star formation oriented surveys over a wide range of wavelengths from radio through submillimeter to infrared and optical, probing the full span of star formation and early stellar evolution. These include: the CORNISH and MMB radio; the JCMT-GBS, JCMT-JPS, and JCMT-SLS submillimeter; the RMS mid-IR; the UKIRT-GCS and UKIRT-GPS and VISTA-VHS and VISTA-VVV near-IR; the IPHAS and VST-VPHAS+ optical surveys. So many surveys are essential, because each is particularly sensitive to different types of stars or regions or gives unique information about sources also studied in other surveys.

c) The surveys are providing the UK with the basis for the kinds of follow-up studies of well selected samples needed to understand the physics of star formation and star formation's impact in areas ranging from the evolution of galaxies to the formation of planetary systems. From 2015, the surveys will be followed up by increasingly accurate astrometry from GAIA (launch in early 2012). Essentially the UK is collecting reliable digital photometry on all of the Galaxy's major star forming regions and will soon have access to a vast array of accurate distances to many of the young stars within them. In many instances, young clusters will be open to precise 3-D mapping, and age-dating that will give insight into how young stars are dispersed into the field. The same datasets will also have a huge impact on our understanding of the evolution of massive stars (detectable at faint red/optical wavelengths, even through 10-15 magnitudes of reddening), and of the way in which they modify the environments into which they are born. For the community to fully capitalise on the immense opportunities created by the survey photometry, follow-up optical and infrared spectroscopy to study radial velocities, abundances, and the intervening ISM will be necessary.

In addition to supplying the censuses of a variety of protostars and young stars, the surveys will reveal information about the distributions and kinematics of ionised, as well as molecular, material around them.
High resolution follow-up observations of the kinematics of the diffuse matter will directly diagnose the physics of the feedback processes, including those driven by the outflows of young low mass stars having discs, in star forming regions. The strength of its community's radio and mm/submm observational experience and modelling expertise and its leading role in the surveys position the UK well to exploit ALMA to conduct high spatial resolution studies of the dynamics of star forming regions. C-CAT will enable wider field observations, with about four times higher spatial resolution than obtained with SCUBA2 on the JCMT, that will complement ALMA data. Infrared observations, including those of important cooling lines, with Herschel and SPICA will also be valuable.

Summary Lists of Relevant Facilities and Resources

Current Grants and Fellowships, EVN, Gemini, Herschel, High Performance Computing, JCMT, UKIRT, VLT, XMM
Becoming available in the next 5 years ALMA (full array 2012), e-MERLIN (2010); GAIA (2012), VISTA (2010), VST (2010)
Becoming available after 5 years or more C-CAT (2016), IXO*(2020), SKA (2018+) SPICA*(2017)

*Depends on ESA selection

3.1 What processes, including those leading to prebiotic molecules, are important for the evolution of dense molecular regions to form stars and planets?

Scope of the question

Stars form in a very wide range of environments: from hot metal-poor, UV and X-ray irradiated gas in galaxies at high redshifts to cold, dark, metal-rich cores in nearby molecular clouds. The stars produced span factors of more than 10^3 in mass and more than 10^7 in luminosity, in systems ranging from isolated sub-stellar mass brown dwarfs to superstar clusters with 10^4 O stars in regions < 0.1pc in size. The goal of much of diffuse matter and star formation research is to obtain an understanding of the relationship between the diverse range of star forming environments, the physical processes involved, and the stars that are produced. Q2.3 also concerns issues related to this goal. Planet formation often accompanies star formation. We are only now starting to appreciate the diversity of planetary systems and of the physical and chemical processes regulating their origin.

Star formation can produce planets that lie in circumstellar habitable zones and possess chemical initial conditions that lead to life. Environmental conditions and processes affecting planet formation include:

a) The elemental composition of protostellar and protoplanetary gas and dust (cf. Q2.2).

b) The masses and types of stars formed. - Though we observe young stars with discs, we have only a rudimentary understanding of the collapse of dense cores (sizes ~ 0.1 pc, particle densities $>10^5$ cm^{-3} within molecular clouds to form them. We also are not certain whether discs play roles in the births of stars considerably more massive than the Sun similar to those that they have in the formation of lower mass stars. Thus, we do not fully understand why stars have the mass distribution that they do.

c) The dynamics of protoplanetary discs and the migration of planets that form within them. - Arguments continue about the nature and evolution of the protoplanetary discs formed by collapse, and the subsequent formation of planets within them. Key outstanding issues include the initial masses and sizes of discs, the role of self-gravity in driving early evolution, the driving mechanism and nature of disc turbulence, the role of dead zones, the growth of solid bodies from meter to kilometer and larger sizes, the modes by which planetary systems form, and the influence of migration processes that determine the final planetary system architecture.

d) The gas phase and surface chemistry of interstellar clouds and protoplanetary discs. The most ambitious effort through September 2009 to understand the origin of complex prebiotic molecules found in meteorites (including all amino acids in terrestrial life forms) is limited to a consideration of the fractions of water and carbon monoxide in the gas phase and ices on grain surfaces and is based on an inadequate description of the accretion envelope and disc dynamics.

UK involvement and strengths, and opportunities

a) The elemental and isotopic abundances and solid constituents of the proto-Solar nebula are addressed in the Q2.2 section.

b) A central problem in star and planet formation concerns the precise properties of dense cores and the evolution of them to produce protostars and protoplanetary discs. The UK millimeter and submillimeter observational star formation community is one of the strongest in the world. Its scientists interpret dust continuum emission and molecular line data, including JCMT data, to diagnose dense cores ranging from those that are starless to those containing young high mass stars. They have helped establish the classification scheme for cores and developed molecular line diagnostics of the structures and dynamics of cores. Some of these same scientists are now leading early exploitation of Herschel to study cores and protoplanetary and debris discs. They will be well placed to play key roles in the use of C-CAT and the ALMA and SKA interferometers to conduct more detailed complementary studies.

A thorough understanding of the chemistry occurring in the gas phase and on the surfaces of nanoparticles is required for the interpretation of observations of dense cores and protoplanetary discs. Chemistry is also fundamental for understanding the ionisation balance in dense protoplanetary discs, which determines the nature and extent of turbulent activity. The 2000 International Perceptions of UK Research in Physics and Astronomy report identified astrochemistry as an area `... where UK leadership is recognised.' UK activity concerns theoretical and laboratory investigations of gas phase and surface processes, as well as observations and modelling (cf. the previous paragraph). Several UK groups have contributed greatly to the development of chemical kinetic models used, by themselves and other UK and international groups, to exploit diagnostic spectral line observations. UK scientists have identified and used highly deuterated species as good tracers of dark regions in which most heavy elements are highly depleted onto grain surfaces - such regions are the immediate precursors of protoplanetary systems. Several strong UK laboratory groups are studying surface processes relevant to the formation of ever more complex molecules; one aim will be to understand the production of prebiotic molecules found in meteorites. The theoretical spectral line identification efforts of a UK group are world leading and have resulted in the detection of water in an exoplanet. That group's future studies will bear on the search for potential signatures of biological activity on exoplanets (and on studies of brown dwarfs and low metallicity stars).

Dense cores are magnetised and weakly ionised and contain charged submicron dust grains that help couple magnetic fields to the flow of neutral material. 3-D multifluid hydromagnetic models including grains are required for the study of disc formation. Due to the presence of densities varying by up to nine orders of magnitude, appropriate numerical techniques (e. g. Adaptive Mesh Refinement (AMR); Smooth Particle Hydrodynamics (SPH) with particle splitting) will be required. A UK group published the first paper on AMR multidimensional multifluid hydromagnetic models including ambipolar diffusion (the relative motion of charged particles and neutrals). Several UK groups have strong records in numerical innovation within the SPH approach. They have performed SPH simulations of the collapse and fragmentation of star forming cores. Results of particular interest concern the origin and properties of binary and multiple star systems and the impact of multiplicity on the initial mass function, especially at the low masses of brown dwarfs and planetary-mass objects that are distinct from planets. The same groups are also investigating the early evolution and structure of star clusters and the associated implications for multiplicity. The UK will be well placed to undertake the complicated computational problem of protoplanetary disc formation from dense cores. One key issue concerns the identification of the initial conditions leading to discs that are massive enough to be gravitationally unstable. Clearly the work described in this and the following paragraph requires state-of-the art HPC facilities.

c) The UK dominates the world in theoretical and computational studies of the dynamics of protoplanetary discs, and plays a leading role in understanding the origin and evolution of planetary systems that form within them. Recently UK scientists have produced agenda-setting research bringing into question our understanding of the Magnetorotational Instability (MRI) as a source for disc turbulence and anomalous viscosity. In complementary efforts, other UK scientists have constructed models of massive discs, including radiative transfer to allow the accurate calculation of radiative cooling, that show that the gravitational instability can drive the required levels of angular momentum and mass transport during early phases when discs are relatively massive. UK scientists have made profound contributions to the understanding of planetary migration in both turbulent and laminar discs, and they have examined the role of migration in determining the final planetary system architecture using large scale N-body simulations which address the issues of habitability and water endowment. Several UK groups have independently made great strides in understanding the transport and concentration of dust and small bodies in turbulent and self-gravitating discs, which are significant issues given our current inability to explain the growth of small bodies to sizes greater than one meter. Understanding such transport is key for the explanation of the processing of meteorites and other solids in the Solar System (cf. the section on Q3.3). UK scientists study the final clearing of gas from discs via photoevaporation, which is potentially important for halting migration and leads to the production of debris discs. UK researchers are active in the theoretical modelling and observations of debris discs, to investigate the early evolution of planetary systems.

The high angular resolution of the James Webb Space Telescope (JWST) and its 30-100 times increase in sensitivity to low surface brightness emission compared to any previous instrument, will allow it to map the detailed structures of protostellar discs and debris discs in diagnostic lines and continuum radiation. JWST will be used to image young gas giant planets that are still in the process of cooling after formation. Gaps in discs created by such recently formed giant planets will be detected with ALMA. Together, JWST and ALMA results will create an opportunity for observers, planet formation and disc theorists, and radiative transfer experts to link their activities. e-MERLIN, EVN, and SKA will allow the use of hyperfine levels to measure magnetic fields in discs. While the JWST will cover the 0.8-30 micron region, SPICA-SAFARI will provide complementary 30-210 micron imaging and spectroscopy. It will allow the dominant cooling lines, including those of water, to be used to probe disc dynamics. Studies of the 44- and 62-micron water-ice features will enable the `snow-lines' in discs to be discerned.

Optical and infrared interferometery is a powerful tool for studying discs. A UK group has used the VLTI to investigate discs around young stellar objects. The VLTI provides direct information for one spatial dimension only, though modelling can yield some indication of the two dimensional structure. UK scientists developing the Magdalena Ridge Observatory Interferometer (MROI) are creating an optical/infrared interferometer that will give model-independent information about two dimensional structure on interplanetary scales in discs. An orbiting far infrared interferometer like FIRI would provide great potential for studying discs at high spatial resolution.

UK scientists use the VLT to obtain high spectral resolution infrared observations of H_2 and CO emission to probe the inner tenths of an AU of discs surrounding young stars. These scales are too small for even interferometers to resolve but are key in governing how much mass accretes onto a star and how much is lost in jets and winds. Radiation pressure from a young high mass star affects its growth, whereas it does not play the same role in the birth of a solar-like star. The physics of the parts of the discs probed by this spectroscopy will determine whether high mass stars grow through disc accretion as the Sun did or must form by a different mechanism. The ELT will allow similar studies of many more discs.

UK scientists lead efforts to use radio interferometers to study dust in protoplanetary discs. As indicated above, major questions concern the growth of solid bodies and whether and for how long the discs are massive enough for gravitational instability to occur. The questions are connected because the masses of discs are estimated from the emissions of solid bodies, and features arising due to gravitational instability affect solid body transport. A UK group will use e-MERLIN to investigate the population of centimeter-sized solids. SKA will allow a huge extension of such work.

d) SKA will also be important for searches for gas phase prebiotic molecules, which are detectable at centimeter but not millimeter wavelengths, in protoplanetary discs. ALMA will also be vital for studies of molecular compositions that provide insights into the structures and dynamics of discs and where chemistry leading to prebiotic molecules may occur. Both instruments will have interplanetary resolution and play major roles in probing discs. Indeed, it is inconceivable that planet formation can be understood without the data that these instruments will provide. The UK hosts the international Program Development Office for SKA and is involved in defining many SKA scientific objectives including that associated with the search for prebiotic molecules. With the strong efforts in millimeter observations of molecular lines and the exploitation of the JCMT, the UK also has the necessary expertise to make major use of ALMA in the study of discs and planet formation.

The UK's great strength in astrochemistry, including laboratory studies of surface reactions, positions it ideally to make world leading contributions to the understanding of the extraterrestrial origin of prebiotic molecules. Interaction between those using SKA and ALMA, the astrochemists (some of whom will observe with SKA and ALMA), and the UK groups studying meteorites, interstellar dust particles impinging on the Earth's atmosphere, and returned samples will benefit all three communities.

Summary List of relevant facilities and resources

Current

Grants and Fellowships, Herschel, EVN, HPC, JCMT, laboratory facilities, VLT, VLTI

Becoming available in the next 5 years

ALMA (2012), e-MERLIN (2010), JWST (2013), MROI (2014)

Becoming available after 5 years or more

C-CAT (2016), ELT (2018+), FIRI (2025?), SKA (2018+), SPICA* (2017)

*Depends on ESA selection

3.2 What are the physical characteristics of exoplanetary systems (including different types of host stars) and how do they evolve?

Scope of the question

The immediate goal of exoplanet research is an understanding of the formation and evolution of exoplanetary systems, including characterization of their host stars. This encompasses stars situated in all parts of the Hertzsprung-Russell diagram and, in particular, at all ages (the planetary system age is inferred from the stellar age). Accurate planetary parameters have so far been determined for transiting systems where the eclipse severely constrains the orbital geometry. This allows the degeneracy in the orbital solutions derived from radial velocity measurements to be resolved. However, in all cases the parameters are derived relative to those of the host star and it is these that are dictating their final accuracy.

To reach our goals there are several milestones:

a) The detection and confirmation of exoplanets of all sizes and masses around bright stars and, in particular, terrestrial planets and Super-Earths. While difficult, the atmospheres of these planets could be studied via transmission spectroscopy or, in the case of the nearest objects, directly. In the future we need to better constrain the host star parameters.

b) Obtaining the planet population statistics in order to provide a powerful test of models of planet formation and evolution. This is required to understand their origin in general, that of habitable planets more particularly, and that of planet Earth especially.

c) Direct imaging of nearby, young and bright, and then old and faint giant exoplanets and their spectroscopic examination; eventually, imaging and spectroscopy of terrestrial planets.

Some of the goals here are shared with Q4.2.

UK involvement and strengths, and opportunities

The UK currently leads the world in a number of areas (in no particular order):

1) Ground-based transit surveys for large planets around bright stars. The WASP project is now the biggest provider of close-in, giant planets. This will continue even in the era of CoRoT/Kepler as the SuperWASP host stars are significantly brighter and hence easier to follow up.

2) Molecular spectroscopy and planetary atmospheric models of gas giants and exo-earths at various stages with and without bio-signatures. Several UK groups are recognized as leading in this area (both observation and modelling).

3) CoRoT - both asteroseismology and planet detection aspects. This mission represents the first significant attempt to detect transiting planets from space. In principle, while the telescope has a relatively small field of view, it has the potential to detect terrestrial planets with periods of several months. The CoRoT team recently announced the discovery of a ~2 Earth radii planet. While the UK is not leading this mission there are certain areas in which we can claim leadership, such as asteroseismology and some aspects of the planet detection programme.

4) Kepler - While not directly involved in the small planet program, the UK community is well represented in the asteroseismology consortium holding a number of positions of responsibility.

5) On UKIRT the near infrared WFCAM Transit Survey (WTS) is an ongoing UKIRT Campaign Survey awarded 200 nights of observations. The aim of WTS is the detection of transiting planets around M dwarf stars at infrared wavelengths, and is probing new parameter space in terms of transiting planet size and host star temperature. WTS has attracted significant European interest and led to the EU Initial Training Network RoPACS (Rocky Planets Around Cool Stars), funded through the European Commission to search for and study cool star planetary systems and explore future space mission concepts to study exoplanets.

6) The AAO Planet search. This is one of the leading programmes for the radial velocity detection of exoplanets and has published objects with minimum masses as low as ~22 Earth masses.

7) Ground-based imaging of old planets around evolved stars. A high spatial resolution, proper motion survey of possible companions to a sample of nearby white dwarfs has been underway for several years. It has produced several candidates but is awaiting confirmatory, second-epoch observations.

8) In the microlensing area the UK is currently providing the leading technology to enable the detection of low mass planets <1 and to understand the statistics of the planet populations in the Galactic disk and bulge. This is achieved through the ARTEMiS (Automated Robotic Terrestrial Exoplanet Microlensing Search) software system. The only observational efforts currently realistically able to achieve these goals are those of the UK-led RoboNet-II, MiNDSTEp (some UK involvement), and MONET (German-led), together forming a world-spanning quasi-network, contending for the first detection of an Earth-mass planet.

Exoplanets and the search for life beyond the Earth constitute one of the areas of greatest public interest in astronomy. This is best demonstrated by the extensive coverage in BBC online news and the level of general media interest (A. Heward & R. Massey, "Finding the Real Media Stars: Analysis of Media Coverage of the UK's National Astronomy Meeting", in "Communicating Astronomy to the Public", Issue 4, pp. 5-11, August 2008).

Summary Lists of Relevant Facilities and Resources

Current

Grants and Fellowships, WASP; WTS (UKIRT - pre-2012), CoRoT (exploitation), Kepler (exploitation), Liverpool Telescope, 3.6m (ESO), HST/SPITZER, SONG (exploitation)

Becoming available in the next 5 years

UPF - UKIRT Planet Finder (UKIRT - not currently funded); HARPS-NEF – WHT; JWST; GPI (Gemini); SPHERE/ALMA/VISTA, GAIA, LOFAR

Becoming available after 5 years or more

PLATO[*], e-ELT (ESO 2018+)

[*]Depends on ESA selection

3.3 How did the Solar System form and what can it tell us about other planetary systems?

Scope of the question

The discovery of many exoplanets has illustrated the diversity of planetary systems in the Galaxy, but it has also highlighted our lack of knowledge about their formation. Despite our Solar System forming >4.5 billion years ago, a wide range of materials date from this period. Comets, asteroids and samples derived from them - meteorites, interplanetary dust particles, Stardust sample-return provide a record of early Solar System (ESS) processes. The goal of understanding how our Solar System formed, and the processes that contributed to defining its final composition and structure (including those processes that gave rise to a long-lived habitable zone), is compatible and complementary with astronomical studies of exoplanetary systems, protoplanetary disks and debris disks, and the formation of young stellar objects. Key questions that can be addressed include:

a) What triggered the collapse of the molecular cloud from which the Solar System formed? The abundance of various short-lived radionuclides and presolar grains indicate a supernova may have occurred in the vicinity of the Solar System but the timing and proximity need to be established.

b) Only a few million years elapse from the condensation of the first solids in the inner Solar System to the differentiation of large planetisemals and the development of the planets. Understanding the nature of the processes and their relative chronology is important in understanding the evolution of the protoplanetary disk.

c) What are the fundamental processes that occurred in the protoplanetary disk, from the formation of the principle components of primitive meteorites (matrix, chondrules, refractory inclusions), through the accretion of planets? Primitive meteorites retain components formed during the earliest stages the Solar System, and recent and future sample return missions will provide even more primitive materials.

d) How was the elemental and isotopic composition of Solar System bodies established? How did we get rocky planets?

e) What processes in the protoplanetary disk and early planetisemals contributed to the development of the inventory of complex pre-biotic organic molecules found in primitive meteorites?

f) What processes occurred on the planetisemals, e.g. aqueous alteration, metamorphism, differentiation, impact disruption/re-assembly, and how might these have controlled the composition of the planets?

g) The study of planetary ring and satellite systems in the Solar System offers laboratories to study in detail processes analogous to those occurring in planetary accretion disks elsewhere in the Galaxy.

UK involvements and strengths, and opportunities

a) ESS material in primitive meteorites contains abundant evidence of short-lived radionuclides – introduced when these minerals formed 4.567 billion years ago. The radionuclides may have a number of different origins (e.g. supernova trigger, background ISM abundances, GCR production, irradiation in protoplanetary disk). UK groups have been at the forefront of developing new techniques, establishing initial abundances of short-lived radionuclides (e.g. ^{92}Nb, ^{126}Sn, ^{205}Pb, ^{247}Cm) – and understanding their formation. Many UK labs have excellent analytical capabilities for studying a wide range of short-lived radionuclides – and are actively attempting to determine their distribution and abundance in early Solar System materials.

b) The short-lived radionuclides provide detailed chronology of ESS processes ($\approx 10^5$ yrs), e.g. condensation of first solids, chondrule formation, accretion, planetisemal differentiation. UK groups have internationally leading, and unique facilities, e.g. several MC-ICPMS labs and ^{129}I-Xe dating by RIMS. UK researchers are leading the attempt to rationalise the different chronometers, and have recently demonstrated a much shorter time span for all chondrule formation than previously determined. Understanding the formation and distribution of short-lived radio-nuclides is critical to validating their use as geo-chronometers.

c) Many processes from ESS formation are recorded in the components of primitive meteorites. UK groups have been at the forefront determining the signatures of nucleosynthetic processes recorded in heavy metal isotopic compositions extracted from carbonaceous chondrites and in the search and characterisation of the presolar grain inventory to understand the sources of the elements and materials. The UK have regularly made major contributions to the formation and subsequent processing of primitive meteorite components (chrondules, matrix, refractory inclusions) with high resolution studies of mineralogy, isotopic and elemental composition, chronology etc).

UK labs were heavily involved on the Preliminary Examination Teams of cometary material returned by the Stardust mission, playing a lead role in characterisation of the sample capture process and contributing significantly to the composition, mineralogy and organic studies. Further development of the UK instrument base (UKCAN, grants) is now permitting more detailed investigation of the isotopic and trace element composition of these micron sized grains. UK groups are also helping to lead the more challenging analyses of interstellar grains also collected by Stardust during the cruise phase that will provide a unique insight into the composition of the present day interstellar grain inventory.

UK leads the Ptolemey experiment on Rosetta, investigating the nature of cometary ices and organics, primitive ESS materials that will be difficult to obtain by sample return missions. UK is also leading the development of new imaging IR spectrometers for investigating asteroidal surfaces (e.g. Marco Polo) and further groups have world leading compact instrumentation for the in situ study of minor bodies, and are well placed to participate and/or exploit future missions (e.g. Gallahad, Osiris, comet nucleus sample return). UK groups have provided significant contributions to remote characterisation of the minor bodies and Solar System science, e.g. the first direct detection of the YORP effect and thermal modelling of the surfaces. Future opportunities exist with modest upgrades to UKIRT/ING and GAIA will provide a large dataset on the nature of new and existing asteroids.

d) Evidence from a large number of isotope systems indicates that a significant fraction of Solar System material experienced high temperatures, and that virtually all inner Solar System materials are depleted in volatile elements – a depletion which effectively gave rise to the compositions recorded by the terrestrial planets. UK groups have been leading much of the recent work attempting to understand the volatility driven elemental fractionation associated with these processes via detailed investigation of the matrix of the most primitive meteorites and world leading high precision trace element isotope measurements.

e) The UK has played a major role in understanding the nature and synthesis of the organic inventory of primitive meteorites – identifying signatures of processes in the ISM, protoplanetary disk and the asteroidal parent bodies, including use of isotopic signatures of individual organic compounds to elucidate the reaction mechanisms. Recently, UK scientists have demonstrated that the amino acids in carbonaceous chondrites are derived from a homogeneous reservoir, in the protoplanetary disk or ISM and that aqueous alteration of the parent bodies has a destructive effect. UK researchers recently demonstrated unequivocally the first indigenous nucleobases in meteorites. UK labs are now involved in determining the relationship between the organics and the mineral matrix, and the role minerals play in the synthesis/destruction of the organics, using new analytical techniques, e.g., chemical tagging and in situ analysis on the micron scale.

f) Asteroidal processes modify and segregate ESS materials, controlling the nature of material accreted to the planets. UK labs have provided major input into understanding the effects, timescales and conditions of aqueous alteration on primitive asteroids via a wide range of unique or world leading instrumentation (e.g. X-Ray microscope, noble gas and light element mass spectrometry). UK scientists have provided evidence for extensive magma ocean on the asteroid 4Vesta, and identified a number of other differentiated planetisemals. UK scientists have made leading contributions to the discovery that planetisemals differentiated within $\sim 10^6$ years of the start of Solar System formation, prompting a major revision of our understanding of ESS materials and where asteroid types originated in the protoplanetary disk.

g) In many respects, the debris rings and mini-satellites around some of the gas giants are controlled by similar processes to those operating during the early stages of planet formation. UK scientists have made major contributions to our understanding of the interactions between rings and satellites in our Solar System. Recent work from the Cassini mission has revealed how repeated collisions within the F-ring of Saturn controls the structure of the ring. The complex relationships between the moonlets and the ring offer a unique opportunity to study up close processes relating to the early stages of planet formation.

Development of world leading analytical instruments has been at the heart of the UK's ability to provide major contributions and leadership in Solar System science. UK labs continue to push development of the next generation instruments, but ongoing investment is essential to keep the UK at the forefront.

The UK is well placed to be involved in the study of the most important samples, e.g. through recent involvement in Stardust and Genesis missions and continue to lead new initiatives to recover better samples. A UK led camera network has recently recovered a fresh fall with a known orbit, offering a new opportunity to link the vast amounts of information from meteorites with observations of asteroids. Recovery of pristine ESS materials by sample return missions to primitive asteroids is a key goal of all major space agencies and the world class expertise and capabilities of UK laboratories will ensure they are at the forefront of the analytical campaign for these mission. The UK is playing a leading role in the sample science of the proposed ESA Marco Polo NEA return mission for which UK expertise in planetary protection provides a leadership role in the required dedicated sample receiving facility.

Summary List of relevant facilities and resources

Current

Grants and Fellowships, Analytical facilities, Laboratory simulation facilities, Cassini, UKIRT, ING, Nullabor Fireball Camera Network

Becoming available in the next 5 years

Rosetta, GAIA

Becoming available after 5 years or more

Marco Polo*, SR Curation Facility, EJSM*

*Depends on ESA selection

3.4 Is there a universal model of magnetospheres and atmospheres?

Scope of the question

Through broad exploration of Solar System magnetospheres and atmospheres (including the Earth's) we can develop a system-level understanding of multiple bodies and make detailed comparisons between them. The main challenges in studies of the space environments of Solar System bodies (including planets, planetary moons and comets) can be divided into two related aspects:

a) Development of a holistic picture of these complex environments at system level, depending on the magnetism and rotation of the body, the nature of the atmosphere or exosphere present, the conductivity of the ionosphere, the nature of plasma sources, transport and sinks, and the degree of solar wind driving.

b) Understanding the physical processes that underlie and influence the structure and dynamics of these environments, and how their relative significance and interplay depends upon system properties.

The ubiquitous plasma processes associated with these astrophysical systems which still need to be understood related to item b) include: 1) atmospheric energy sources and sinks, global methods of energy distribution, and atmospheric/exospheric variability and evolution (see Q3.5); 2) plasma particle pick-up from neutral gas sources, related wave-instabilities and particle thermalisation; 3) flux tube interchange processes and radial transport in rapidly rotating systems including magnetosphere-ionosphere-thermosphere feedback effects; 4) field-aligned currents in magnetosphere-ionosphere coupling, auroral acceleration, related radio and auroral emissions, and feedback effects on and from the ionosphere and thermosphere; 5) magnetopause magnetic reconnection and solar wind coupling, including dependence on plasma properties; 6) tail magnetic reconnection driven by both mass loading and the solar wind interaction, their mutual interactions, and spontaneous and driven dynamics; 7) origins and transmission of planetary-period oscillations in planetary magnetospheres due to dipole tilt and other processes; 8) and multi-scale interactions of the key processes (see Q5.2).

These challenges link directly to the study and understanding of exoplanets, whose electromagnetic outputs (yet to be detected) will be determined by directly-related properties and physical processes.

UK involvements and strengths, and opportunities

In order to make significant progress in this area we must first continue to develop a system-level understanding of the Earth's space environment. Without a comprehensive understanding of the way the Earth's space environment operates (see Q2.1), we cannot place extraterrestrial observations into context.

The UK space physics community has provided the back-bone to the ESA Cluster mission, with major hardware provision and science data exploitation efforts occurring at >10 UK institutes. The UK has led or participated in many of the science highlights of the mission. For example, UK scientists have used multi-point Cluster data to shed new light on the structure and formation process of flux transfer events on the dayside magnetopause. Significant progress has also been made on understanding the structure of the magnetospheric cusps, and particularly the processes by which solar wind plasma may gain access to the low-altitude portions of these structures. Analyses by UK researchers has also revealed the structure of magnetopause boundary waves, which has not previously been possible with single point measurements, and of plasma sheet waves and magnetic flux rope type structures forming in the terrestrial magnetotail.

The UK has exploited the range of ground based facilities which they have built, operated, and lead (including radars, radio instruments, and cameras) in order to make significant contributions towards the understanding of the Earth's magnetosphere at system level. A recent example of such a contribution is a statistical investigation into the fast-mode magnetosonic Mach number, M_f, dependence of the efficiency of reconnection at the Earth's dayside magnetopause. Previously assumed to decrease with increasing Mach number, it in fact shows a modest increase with increasing M_f. This result has implications for the solar wind-magnetosphere interaction at the outer planets where M_f is typically much higher than it is at 1AU. In addition, scanning Doppler images of the atomic oxygen 630 nm red line emission, originating in the upper thermosphere at around 250 km, have been used to determine neutral winds and temperatures from multiple zones within an extended spatial field. Wind enhancements of several hundred m/s are observed, revealing structure on scales not currently considered in thermospheric general circulation models (GCMs).

Two UK groups have strong, internationally recognised atmospheric modelling programmes and expertise in comparative aeronomy. Two UK groups also lead a strong activity in outer planet (atmosphere) observations using ground-based (IRTF, Keck, VLT), and space-based (HST, XMM, Chandra) telescopes. These studies have led to increased understanding of outer planet auroras and their driving mechanisms and the details of Jupiter's X-ray aurora. Atmospheric modelling studies have led to an increased understanding of the time dependent processes within the upper atmospheres and ionospheres of Jupiter and Saturn as well as the global forcing arising within Jupiter's thermosphere. Theoretical modelling comparing Jupiter's and

Saturn's magnetosphere-ionosphere coupling systems and the implication for the production of auroral emissions has led to a significant increase in our understanding of these systems collectively.

The UK has significant hardware involvement in current non-terrestrial missions (e.g. Cassini-Huygens, Mars Express, Venus Express) which is providing the means to make progress in this area. Recent system-wide observations of Saturn's magnetosphere with the Cassini mission have resulted in major UK-led discoveries. These include the discovery of a dynamic, water-based atmosphere at Enceladus; confirmation of the resulting Enceladus plume as the main Saturnian plasma source; uncovering the origin of Saturn's auroras, understanding the warped nature of Saturn's magnetodisc, as well as major developments towards understanding the unusual rotational periodicities in Saturn's magnetosphere. The discovery of heavy negative ions in Titan's atmosphere and their relationship to prebiotic processes was led by a UK team; as was the discovery of rings around Rhea.

Hardware involvement in upcoming missions such as BepiColombo and Rosetta and science roles on Juno ensure the UK community has secured a very strong position to continue their high profile work in this area long into the future. In the longer term, a number of UK institutes are leading both mission and instrument studies for ESA Cosmic Vision (including Europa Jupiter System Mission and Cross-Scale). This should evolve into leadership roles in both hardware and science for the UK, dependent on Cosmic Vision selections. As such the UK community is extremely well placed in order to lead direct comparison of system-level plasma processes across diverse plasma environments.

Summary Lists of STFC Facilities and Resources

Current

Grants and Fellowships, Cluster/Double Star, Ground based STP facilities, Theory and modelling (inc. High Performance Computing), Cassini, Venus Express, Mars Express, UKIRT, Keck, VLT, HST, XMM-Newton

Becoming available in the next 5 years

KuaFu, LoFar, Rosetta

Becoming available after 5 years or more

BepiColombo, EJSM*, Cross-Scale*

*Depends on ESA selection

3.5 How do planetary bodies evolve and what can they tell us about the history and climate of Earth?

Scope of the question

Even amongst the planets and satellites in our own Solar System there is a great diversity of environments. Comparative planetology offers the opportunity to gain better insight into the fundamental processes that operate on a planetary scale, and for the foreseeable future, the information required to understand such processes can only be obtained from detailed study of objects within our Solar System. This basic knowledge also provides input into our understanding of the processes that shaped the Earth and continue to operate today - ranging from the early stages of formation and differentiation through to present-day atmospheric dynamics and help predict the consequences of major human (e.g. emissions) and natural (e.g. volcanic dust) events.

(a) How did planetary bodies form and their internal structures develop? What were the timescales and mechanisms of planetary accretion, differentiation and core formation.

Scope of the question cont'd

(b) The Moon was probably formed following an impact between a Mars-sized object and the early Earth – samples of the Earth-Moon system provide a unique opportunity to study how proto-planets interact to form terrestrial planets. The timing and nature of this event and how materials and geochemical signatures were distributed between the impactors and the resultant Moon remains poorly understood.

(c) How did the atmospheres of the planetary bodies form? How did rocky planets accrete and retain their volatile inventories? How have the atmospheres of planetary bodies evolved with time? What mechanisms drive the circulation in planetary atmospheres, and what are the energy sources and sinks? How do we resolve the energy crisis within giant planet atmospheres? What are the important chemical reactions in the different planetary atmospheres? How are thermospheres, ionospheres, and magnetospheres coupled at the various planetary bodies and their moons?

(d) How have planetary surfaces evolved? What are the roles of impacts, large and small? How does the surface interact with the atmosphere? How does the magnetosphere interact with the upper atmosphere and thermosphere, and vice versa?

UK involvements and strengths, and opportunities

(a) The internal structure of the planets can only be determined indirectly, by three principal routes – from in situ measurements of the local environment (for example magnetic and gravity mapping), seismic profiles from surface seismometer networks and geochemical analysis of surface materials either in situ or via returned samples.

UK scientists have led many recent discoveries with the Cassini mission, e.g. the dynamic atmosphere at Enceladus, heavy ions in Titan's ionosphere and their relation to pre-biotic processes, the origin of Saturn's aurora, the ring system at Rhea and the Saturn's north polar hexagon at mid-IR wavelengths. UK modellers have constructed the first global time-dependent models of the Jovian and Saturnian upper atmospheres, and extended them to Titan (for example). UK scientists are participating in research and modelling relating to data from Venus Express and Mars Express.

UK scientists have developed micro-seismometers for planetary surfaces, initially for ExoMars. Placing a network of seismic stations on planetary surfaces is difficult and expensive, but UK teams have been leading the development of small planetary penetrator probes that can be deployed much more readily and affordably. Incorporating micro-seismometers in penetrators offers the opportunity for investigation of the interior of the Moon and Mars (via MoonLite and Aurora) as well as Ganymede and Europa (via EJSM). The UK also has world leading technology and expertise in X-ray spectrometers for mapping of the chemical composition of planetary surfaces as PIs for CIXS (on Chandrayaan-1). UK teams also lead the MIXS X-ray spectrometer on BepiColombo – which will provide new information on the composition of Mercury and the development of its crust/interior, and will also shed light on the generation of X-rays from magnetospheric particles. UK teams are also well-placed to make extensive use of the data from other lunar missions such as the current Lunar Reconnaissance Orbiter and future lunar exploration missions.

Isotopic signatures resulting from the decay of short lived nuclides present at the birth of the Solar System can be used to record the rates of planetary growth and primary differentiation. UK scientists continue to provide world-leading contributions in developing and applying new analytical techniques for the study of a range of isotopic signatures at very high precision, unravelling the isotope geochemistry of differentiation and accretion of Earth, Moon and Mars, as well probing the composition of the cores. The UK also provides major contributions to mineral physics at high temperatures and pressures including those involving segregation of metal and silicate during core formation.

(b) UK scientists have been at the forefront of the investigation of the effects of the large impact with the proto Earth that led to the formation of the Moon, recently contributing to the new finding that this event occurred up to 100 million years after the start of accretion and exploring the effects of the impact on the composition of the Earth and Moon. Future lunar sample return offers the opportunity for older and more diverse samples to investigate the origin of the Earth-Moon system while Mars Sample Return is required for a deeper understanding of the Martian interior composition. A seismic network on the UK-led MoonLite mission is required for a more complete understanding of the internal structure of the Moon.

(c) The UK has a long established leading role in the study of planetary atmospheres through involvement in orbital flight instrumentation. UK scientists are Co-I's on a number of orbital/probe instruments principally aimed at atmospheric science - aboard Mars Express (Beagle2 sensors), Mars Reconnaissance Orbiter (Mars Climate Sounder), Venus Express (VIRTIS), Cassini (CIRS) and Huygens (HASI). Key aeronomy topics studied in the UK by a combination of data analysis and modeling include atmospheric structure, thermal balance and chemistry, magnetosphere-ionosphere-thermosphere coupling, atmospheric variability and the response of the Earth's or planetary atmospheres to solar and magnetospheric forcing.

UK teams are also leading future instrument and mission studies, including those to Mars as part of the Aurora programme (Advanced Environmental Package and the Entry Descent and Landing Science) and new combined sub-mm/far IR sensors for EJSM to allow for more complete investigation of composition and dynamics over a range of altitudes in Jupiter's atmosphere and in addition are well placed to make use of data from other planetary missions, particularly NASA's Juno and Mars Science Laboratory missions. A future return to Titan offers the opportunity to study the atmosphere, surface and geology of a primitive Earth-like body.

UK groups have played major roles in developing the software for the climate statistics and contributed components of the numerical models for the ESA Mars Climate Database. UK-based scientists have also made leading contributions in atmospheric circulation theory as applied to Mars (e.g. predicitability of cyclone weather systems, mechanisms for initiating dust storms), Venus (e.g. mechanisms for super-rotation), Titan (e.g. thermospheric circulations) and gas giants (includes mechanisms for several major structures of wind and cloud on these planets and their relationships to the deep interior) and to the quest for a universal theory of planetary atmospheric structure, circulation and climate which feeds into our understanding of the terrestrial atmosphere as well as those of exoplanets.

The origin of the atmospheres of the rocky planets remains perplexing. Knowledge of the chemical and isotopic composition of these atmospheres will provide valuable insight into their origin and evolution. UK has world leading mass spectrometer systems for such analyses – both in situ and returned samples (e.g. Aurora landers and MSR, EJSM).

(d) Much of surface evolution is covered in the Limits for Life question (Q4.1). UK teams have provided leading contributions to our understanding of the fluxes, timescales and nature of the impact generation of regoliths, and are well placed to make major contributions to refining the terrain dating of the Moon and the nature of early heavy bombardment with future returned lunar samples. UK teams are providing significant contributions to on-going (MUPUS on Rosetta) and future (HP3 on ExoMars/Aurora) heat flow experiments seeking to understand interior structures and heat sources and flows, particularly for the near surface environments and potentially to penetrator studies on Ganymede/Europa (EJSM) and the Moon (MoonLite).

Summary List of relevant facilities and resources

Current
Grants and Fellowships, Venus Express, Mars Express, PDS data mining (e.g. MERs, Odessey, MRO), Analytical facilities/ Laboratory simulation facilities, , Cassini, HPC, Chandrayaan-1

Becoming available in the next 5 years
Rosetta, MoonLite

Becoming available after 5 years or more
Aurora (Mars Trace Gas Orbiter (2016), ExoMars (2018), NASA Cache Rover (2018), Network Mission (2020), Mars Sample Return), EJSM*(2020), BepiColombo, Lunar Sample Return

*Depends on ESA selection

4.1 What are the limits for life, past and present, in the Solar System?

Scope of the question

An important scientific and philosophical questions for humanity is "Is there life beyond Earth?". Discoveries that life on Earth can survive, or even thrive, in extreme environmental conditions (e.g. extremes of temperature, pH, radiation, desiccation, pressure, salinity) and that there are vast reservoirs of abiotically-formed complex organics, including some of the basic building blocks of life (e.g. amino acids and nucleobases), in space heighten our expectation that life may exist elsewhere.

The Solar System contains a great diversity of planetary environments, many fulfilling requirements that we understand to be necessary for the growth of life – i.e. presence of liquid water, an energy source, nutrients, some stability offering protection from extreme conditions. The exploration of those planets and satellites where such conditions exist, may exist, or may have existed in the past offers by far the best possibility of detecting unequivocal evidence for life existing on a planetary body other than the Earth. Virtually all information about the nature of this early life, and the environments in which it arose and evolved has been obliterated by geological processes, such that the origin of life on Earth remains unclear. The discovery of primitive (i.e. microbial) life elsewhere in the Solar System, and the environments where it has, or has not developed will provide unique insights into the mechanisms of the development of life, and potentially the origin of life on Earth. The principal goals in this area concern:

a) Where are, or were, habitable environments in the Solar System? Understanding where and when key parameters for life such as liquid water, suitable temperatures and pressures, energy sources, and supplies of nutrients, etc. were present simultaneously are important in the search for life. The existence of liquid water is particularly important, as is understanding its origin, effects and interactions, and fate.

b) Is there, or was there life elsewhere in the Solar System? Like the Earth, the surface of Mars shows evidence for modification by water, and so may be a likely place to find evidence for life. Outer planet satellites Enceladus, Ganymede, Europa and Titan display evidence for the presence of complex organics and/or liquid water – key ingredients for life and therefore are also places where life may have developed.

c) How has planetary evolution influenced the development or destruction of habitable environments? Large impacts have a major effect on planetary surfaces – what is their role in the development of life?

d) How and where are the large reservoirs of complex organics and key volatiles found in different planetary bodies formed? Could they have a role in the development of life and how are they delivered to regions most conducive to the development of life?

e) How does the space environment impact on the origin and development of life? What role does a planet's magnetosphere and/or atmosphere play in protecting life, e.g. from harmful radiation effects from the Sun?

UK involvements and strengths, and opportunities

Exploration of Solar System bodies to understand habitable environments and seek evidence for life progresses along four inter-related principle paths – remote observations from orbiting or passing spacecraft, in situ analyses performed by planetary landers and rovers, detailed investigation of samples returned to Earth, and studies of life in extreme environments on Earth and in simulation facilities.

a) UK groups continue to provide high quality analysis of the vast amount of remote observations of the Martian surface, including as Co-Is on the Hi-Resolution Stereo Camera on Mars Express. They also provide significant contributions in the field of geomatic engineering. UK groups have made major contributions to studies of the effects of the freeze/thaw of water ice on Mars and putative evidence of frozen seas on Mars. UK groups also provide major contributions to understanding the properties of ices and salts and their effects on Mars and the interiors of icy satellites through laboratory simulations.

In terms of in situ investigation, UK teams have world leading expertise in instruments for planetary landers and rovers for the characterisation of the mineralogy, chemistry and interior structure of planets. Such instruments or systems include miniaturized mass spectrometers (Beagle2, Rosetta), cameras (Beagle2, ExoMars), X-/γ-ray spectrometers (Beagle2 and other missions e.g. Marco Polo, Aurora), environmental sensors (Huygens), IR microscope, microseismometers and laser based spectrometer systems. UK industry is also playing a major role in the development of technology for planetary exploration – e.g. leading the development of the ExoMars rover. The Aurora programme of robotic exploration and the search for life, with a number of joint ESA/NASA missions to explore the Martian surface, ultimately leading to Mars Sample Return (MSR), provides opportunities for UK leadership for a range of instruments characterising the surface environment and geology of Mars and seeking evidence for life. Many of these instruments also have roles in other areas of planetary science such as lunar exploration. UK expertise also provides the opportunity for contribution to other Mars missions such as recent Phoenix on-going MERs, MRO and future missions such as MSL. Sample return is required to provide detailed information on the surface environments –to understand their formation temperatures, chronology, composition of the fluids, nature of organics, etc. UK laboratories have long been involved in the investigation of martian meteorites, providing significant contributions into the nature and conditions of fluids interacting with the rocks. Continued support of the world-class ground based analytical capabilities is hence also essential if UK is to be in a position to provide a lead in the analysis of samples from MSR.

Beyond Mars, the joint ESA/NASA Europa Jupiter System Mission (EJSM) will provide an opportunity for investigations of Europa and Ganymede (and Callisto), seeking to characterize sub-surface oceans, the ice shells and their deep internal structure. UK developed penetrator probes and instrumentation would (if flown) provide the first in-situ characterisation of the surface of these bodies.

b) The UK-developed and built Gas Analysis Package for Beagle2 was the first instrument flown to Mars designed to investigate the light element stable isotope geochemistry of the Martian surface – including any organics present. Since then, UK teams have been involved in the development of further life detection instrumentation for the Aurora programme (initially ExoMars) – developing a new life-marker chip technology for the detection of specific bio-molecules and in the development of high sensitivity organic molecule detectors. Deployment of such instrumentation on ExoMars or subsequent Aurora programme missions will place UK in a leading role in the search for life. Opportunities for similar exploration of outer planet satellites will be optimised following investigation with EJSM. Building upon Beagle2 and ExoMars Phase A, B work, the UK is the European lead in planetary protection for the fabrication of planetary landers – key expertise in the search for life and in the development of the Mars Sample Receiving Facility that is fundamental to MSR and is leading an ESA study for such a facility.

Characterisation of any life found will require laboratory analyses back on Earth, an area in which the UK has world-class instrumentation for and in expertise for the study of organic materials, as well as strong links with the UK microbiology community that have teams leading projects characterising the nature of trace levels of life in extreme environments here on Earth e.g. impact craters, volcanic environments, glacial environments, hydrothermal systems and deep underground ecosystems. UK teams have also characterised novel microorganisms in samples exposed to space conditions in orbital facilities, yielding new insights into the limits of life under extraterrestrial conditions.

c) A period of heavy bombardment may have limited the early development of life on Earth, although details of this flux during the first 10^9 year remain unclear. UK laboratory-based studies have made significant contributions to our understanding of the impact flux on bodies such as the Moon through detailed isotope chronology of lunar samples. The possibility of future missions to the Moon returning (further) samples will provide a more accurate determination of the impact history of the inner Solar System and a record of material transfer between planets during the heavy bombardment. While large impacts have a largely sterilising effect, UK scientists have demonstrated that large impacts also create opportunities for microbes.

d) The formation of complex organics by abiotic processes is largely covered elsewhere (cf. Q2.2, Q3.1 and Q3.3) – but note that UK leadership in these areas extends to life critical-compounds – e.g. recent discovery of indigenous nucleobases in meteorites. However, the transport of organics, and associated volatiles is potentially key in understanding the development of life. UK groups have been at the forefront of new studies - quantifying the survival of organics in dust during atmospheric entry potentially a major source of material to the early Earth and recently demonstrating survival of complex organics ejected during hypervelocity impacts. Further characterisation of the organic inventory of the asteroid belt (sample return missions such as Marco Polo) and new observations of icy satellites (EJSM, including penetrators potentially), comets (Rosetta), lunar surface (MoonLite) will provide further constraints on the organic inventory in the Solar System.

e) The UK space physics community are well-placed to consider how the space environment impacts on the development and sustainability of life through studies of a wide-range of Solar System bodies and their local environments. Comparative studies of magnetospheres and atmospheres (see Q3.4) and continuing studies of the Sun-Earth connection (see Q2.1) are directly relevant to this question.

Summary List of relevant facilities and resources

Current

Grants and Fellowships, Mars Express, Analytical facilities/Laboratory simulation facilities, Cassini, PDS data mining (e.g. MERs, Odessey, MRO)

Becoming available in the next 5 years

Rosetta, Mars Science Laboratory, MoonLite

Becoming available after 5 years or more

Aurora, Mars Trace Gas Orbiter (2016), ExoMars (2018), NASA Cache Rover (2018), Network Mission (2020), Mars Sample Return), EJSM*, Curation Facility, Marco Polo*, Lunar Sample Return

*Depends on ESA selection

4.2 What is the frequency of habitable planets in the Universe and can we detect bio-signatures in their atmospheres?

Scope of the question

One of the major aims of modern astrophysics is the determination of the frequency of terrestrial planets in exoplanetary systems and in particular in habitable zones of solar type stars. Whilst the habitable zone is usually defined as the region in which water can exist as a liquid, there are also dependencies on stellar activity and variability (which encompasses stellar evolution). Current technology allows us to probe the rocky planet frequency in low mass stars. As these objects are of low luminosity, their habitable zones are correspondingly smaller. As technology matures, the detection of earth-analog systems will become feasible.

Current research suggests that oxygen, ozone, water, carbon dioxide and methane would typically signify a habitable atmosphere similar to that of the Earth’s. But the evidence suggests that the Earth's atmosphere has been significantly different at other stages of its evolution. Our understanding of the evolution of planetary atmospheres, their constituents and bio-markers is rudimentary.

Over the next 15 years we would expect to progress towards the following milestones:

a) Understanding stellar activity and its relationship to stellar evolution and effect on the habitable zone. While there is some understanding on the effects of flares (in M-dwarfs) on habitable planets (around M-dwarfs, planets with periods of just a few days to weeks are in the habitable zone) the long term effect of stellar dynamos and other activity on their habitable zones in normal stars is still unexplored. However, the long term activity cycles in stars (even the Sun) are not well known but understanding of them could be crucial to the identification of the necessary conditions for the development of life (see Q1.1).

Scope of the question cont'd

b) The detection of transiting terrestrial planets in M-dwarf systems. In the case of transiting systems the eclipse depth is dependent on the ratio of planet's and the star's radii. Transit surveys of small stars enable us to probe to smaller planetary radii. While the transit probability drops off rapidly with orbital period, the habitable zone in such low luminosity stars occurs at short orbital periods (P ~ days). For the brightest transiting systems, low resolution UV, optical and IR spectroscopy may reveal bio-markers in their atmospheres.

Radial velocity surveys of M-dwarfs have been attempted at optical wavelengths but have produced controversial results. This may be because at these wavelengths turbulence or 'jitter' in the stellar atmosphere makes the detection of planets difficult but could also be indicative of a dearth of large gas planets in these system (possibly caused by the smaller pre-stellar disc). However, at IR wavelengths cool dwarfs are sufficiently quiet that the radial velocity signature of a terrestrial planet should be detectable. M-dwarfs are also significantly brighter at these wavelengths than in the optical. While radial velocity surveys can only give a minimum planetary mass by observing a significantly large sample of targets, an estimate of the mass distribution (etc) of the planet population can be inferred.

c) Detection and analysis of the terrestrial planets in the habitable zones of solar type stars and the analysis of their atmospheres (see Q3.2). It is unlikely that ground based observations will ever realise sufficient accuracy to allow rocky planet detection. While Kepler is expected to give us some statistical information on this, the faintness of the its stellar population implies that a further transit survey of bright stars will be required. Consequently, a further mission aimed at brighter stars is required. Atmospheric analysis would be possible through transmission spectroscopy, while, for the nearest stars direct imaging and spectroscopy of their planets may be possible.

UK involvement and strengths, and opportunities

a) Transiting M-dwarf systems may be detected either through targeted monitoring or through wide field surveys. The UK is exploiting the second of these techniques through the WYFCAM Transit Survey (WTS) at UKIRT. This is described in Q3.2.

b) M-dwarf radial velocity surveys are difficult observations to obtain. The spectral resolution and signal to noise needed mean that observations at optical wavelengths are limited to the few hundred brightest objects. For a number of years the UK has been championing the construction of a stabilized IR spectrograph that would be optimized for observations of these objects and quite capable of detecting small bodies. Unfortunately, circumstances have led to delays and cancellations (e.g. PRVS for Gemini) and the latest design, the UKIRT Planet Finder or UPF, is currently in the pre-funding stage. It is imperative that this project should be funded as soon as possible or it will no longer remain competitive.

While microlensing surveys are still the fastest route to the lowest mass planets, their main contribution will be in deriving planetary population statistics. Given that M-dwarfs dominate the field population, microlensing techniques basically probe the planet population in these types. While the number of lensed planets is still small, there are some possibilities to improve the detection techniques in the near future.

c) Stellar activity. The UK has much expertise in stellar activity primarily in cool stars atmospheres. Only now are a few individuals starting to take tentative steps in looking at the effects on habitability. In the future this will become more important.

d) Biomarkers and Planetary atmospheres. In the UK the main expertise lies is in transmission spectroscopic studies of exoplanetary atmospheres and the calculation of the required spectroscopic data (See Q3.2).

Current

Grants and Fellowships, WTS (UKIRT) (pre-2012),ING, ESO, Gemini, HST, Spitzer

Becoming available in the next 5 years

VISTA, UPF (UKIRT Planet Finder), JWST

Becoming available after 5 years or more

SPICA*, PLATO*, e-ELT (2017)

*Depends on ESA selection

5.1 What are the fundamental laws of physics under extreme conditions?

Scope of the question

Physical laws must be applicable to environments with conditions that are not achievable in terrestrial laboratories. The investigation of some astrophysical environments allows the exploration of physical laws under extreme conditions.

a) What is the behaviour of matter at extreme densities? – The central densities of neutron stars exceed that of atomic nuclei by up to an order of magnitude. Hence, they can serve as macroscopic bodies for the study of the equation of state under such conditions. Current theories provide different descriptions of matter at such super-nuclear densities; the matter may be in the form of bound quark states, or of strange quark matter. Constraints on the validity of those theories come from the observational determination of the mass-radius relation for neutron stars.

b) What is the behaviour of matter in extreme magnetic fields? - Magnetic fields in white dwarfs reach up to 100,000 T, a few thousand times stronger than achieved in laboratories. Detailed spectroscopy of such stars can be used to test fundamental atomic theory. Fields of neutron stars reach up to 10^{10} T, at which the atomic structure itself is altered. At the very highest fields QED effects, such as vacuum polarisation, become important for radiative transfer in magnetised plasmas.

c) What sources within the Galaxy emit gravitational wave radiation? The existence of gravitational waves is a fundamental prediction of general relativity. However, to date no source of gravitational wave radiation has been detected directly. Some of the best indirect evidence comes from relativistic neutron star binaries, in particular the Double Pulsar. The direct detection of non-electromagnetic radiation will open an entirely new window on our understanding of extreme objects in our Galaxy. Close compact binaries and pulsars are among the firmly expected sources of gravitational wave radiation.

Overlap: The compact remnants of intermediate- and high-mass stars (Q1.3) and binary stars containing one or two compact objects (Q1.4) are prime environments for the study of physics under extreme conditions. Extreme astrophysics is also a key theme in FUAP.

UK involvement and strengths, and opportunities

UK astronomers are strongly involved in the identification and observational characterisation of magnetars, soft gamma-ray repeaters, anomalous X-ray pulsars and isolated X-ray dim neutron stars, which hold the potential to reveal the laws of physics under extreme conditions. Only a small number of these sources are known, and enlarging the sample requires continued access to X-ray facilities. A deeper understanding of these objects relies on broad multi-wavelength observations, and given the extreme faintness at optical/IR wavelengths needs large aperture telescopes. The current workhorses in that respect are the ESO/VLTs. The larger aperture of the ESO/ELT will permit quantitative spectroscopy rather than broad-band imaging. Equally, future large X-ray missions such as IXO will provide much more detailed information about the thermal emission from the neutron star surface.

The UK has been leading the study of pulsars since the discovery, by UK researchers, of pulsars in 1968, and strong UK participation is continuing in this area in the era of gravitational wave experiments. In light of the conflicts between general relativity and quantum mechanics, it is crucial to answer the question of whether general relativity is the best theory of gravity. Combining many Earth-pulsar pairs distributed throughout the sky in a so-called pulsar timing array (PTA) allows the detection of any stochastic gravitational wave background as well as a number of burst-like sources. A PTA is sensitive to gravitational waves with periods T >1year corresponding to frequencies of f ~ 1/T, and therefore probes the nano-hertz gravitational wave sky, $f_{GW} < 10$nHz. The UK is currently co-leading the European pulsar timing array and its ambitious LEAP project, which combines data from a number of European telescopes, including the Lovell telescope. The detection of gravitational waves is part of one (out of five) key science projects for the SKA.

LISA, a candidate ESA L-class mission, would be able to detect up to 10,000 close binary systems consisting mainly of white dwarfs and neutron stars, including progenitors of type Ia supernovae, millisecond pulsars, or short gamma-ray bursts. Third-generation ground-based gravitational wave detectors have the potential of providing insight into the mechanisms of core collapse supernovae and the formation of pulsars and stellar black holes.

Summary Lists of Relevant Facilities and Resources

Current

XMM, Swift, Gemini, ESO/VLT, Grants and Fellowships, Lovell Telescope, LIGO

Becoming available in the next 5 years

e-MERLIN, LoFAR, Advanced LIGO

Becoming available after 5 years or more

ESO/ELT, SKA, LISA*, IXO*, ET

*Depends on ESA selection

5.2 What are the fundamental processes that transport, convert, and release energy in plasmas?

Scope of the question

The majority of matter within the visible Universe (including our own Solar System) exists in the plasma state. Thus, most astrophysical phenomena are controlled by a small number of fundamental processes that arise as the result of charged particle populations interacting with large-scale electromagnetic fields. Such processes include: the generation and evolution of shocks; wave propagation and wave-particle interactions and turbulent cascade, dissipation, and transport; magnetic reconnection. Consequently, we must understand these processes if we wish to explain many astrophysical phenomena.

a) Collisionless plasma shocks, generated by supernovae, stellar winds, jets, and other rapidly moving objects such as neutron stars, trigger some of the most energetic events in the Universe, including the formation of star clusters, as well as structured emission regions on galactic and even larger scales. They heat and deflect plasma flows, and can accelerate a single galactic particle to an energy of 10^{15} eV and possibly orders of magnitude higher (see Q 5.3). Key open questions in this area include: 1) How is incident energy re-partitioned by the shock between thermal particles, nonthermal particles, the electromagnetic field, turbulence, and ordered motion? 2) How do shocks respond to changes in the upstream plasma? 3) How do shocks accelerate particles?

Scope of the question cont'd

b) Plasma waves and turbulence exist under a wide range of conditions in astrophysical plasmas, as well as in laboratory confinement devices. Plasma turbulence controls both the acceleration (see Q5.3) and transport of particles, but due to turbulence's time-varying, highly non-linear, and structured nature many aspects are still poorly understood. The lack of multi-point measurements on appropriate spatial scales severely limits our current understanding of how turbulence transports plasma and how it accelerates particles. It is also unclear what the relationship between dissipation and cascades in turbulent collisionless plasmas is.

c) Magnetic reconnection is of fundamental importance in astrophysical plasmas, and is likely to occur wherever magnetic fields and plasmas of different origins interact. The coupled solar wind - terrestrial magnetosphere and ionosphere system is controlled by magnetic reconnection and the transfer of energy and momentum from the solar wind to the planet. Magnetic reconnection is critical in the onset of solar and stellar flares and Coronal Mass Ejecta (CME) formation, in the interaction of the heliosphere with the interstellar medium, and in astrophysical environments such as pulsar magnetospheres and magnetars. Theoretically, reconnection is expected to take place on small (i.e. ion and electron gyromotion) length- and time scales. The basic properties of magnetic reconnection are well understood, but the details on the micro-scale are not. We still need to understand: 1) How reconnection is triggered within thin current sheets? 2) What governs the physical properties of the reconnection site? 3) What effect does external driving of a system (e.g. stellar wind interaction with a magnetosphere) have on the onset of reconnection? 4) What are the large-scale consequences of reconnection?

UK involvements, strengths, and opportunities

An underlying process involved in all solar (and thus stellar) phenomena is the transfer of magnetic energy into thermal energy, kinetic energy and the acceleration of particles. The UK solar physics community has a very strong international track record in this area including in MHD and plasma theory, magnetic reconnection, and modelling the response of plasma to heating. Groups in the UK have had pioneering roles in understanding MHD wave theory in the solar atmosphere and the development of coronal seismology to use observed wave motions to determine the local plasma properties, and in the development of the theory of 3-D magnetic reconnection, particle acceleration and transport, including kinetic theory. The UK is also internationally strong in the provision of the state of the art atomic data that is required to interpret remote spectroscopic observations of astrophysical plasmas, as is evidenced by the widespread use of the ADAS and CHIANTI packages throughout the international community, and in X-ray diagnostics (RHESSI) for out-of-equilibrium electron distributions. Our expertise in interpreting spectroscopic observations is widely sought after throughout the international community. The UK has been responsible for leading the development and exploitation of some of the most successful EUV and X-ray spectrometers flown on solar missions over the last three decades and we are actively sought as partners whenever such instruments are required. This is a key hardware strength for the UK.

We are well placed to build and extend these strengths in the coming years if we invest strategically in both theory and observation. For example, a key challenge over the next decade will be to interface MHD theory in a predictive framework with kinetic theory to model plasma processes, both in and out of equilibrium (cf. non-Maxwellian velocity distributions, transient ionization/recombination and radiative transfer for cool plasma). This critically requires continued access to the primary datasets collected by current instrumentation (Hinode, ROSA, STEREO) which provide complementary measurements for low-level resources through the PLS and grants line; and the collection of primary data from future missions such as Solar Orbiter (2017), ATST (2015)/EST (2020), Solar C (2015) and HiRISE (2021), which will provide state-of-the-art high resolution measurements that will allow us to sample and diagnose the plasma at the relevant physical scales and refine the models. Resources to exploit complementary datasets to obtain a complete picture of the solar plasma are critical and should be available through the grants line. The UK has an established strong hardware and science leadership role in Solar Orbiter, and defining science roles in Solar C and ATST/EST. Solar C and ATST in particular promise significant and fundamental breakthroughs in this area, through their unprecedented diagnostic capabilities. ATST will be the largest and most capable ground-based solar telescope in the world, but will be somewhat unique in solar physics in not supporting a completely open data policy. A UK role in this is therefore absolutely necessary if we are to have access to the telescope, and would build naturally on the already considerable success of our involvement in ROSA.

The UK space physics community has provided the back-bone to the ESA Cluster mission, with major hardware provision and science data exploitation efforts occurring at >10 UK institutes. The UK has led or participated in many of the science highlights of the mission. For example, UK scientists have made the first measurements of the divergence of the electron pressure tensor, thought to be a fundamental quantity in supporting the driving electric field within a reconnection diffusion region. In addition, UK researchers have used Cluster data to significantly advance our understanding of the fundamental process of turbulence, in particular revealing how the power and scaling of the turbulence can be anisotropic with respect to the magnetic field direction. UK Cluster scientists have also determined the properties and conditions of formation for cavities and hot flow anomalies that are observed upstream of the Earth's bow shock. In addition the UK has exploited the range of ground based facilities which they have built, operated, and led (including radars, radio instruments, and cameras) in order to make significant contributions towards the understanding of fundamental processes. For example, one UK group have discovered that wave-particle interactions between small-scale magnetohydrodynamic waves standing on geomagnetic field lines and the energetic particles of the Earth's radiation belts mediate the transport of energy from the collisionless magnetosphere to the collisional upper atmosphere, providing a significant new loss process for radiation belt particles. The latest generation of ground-based cameras have enabled spectroscopic analysis of auroral emissions, providing estimates of the changes in energy and flux of precipitation within scale sizes of 100 m, and with a temporal resolution of 32 frames per second, enabling the estimation of precipitating particle energy within the smallest auroral structures. SuperDARN measurements have provided remote sensing of the reconnection electric field in the magnetosphere, relating to the reconnection rate. This is the only way to measure the reconnection electric field as a function of magnetic local time, and over a prolonged period. In related modelling work, one UK group has pioneered non-linear/complex approaches to data analysis with applications to turbulence and to the Sun-Earth connection (see Q 2.1). These techniques and approaches are essential for understanding the fundamental physics discussed here.

The UK has significant involvement in non-terrestrial missions (e.g. Cassini, BepiColombo, and EJSM) that are and will providing observations of these fundamental processes in different contexts than in near-Earth space. As such the UK community is well placed to make direct comparison of processes (such as the role of reconnection) across diverse plasma environments. In order to make substantial progress in this area into the future, it is imperative that we directly examine these processes through in situ observations at both the global and micro scale. The terrestrial magnetosphere and local interplanetary medium is the ideal place for making such measurements. The long term prospects for this area will be greatly enhanced by the development of viable constellation class missions, such as the proposed ESA Cross-Scale mission. The UK leads the Cross-Scale mission study, which if successful in the ESA Cosmic Vision selection process, will make unprecedented measurements on the multiple spatial and temporal scales required to understand these fundamental processes. A number of UK institutions are leading instrument studies for the ESA Cosmic Vision studies, which should evolve into leading hardware and science roles for UK community members whatever missions are selected.

Summary Lists of Facilities and Resources

Current

Grants and Fellowships, Cluster/Double Star, Ground based STP facilities, Theory and modelling (inc. High Performance Computing), Cassini, Venus Express, Mars Express, HINODE, ROSA, STEREO, SOHO

Becoming available in the next 5 years

KuaFu, LoFAR

Becoming available after 5 years or more

Cross-Scale*, Solar Orbiter*, Solar C, HiRISE, ATST, EST, BepiColombo, EJSM*

*Depends on ESA selection

5.3 How and where are particles accelerated in nature?

Scope of the question

Particle acceleration occurs in explosions in astrophysical plasmas and also in more persistent structures, such as thin boundary layers, which exhibit strong gradients, instabilities, and turbulence. In situ probing of acceleration sites is conducted with space physics missions in the near planet environments. Investigations of the Earth's magnetosphere are also performed with ground-based facilities, which can sometimes be used to control properties of the acceleration regions. The pervasive nature of energetic particles and the impact that they can have on planetary environments and their evolution make them highly important.

Energetic particles radiate radio, X-ray, and gamma-ray emissions. Such radiation from the Sun, stars, planets, supernovae remnants (SNRs), and jets can be detected remotely to reveal the acceleration sites. Much of such radiation from diffuse sources outside the Solar System is emitted by energetic electrons. However, nonthermal protons are usually the dynamically important energetic particles in those sources. Hence, in situ Solar System studies of proton acceleration are vital for understanding acceleration in more distant sources.

Scope of the question cont'd

The two main physical mechanisms believed to be responsible for accelerating particles are direct electric field acceleration and Fermi acceleration in which particles interact with moving or turbulent magnetic fields, gaining small amounts of energy at each interaction. This mechanism is believed to operate in shock waves and in turbulent regions associated with reconnecting magnetic fields. However, the relative roles of these processes, the origin of the seed particle populations, and the role of geometry remain unclear. How the acceleration, magnetic field fluctuations on which the particles scatter, and larger scale dynamics moderate each other is also not understood.

a) The only place where particle acceleration processes can be studied in situ is in planetary magnetospheres. The most important acceleration regions in or near a planetary magnetosphere are the bow shock, the magnetotail, the magnetopause, the high-latitude auroral regions, and in the radiation belts. The acceleration processes (for example acceleration through wave-particle interactions, field-aligned voltages, and magnetic reconnection) may produce suprathermal as well as very energetic particle populations. Highly energetic particles can degrade satellite instrumentation and subsystems; consequently, the identification and modelling of acceleration mechanisms are crucial for the prevention of detrimental space weather effects.

b) The Sun is the most efficient particle accelerator in the Solar System and is capable of emitting highly energetic directed beams and producing large showers of energetic particles that fill the heliosphere with ionizing radiation. Fluctuations in the solar magnetic field are also responsible for the modulation of cosmic rays within the heliosphere.

c) Nonthermal electrons generate radio and TeV emissions. Though the electrons are dynamically insignificant, such emissions trace the sites, outside the Solar System, of particle acceleration.

d) Computational modelling is revealing insight into the complicated feedback between non-thermal particles, magnetic fluctuations and structures, and the dynamics of the bulk plasma.

UK involvements and strengths, and opportunities

a) The UK space physics community has made contributions to this area in terms of both theoretical developments, and using spacecraft (e.g. Cluster) and ground based terrestrial data. Significant progress has been made and led by the UK, for example, in our understanding of wave acceleration of electrons in the formation of the radiation belts at Earth. This development has challenged previous theory and is applicable to non-terrestrial magnetospheres. In addition, UK scientists are (for example) studying the acceleration of particles at the magnetopause through the examination of flux transfer events (FTEs) using data from Cluster. Ground based studies are examining the location and intensity of the aurora, and how the ring current feedback affects solar wind coupling processes. UK scientists are utilising Cassini data to begin to understand this complex process in Saturn's magnetosphere (e.g. tail reconnection, acceleration of electrons in auroral processes).

b) One of the UK solar physics community's strengths is the theory of particle acceleration and transport, including kinetic theory. Particular strengths include modelling and simulations of particle acceleration in reconnecting magnetic fields, bringing together both MHD and kinetic approaches, and the development of X-ray diagnostics for energetic particles. While the UK had no hardware role in RHESSI, it has played a key role in the provision of software in this area, and a leading role in the exploitation of data as demonstrated by the fact that UK scientists are lead authors on the majority of chapters in the forthcoming RHESSI review volume. In addition, the UK has a leading science role within the LOFAR consortium and Co-I roles in the Solar Orbiter

STIX instrument. UK scientists have positioned themselves strongly within the RHESSI community and are very well placed to continue to make a significant contribution in this area for a modest investment through the grants line. In addition, Hinode and STEREO provide vital information that is helping us to begin the clarification of the roles of flares and Coronal Mass Ejections (CMEs) in the acceleration process. However, Solar Orbiter will provide a crucial further step through its proximity to the Sun, by allowing the precise determination of the sequence of events that occur during reconnection at the Sun (utilizing data from all of the instruments on board), the relationship between accelerated particles that remained trapped and those that escape from the solar atmosphere, and the relative roles of flare and CME related acceleration in solar energetic particle events and their impact on the evolution of particle spectra.

c) Radio synchrotron emission has been used for decades to probe sources, including relativistic jets, pulsars, and SNRs, of energetic electrons. e-MERLIN, EVN, and SKA will all enable more sensitive observations at various high spatial resolutions. TeV gamma rays induce atmospheric Cerenkov radiation, and techniques to observe these emissions have been evolving for several decades. A UK scientist made major contributions to the development of methods to interpret the observations of the Cerenkov radiation. This resulted in one group's key involvement in collaborations with US partners. Two UK groups have members in the European HESS collaboration. The HESS Galactic Plane Survey has resulted in the discovery of many tens of sources. HESS has been used to detect compact objects and to map SNR, pulsar wind-blown nebular, and other extended sources. Radio and HESS results are routinely compared. The CTA (Cerenkov Telescope Array) will lead to an order of magnitude increase in sensitivity and extended energy coverage down to tens of GeVs. A UK group has used optical emission from thermal gas to diagnosis the dynamical effects of cosmic ray protons on a SNR shock; related efforts abroad have been based on the interpretation of thermal X-ray observations.

d) The UK has made major contributions to theoretical studies of cosmic ray acceleration for over three decades. Recent important UK numerical findings include those showing that turbulence driven by cosmic ray streaming gives rise to cavities in which the thermal particles' density and the magnetic pressure are very low but the cosmic ray density is enhanced. This result indicates that naive interpretations of astrophysical radio and TeV emissions will not lead to reliable inferences concerning the diffuse source environments. Continued theoretical and computational efforts require grant and HPC support.

Summary Lists of Facilities and Resources

Current

Grants and Fellowships, HINODE, STEREO, Cluster/Double Star, Ground based STP, Cassini-Huygens, Theory and modelling, EVN, HESS, HPC

Becoming available in the next 5 years

e-MERLIN (2010)

Becoming available after 5 years or more

Cross-Scale*, Solar Orbiter*, Solar C, EJSM*, BepiColombo, CTA (2015+), SKA (2018+)

*Depends on ESA selection