Science Strategy document for the Far Universe Advisory Panel (FUAP)

Introduction

We present here the science strategy document from the Far Universe Advisory Panel (FUAP) to the Particle Physics, Astronomy and Nuclear (PPAN) Physics Science Committee of the Science and Technology Facilities Council (STFC). The official tasks of FUAP can be found on the main PPAN webpage[1], which we have broadly interpreted as providing STFC and PPAN with:

- **A long-term science roadmap** for the extra-galactic community, which we will update over the coming years with community input, which will inform PPAN and STFC with far universe science priorities for the coming decades.

- **A positive and forward looking statement** on the facilities, projects and experiments needed both today, and in the future, to achieve the science roadmap, and maintain UK leadership in strategic areas and to facilitate knowledge exchange and outreach activities.

- **A broad view** of the UK science productivity, which should include all aspects of a successful and healthy UK astronomical community.

The science remit of FUAP covers "*parts of the astronomy and space science programmes concerned with the global properties of our galaxy, with objects beyond our galaxy, and with cosmology*." For further, and up-to-date, information on FUAP, please consult our webpage (http://research.icg.port.ac.uk/wikis/fuap).

Consultation

During the drafting of this science strategy document, we have consulted with other STFC advisory panels and reviews. In particular, we have work closely with NUAP[2], regarding possible overlap of various science areas, and coordinated with the Ground Based Facilities Review[3] (GBFR). We will continue to undertake such coordination, e.g., joint phone conferences and shared membership.

In June 2009, we undertook a web-based consultation with the astronomical community and received 98 submissions regarding an initial version of this document. We have iterated both the content and style of our science themes presented below based on this consultation exercise and provide a supplementary document outlining our general response to this community

[1] http://www.scitech.ac.uk/About/Strat/Council/AdCom/tor.aspx
[2] http://www.scitech.ac.uk/about/strat/council/adcom/NUAP.aspx
[3] http://www.scitech.ac.uk/About/Strat/Council/AdCom/oth/GBFR.aspx

feedback. We thank the community for their comments and will continue to seek community input in the future.

Priorization

We provide here four key science themes for extra-galactic astronomy and astrophysics in the coming decades. With each theme, we provide the critical questions that need to be addressed written in language that should be understandable to a majority of the public. The associated text within each theme is designed to be more detailed and at a level understandable by professional scientists. We have iterated these themes based on our consultations with NUAP and the public.

In drafting these themes, questions, and text we have tried to be strategic in selecting areas of astronomy and astrophysics that will be key areas of international research with strong UK leadership (or areas where we believe there should be strong UK leadership). This list is not meant to be an exhaustive description of all the extra-galactic science UK scientists are engaged in and represent the key areas of astronomy and astrophysics the UK should be involved in.

We also provide below a broad priorization of the critical science questions within each theme. Each question is classified into one of three possible bands, namely A, B and C (with "A" having the highest merit). This ranking was done internally to FUAP partly in response to the public feedback we received, which encouraged us to provide some level of priorization of these science areas, and partly in response to the needs of PPAN in these difficult financial times. The ranking was based on a combination of science excitement behind each question and a judgement of the UK's reputation and leadership in the area of research. Therefore, an "A" ranked question is seen to be an area which excels in all of these areas, i.e., it is scientificially compelling with world-leading UK involvement in that area. Lower ranked questions were judge to not possess a similar level of excitement and/or leadership and reputation. We have not attempted to rank the four science themes.

We appreciate that our vision can be seen as too conventional and narrowly focused on areas of astronomy where likely returns on any investment can be guaranteed and quantified. We accept the public's feedback that astronomy should also embrace the "unknown and unexpected" as this has a rich history of making key astronomical discoveries. We endorse the view that part of the wonder of science is exploring new domains that have no clear payback at the beginnining. This also includes multi-disciplinary research where the outcomes often appear diluted at the start, but in reality can lead to major breakthroughs in science by sharing knowledge and resources.

COSMOLOGY

(A) What is the nature of the dark matter and dark energy?

(B) What are the physical laws that govern the beginning of the Universe?

(B) Are the correct laws of physics and assumptions used when calculating cosmological evolution?

(B) What is the origin of large-scale structures in the Universe?

In the past decade, a standard model of cosmology has emerged consisting of a nearly flat universe described by general relativity, with 4% of the energy in the form of ordinary baryonic matter, 21% in “dark matter”, and the remaining 75% in some form of “dark energy” thought to be responsible for the present accelerated expansion of the Universe. Galaxies and large-scale structures are assumed to have grown gravitationally from primordial seed perturbations, possibly generated during a period of inflation in the early Universe.

However, there remain many unanswered questions with this model. For example, the origin of the primordial perturbations depends critically on the uncertain physics of the early Universe. Within the context of inflation, the scale dependence of the primordial density perturbations, the extent to which they obey Gaussian statistics, and the amplitude of any primordial background of gravitational waves will be key observational tests for discriminating between models. Moreover, recent progress towards realising inflation in fundamental (e.g. string) theory suggests a richer phenomenology than the simplest models, including large non-Gaussianity, cosmic superstrings, isocurvature modes and primordial magnetic fields. The most direct constraints on the primordial perturbations come from the cosmic microwave background (CMB), but observations of galaxy clustering, weak gravitational lensing, the clumping of the inter-galactic medium, as traced by HI, and the abundance of galaxy clusters will play an important role in constraining the scale dependence and Gaussianity of the primordial perturbations on smaller scales than the CMB.

Cosmologists also need to tackle the conundrum of the "dark universe", which now includes two mysterious ingredients: dark matter and dark energy. The basic properties of the dark matter, including its temperature and cross-section, can be probed astronomically by a range of cosmological observations, detailed investigations of the structure and dynamics of the local group, and searches for dark matter annihilation products. In addition, observations of the small-scale clustering of matter provides a promising route to measuring the absolute masses of neutrinos. Dark energy can be quantified using both the expansion rate of the universe, via geometrical tests from galaxy clustering and supernovae, and its impact on the growth of large-scale structures in the universe, probed using weak gravitational lensing, and galaxy and cluster surveys. The future of dark energy research is the combination of all these probes allowing cosmologists to test the underlying fundamental assumptions of the standard cosmological model (e.g. general relativity), and isolating them from systematic uncertainties in the observations.

It is likely that large surveys of the Universe will continue to drive cosmology in the coming decades. The UK has a rich history in this field and should continue to play a leading role in forthcoming international CMB, radio, optical and infra-red imaging and spectroscopic surveys. Moreover, the UK has underpinned this work with world-leading theoretical expertise and it is essential to maintain this if we are to capitalise on the scientific potential of our observational programmes.

FIRST LIGHT

> (*A) How and when did the first stars, black holes and galaxies in the Universe form?*
>
> *(B) How and when did the Universe become re-ionized?*
>
> *(C) What are the best ways to find these first objects in the Universe?*
>
> *(C) How and when did the Universe become enriched with all the complex elements we see today in galaxies?*

Observing and understanding the cosmic "dark ages", before the first objects lit up, is a long-standing problem in astronomy. This is the least studied and understood phase of cosmic evolution and should be a major goal of UK astronomy in the coming decades. A key issue is the formation of the first stars which were likely massive objects, with short lifetimes, that rapidly enriched the surrounding gas to then form into newer stars. Observationally, this must have happened by $z\sim7$ as we can observe massive galaxies at this redshift with stellar masses a billion times the mass of our Sun.

To look beyond $z\sim7$, astronomers will need new techniques and instruments since these first objects will have faint fluxes. There are solid theoretical reasons to believe that the first stars may end as supernovae, and/or gamma-ray bursts, suggesting variability searches would be fruitful in finding them. It is also possible that other wavelengths, such as X-rays from early accreting black holes, may lead to the detection of the first objects.

Beyond the study of the first objects, we know that at $z>5$ the neutral hydrogen made at recombination ($z\sim1100$) was ionized again. This must have occurred as a result of the formation of the first objects, and therefore the study of this “Epoch of Re-ionization” will be a major effort over the next decade. How and when this transition in the Universe occurred is still open for debate, but based on observations of the Gunn-Peterson effect, and results from the Wilkinson Microwave Anisotropy Probe (WMAP), our best estimate is z~10 which redshifts the 21cm hydrogen line into the megahertz (radio) regime of the electromagnetic spectrum. New experiments are already underway to probe this new frontier, with more on the horizon.

Today, we witness that the Universe is thoroughly enriched by heavy elements, most of which were probably produced through stellar evolution processes. The details of how the Universe became enriched is an important question for astrophysicists, and based on elemental abundances in high redshift quasars (and damped Lyman-alpha systems), it is clear that this enrichment occurred rapidly at an early epoch, probably via a feedback mechanism related to the evolution of first stars and black holes (e.g., stellar winds, and supernovae). Therefore, a combination of observational (e.g., absorption line studies and direct measurements of abundances within galaxies through spectroscopy) and theoretical simulations is required to trace the entire chemical enrichment history of the Universe from the start until today.

The UK has been one of the leading places for studying the earliest galaxies thus far discovered, and it will be important in the coming decades to expand this to the first objects to form in the Universe, and measurements of the epoch at, and before, reionization.

3. GALAXIES

(A) How do galaxies form and evolve?

(B) What is the role of environment and interactions in galaxy evolution?

(B) What are the contents of galaxies and their internal structures and mechanisms?

(C) What lies between the galaxies?

Rapid advances in observational astronomy are starting to reveal an intricate picture for how galaxies formed and have evolved. Moreover, numerical simulations have become increasingly sophisticated in modeling how structures emerge in a cosmology dominated by dark matter and dark energy. However, many fundamental problems remain unsolved due to the large dynamic ranges in scale and mass involved in such research, and the complexity of the astrophysical processes involved (e.g. star formation, mergers, feedback from supernovae and active galactic nuclei).

In the next two decades, new radio, optical, X-ray, gamma-ray, and gravitational wave facilities will be used to study galaxy formation, by probing the Universe to unprecedented depth in time and mass using many complementary techniques and wavelengths. New insights will also be gained into how stars, dark matter, central massive black holes, cosmic magnetic fields and, increasingly, the neutral and cold gas evolve in galaxies as a function of time. Astronomers will also probe the internal kinematics of stars and gas in galaxies to high redshift using the next generation of radio and X-ray telescopes, as well as extremely large optical telescopes and integral-field spectrographs. In parallel, wide-field surveys of the Universe will statistically map the distributions of galaxy properties as a function of environment, which will provide an insight into the role of energy feedback and chemical enrichment to explain the inter-galactic medium. It will also help determine the importance of mergers and interactions in shaping the properties of galaxies.

Nearer home, the global properties (including the kinematics, substructure and the central massive black hole) of our own Galaxy will be studied with both ground-based facilities and space satellites. The dynamics and chemical composition of billions of stars in our Galaxy, and nearby companions, will be used to untangle the formation history of these individual objects, thus allowing scientists to directly challenge cosmological galaxy formation simulations on sub-galactic scales.

The UK is leading the world in the interplay between the observational and theoretical study of galaxies. We should invest in this area to maintain our reputation and involvement in the next generation of observational and high performance computing facilities.

EXTREME ASTROPHYSICS

(A) What are the sources of gravitational waves and neutrinos?

(B) Do the known laws of physics on Earth apply under extreme conditions in the Universe?

(B) What is the astrophysics behind accretion of matter and energetic feedback around compact objects?

(C) How and where does relativistic particle acceleration occur?

One of the most fundamental questions we can ask is whether our laws of physics work under the most extreme physical conditions. The Universe is the most natural laboratory available to scientists for such tests as it provides extreme ranges of gravity, density, temperature, magnetic field and radiation. By observing these regimes across the entire electromagnetic spectrum, and via gravitational waves, cosmic rays, and neutrinos, we can, by comparison with detailed theoretical models, provide the strongest possible test of our understanding of astrophysics.

The behavior of light and matter close to a neutron star or black hole probes the strong-field regime of general relativity where the effects of light bending and "frame drag" are maximal. The coupled processes of accretion and outflow, whether radiatively or magnetically driven, link accreting objects to their surroundings via a feedback mechanism. This is the route by which massive black holes grow across cosmic time, changing the black hole mass and spin. Outflows from the centers of galaxies combined with those from star-forming regions result in large amounts of energy being deposited into the host galaxy and beyond helping to drive star formation, regulate galaxy evolution and heat the ambient medium. The observation of gravitational waves or neutrinos provides unique insights into the formation and evolution of systems such as binary mergers and core-collapse supernovae. Extreme environments are also prime sites for relativistic particle acceleration, often resulting in intense non-thermal radiation from phenomena such as pulsars, gamma-ray bursts and giant radio galaxies.

The UK has an excellent track record in this area, both in constructing and exploiting facilities that make use of naturally occurring cosmic environments in our Galaxy and beyond to test the laws of physics. Extreme astrophysics is an area where we can learn much by comparison of the properties of stellar-mass scale objects in the local Universe and massive objects in the distant Universe. To ensure continued UK leadership in this research, astronomers need a multi-wavelength view of the Universe, with high-resolution observations in time, frequency and space.