

Stellar Astrophysics – NUAP draft report

Introduction

Stellar physics is a thriving and complex research area, with its individual components being highly interlinked. As newly formed stars age, stellar winds and stellar explosions inject the products of nuclear reactions into the ISM and provide the seeds for dust formation. Subsequent generations of stars form at higher metallicity, and the increasing dust content drives the formation of planetary systems. Massive stars die as core-collapse supernovae, do these supernovae explosions trigger further star formation, or do they blow out the clouds and halt star formation? Partially degenerate low-mass stars share many properties in their structure and atmospheric properties with Jovian-type exo-planets.

Many topics of fundamental physics are closely tied to stellar physics, a key example being precise tests of general relativity based on observations of binary pulsars. In the near future, we will be able to directly detect gravitational waves, and white dwarf binaries in the Galaxy are expected to dominate the **LISA** signal at low frequencies.

Stellar physics is also at the heart of many astronomical questions beyond our Galaxy. The success in modelling galaxy evolution stands and falls with a holistic understanding of stellar physics. A key science objective should hence be to connect experts of stellar populations in our Galaxy with galaxy modellers, since it would be absurd to assume that distant galaxies are less complex than our own. Therefore it is essential to understand the diversity and physics of stellar populations in the Galaxy first. Supernovae Ia are one of the fundamental cosmological distance rulers, identifying their progenitors requires a deep understanding of the evolution of binary stars. Outflows from AGN are a key ingredient in galaxy evolution, but the physics of jets can be studied in detail in galactic X-ray binaries and young stars. Gamma-ray bursts, the most powerful explosions sending us information from the early days of the Universe, are inherently linked to the evolution of the most massive stars.

GAIA, ESA's astrometry mission to be launched in 2011, will revolutionise all fields of stellar physics, as it will provide accurate distances, along with proper motions, multi-colour photometry and variability information for about a billion stars ($V < 20$) and radial-velocities for all stars with $V < 17.5$.

The UK has a healthy and internationally respected community working in a wide range of key areas of stellar physics. Below we outline some of the areas in stellar physics where the UK can claim international leadership.

Low-mass stars and sub-stellar objects

The low-mass end of the initial stellar mass function is very uncertain, and so are the structure and atmospheric properties of low-mass stars and sub-stellar objects. Observational and theoretical constraints on the formation, structure, and evolution of low-mass stars and sub-stellar objects is a key objective in stellar physics.

Sub-stellar objects occupy the mass range below that of main sequence hydrogen burning stars (< 0.075 solar masses), and encompass brown dwarfs and giant exo-planet populations. Since 1991 many sub-stellar objects have been discovered in the solar neighbourhood, ranging from 5-10 earth masses up to the bottom of the main sequence of stars. Some of these are in orbit about other stars, and others are free-floating objects with masses down to a few times that of Jupiter. The configuration

of the exo-planetary systems has challenged pre-discovery theories of planet formation, with a range of unexpected systems being discovered, and some theories even predicting ejection leading to free-floating planet populations.

The defining observable properties of sub-stellar objects are effective temperature (T_{eff}), surface gravity ($\log g$), and atmospheric composition $[M/H]$, with these properties being inherently sensitive to an object's mass, formation mechanism, environment, and age. Sub-stellar objects with quite different masses can all span the wide temperature range, e.g. young and old brown (L/T) dwarfs are typically found with $T_{\text{eff}} \simeq 700 - 2300$ K, and cool/hot Jupiters cover the 100–2000 K range. Understanding the physics of these atmospheres is absolutely critical to constraining the properties of sub-stellar populations, and thus interpreting their formation and evolution. However, the atmospheric physics is very challenging due for e.g. to the presence of complex molecular opacities, atmospheric dust formation (grain and liquid droplet clouds), and non equilibrium chemistry. A particularly crucial area is the previously un-explored extra-solar atmosphere discovery space < 600 K. Establishing a well-observed sample of objects in this regime will allow a step change in our understanding of such sub-stellar objects, where previously the only examples we could study were the giant planets in our own solar system.

Based on **UKIDSS** and its systematic follow-up with **Gemini**, the UK is a world-leader in the discovery and characterisation of low-mass stars and sub-stellar objects, and exploitation of ongoing and new ground- and space-based survey facilities (**UKIDSS**, **VISTA**, **AKARI**, **WISE**) will reveal new sub-stellar object populations probing new ranges of T_{eff} and mass, with accurate studies expected in the T_{eff} range down to $\simeq 300 - 400$ K. **WISE** has the potential to explore even lower T_{eff} regimes, with predicted sensitivity to very nearby ($\simeq 3$ pc) sub-stellar objects with $T_{\text{eff}} \simeq 150$ K, if they are to be found. A greatly increased understanding of 150–700 K atmospheres will be vital if the observable properties of such atmospheres are to be better understood. In the longer term, these ultra-cool populations will be prime targets for greatly improved spectroscopic study using **ELT** technology in the optical and near-infrared, and detailed work extending into the mid-infrared via the **JWST**. All of this will lead to well constrained physical conditions (T_{eff} , $\log g$ and $[M/H]$) for sub-stellar objects, and provide a critical test-bed to improve theoretical understanding and reveal the physics at work.

Long term access to **4m**, **8m**, and **ELT** follow-up facilities in the north and south, as well as the necessary human resources are vital to achieve these challenging scientific goals, and to maintain the UK's current lead in this field. Without this support, the investment in **UKIDSS**, **VISTA**, **JWST**, **ESO** and **ESA** will not lead to a measurable UK science impact.

High-mass stars

High mass stars (> 8 solar masses) are the progenitors of core-collapse supernovae, which represent an important element in the chemical evolution of galaxies. Due to their brightness, they serve as tracers of star formation out to large redshifts. Also long GRBs are associated with the death of very massive stars, and are the current record-holders as the most distant object detected in the Universe.

Despite the importance of massive stars in a variety of astrophysical environments, their evolution is still fairly poorly understood. Massive stars formed deeply embedded within cores of Giant Molecular Clouds as part of Orion-like clusters, severely limiting observational tests of theoretical formation scenarios. Radiation pressure hinders accretion onto luminous proto-stars in excess of 10–20 solar masses although stars up to 150 solar masses are observed. Infrared sky surveys with **2MASS** and **Spitzer** have allowed the discovery of young, high mass star clusters in the Milky Way, whose masses approach 10^5 solar masses.

Establishing the mechanism for accretion onto massive proto-stars will require high spatial resolution mid- and far-infrared/sub-mm with large ground- and space-based telescopes (**JWST/ALMA**). In addition, highly multiplexed capabilities of large ground-based optical spectrographs (**VLT, Gemini, E-ELT**) allow the detailed stellar content of these young clusters within the Galaxy and Magellanic Clouds to be obtained. These represent spatially resolved versions of starbursts witnessed in external star forming galaxies, allowing empirical tests of evolutionary synthesis models.

Because of the large luminosities of core-collapse supernovae and long GRBs, the physics of massive stars very tightly overlaps between the remits of NUAP and FUAP, with multi-wavelength large-scale time domain sky monitoring such as **PanStarrs, SkyMapper, Palomar Transient Factory, LIGO, LO-FAR** playing a key-role in finding rafts of stellar deaths in external galaxies. The UK involvement in massive star/supernova/GRB research beyond the Galaxy is expected to be outlined by FUAP.

Several groups in the UK are developing cutting-edge models of massive stars, including in detail relevant processes such account binarity (a large fraction of massive stars are formed in binaries) or rotation. The massive time-domain surveys will provide samples of 1000s of core-collapse events (and SN Ia, see below), uncovering the full variety in the way that massive stars die. The investment in such surveys will only be recouped if the theoretical work on the evolution of massive stars keeps pace with the observations, and stronger UK support of fundamental supernova physics is desirable. The theoretical modelling efforts are very computationally intensive, and need a continued investment in the UKs **high-performance computing facilities**.

Globular clusters

Stellar clusters are our primary test-beds for our understanding of stellar physics, and are likely to remain so for the future.

Recent work on globular clusters (GCs) suggests, however, that their nature is not as simple as assumed in the past. The discovery of split main sequences, multiple turn-offs, abundance correlations in giants, horizontal branch morphology all suggest that many (perhaps most) GCs contain multiple distinct populations. Open questions are what triggers the second (third, fourth) generation stars in GCs? Is there a link between GCs showing multiple populations and cores of dwarf galaxies? Why do some clusters (e.g. Omega Cen, NGC 2808) show distinct populations, whereas others (e.g. 47 Tuc) seem to show at most a mild spread in their properties?

Formation and evolution of GCs is also an area with large gaps in our understanding. N-body models of the evolution of GCs at the full resolution ($> 10^5$ stars) may become feasible in the near future with the advances in high-performance computing. One of the main issues in GC dynamics is how to (re)heat the cluster, preventing it from collapsing. Binaries have been considered one possibility, and observational constraints on binary populations are extremely important.

GCs are commonly used as tracers for the history of star formation, and of the interaction history of galaxies and their dark matter halos. As such, it is vital that we develop a better understanding of the GCs in the Galaxy. This work requires high spatial resolution and photon collecting area, and hence relies on **4–8m class telescopes equipped with AO/IFU/MOS** instruments. However, of equal key importance are **high resolution X-ray and ultraviolet imagers and spectrographs**. With the demise of **Chandra**, high-resolution X-ray observations will be no longer possible, and currently no successor is on the horizon. In the ultraviolet, **ATLAST** could provide truly break-through capabilities, and an UK/ESA-involvement in this mission would be extremely important to secure facility access of the UK community.

The impact of multiplicity on stellar evolution

A large fraction of all stars in the Galaxy are part of multiple stellar systems, and a significant fraction of them will interact at some point in their lives. Among descendants of binary evolution are short GRBs (and possibly some long GRBs), binary pulsars, supernova Ia, X-ray binaries, milli-second pulsars, double-degenerate binaries, cataclysmic variables, symbiotic stars, many or even most subdwarf-B stars, just to name a few. A subtle example of the importance of binary evolution are hot subdwarfs, formed mostly in binary systems in our Galaxy, which must at least in part be responsible for the UV excess in elliptical galaxies.

Major open questions are what is the efficiency of common envelope evolution? Do we even have the right recipe? At what rate does magnetic braking drive angular momentum loss from the binary orbit? These are key ingredients determining the evolution and total numbers of all types of binary products – including GRBs and SN Ia. What are the progenitors of SN Ia? There are at least two populations, prompt and delayed, but we have no idea if these are made up of more sub-populations. At a time when astronomers think about new expensive space missions to use SNe Ia to measure the time evolution of the equation of state of the Universe, it is mandatory that the physical nature of the different SN Ia progenitors is known and that subtle differences related to different production channels, metallicity, etc. are well-understood.

Detailed theory of stellar evolution in multiple stars is a tough task with a long road to go. The UK has some key players in the field, supporting human resources and computing facilities is essential to stay on top of the game. Observational constraints to many of the key questions outlined above come from population studies of carefully selected samples of binary stars. **SDSS** is currently the main source for sample selection, but **PanSTARRS**, **Skymapper**, and **GAIA** will take over in the near future. The necessary follow-up observations require continued intensive access to 4–8m class telescopes (**WHT**, **ESO**, **Gemini**).

Stellar remnants: white dwarfs, neutron stars, and black holes

Stellar remnants are key objects in the study of physics under extreme conditions, and represent a fossil imprint of the galactic star formation history.

Short-period double-white dwarfs represent a major class of gravitational wave radiation (GWR) sources that will be detected by **LISA**. Their total number is still highly uncertain, both from the perspective of models of binary stars, as from the observed population, and it may in fact be that they dominate the **LISA** GWR signal at low frequencies. Improving our knowledge about the galactic population of double-white dwarf binaries is hence crucial for a detailed understanding of the **LISA** data stream.

GAIA will discover $\simeq 400\,000$ white dwarfs, and play a central role in calibrating the initial mass/final mass (IMF/FMF) relation for white dwarfs, as well as probing in detail the white dwarf mass-radius relation. White dwarfs have been used as cosmo-chronological probes – yet, the coolest/oldest white dwarfs have not yet been discovered. Deep multi-colour and astrometric surveys, foremost **GAIA**, but also **PanSTARRS** and **LSST** will provide a complete sample of white dwarfs within 100 pc, down to the very bottom of the white dwarf luminosity function. Follow-up studies of these white dwarfs will provide accurate masses, T_{eff} , and cooling ages for the remnants of a representative sample of the galactic disc population with masses in the range $\simeq 1 - 8$ solar masses, and thereby tracing the star formation history in the galactic disc. Follow-up facilities are **4–8 m class telescopes (WHT, ESO, Gemini)**, the **refurbished HST**, and a **future large-aperture ultraviolet space mission**.

The white dwarf – SN Ia connection has been outlined already above.

The superb sensitivity and low observing frequency of **LOFAR** will allow us to find the complete local population of pulsars and thereby probe the low-luminosity function of pulsars (and hence to project the full galactic population to be discovered with the **SKA**), including valuable and rare objects. Probably the best-known extreme pulsar, the double pulsar, has had a special role, providing the most stringent tests on the predictions of general relativity – more, and more powerful of such objects are expected from these deep wide-area surveys. In the light of the conflicts between general relativity and quantum mechanics, it is crucial to answer the question whether general relativity is the best theory of gravity after all. The detection of gravitational waves is part of one (out of five) key science projects for the **SKA**. 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 $T > 1$ year corresponding to frequencies of $f \sim 1/T$, and therefore probes the nano-hertz gravitational wave sky, $f_{\text{GW}} < 10$ nHz.

Before future telescopes like **LOFAR** and **SKA** come online, current facilities like the **Lovell telescope** are used in the world's most ambitious and successful pulsar timing programme. The programme is aimed at making both astrometric measurements as well as studying the evolution and stability of the rotation of the pulsars themselves. This project provides a fundamental base to the study of objects with extreme magnetic fields, the most extreme dense matter in the observable Universe and its equation-of-state, the evolution and core collapse of massive stars and plasma physics in extreme electric and magnetic fields.

Accretion inflows and outflows

Inflows and outflows of matter are an ubiquitous phenomenon in the Universe, and encountered over a vast range of scales. Yet, the most detailed observations of accretion discs and jets are obtained in galactic sources: cataclysmic variables, young stellar objects, X-ray binaries. These objects are excellent probes of fundamental physics in nearby stellar systems that have direct applications to extragalactic systems (e.g. AGN, including AGN feedback). One example are the timing properties of quasi-periodic oscillations which scale directly from stellar-mass black holes in the Galaxy to super-massive black holes in AGN. Many fundamental questions remain to be answered. What is the nature of viscosity in accretion discs? What is the mechanism responsible for jet formation? What is the nature of ultraluminous X-ray sources (ULXs) – are some ULXs related to intermediate-mass black holes? If so, how are those IMBHs formed? Answering these questions involves **broad-band radio to X-ray** observations, as well as theoretical modelling using **high-performance computing facilities**.

Resources

The UK community has access to a rapidly growing number of large survey missions/facilities, either through direct involvement or public access routes, e.g. **SDSS**, **UKIDSS**, **VISTA/VST**, **PanSTARRS**, and **SkyMapper** in the present/immediate future, **GAIA**, **LOFAR**, **SKA** coming along in the intermediate future, and still further ahead **LSST** and **LISA**. These surveys will uncover gigantic samples of stars spanning the entire parameter space of mass, age, luminosity, and metallicity. More important than size will be the ability to produce complete samples. It is also guaranteed that a substantial number of extreme/rare objects will be found that will shed light on short-lived phases in stellar evolution, or truly new outcomes in stellar physics.

Follow-up observations of these surveys, accompanied by detailed stellar modelling, is likely to provide answers to many of the unresolved problems in stellar physics, and to approach the ultimate goal of a coherent understanding of the entire stellar population of the Galaxy.

The breadth of topics covered by the UK stellar physics community relies on continuity in access to multi-wavelength multi-aperture follow-up instrumentation. In the optical-IR, 4–8 m telescopes (**WHT, ESO, Gemini**) are irreplaceable. **UKIRT** occupies a special position, finishing **UKIDSS** on time, and potentially expanding the survey area, has an outstanding legacy value. **ELT**-size telescopes will be important in some areas, however, can not replace the bread-and-butter 4–8 m class. **JWST** will be a key facility in the infrared, and a substantial demand for **LOFAR** and **SKA** is evident. A successful Service Mission 4 will re-enable access to the ultraviolet with **HST**, however, it is important that the UK gets involved in future ultraviolet mission, such as **WSO** or **ATLAST**.

With a number of huge and shiny new facilities on the horizon one should not forget that whatever scientific potential the available instrumentation offers, it takes **humans** to exploit this potential by planning and carrying out experiments and analysing the resulting data. Therefore it is of outmost importance that the grants line is protected against further cuts to pay for new facilities. The horror scenario is that the UK contributes to funding international projects such the **ELT** or **SKA**, but fails to exploit these investments.

Great care should also be taken that the observational efforts are accompanied by corresponding investment in theoretical work, where again **human resources** are essential, along with a continued upgrade of the UK's **high-performance computing** facilities.

Broader benefits

The biggest benefit which astronomy research provide is human capital. Astronomy is a key topic bringing A-level students into physics departments, and physics graduates into postgraduate studies. Astronomy students get trained in a variety of key skills such as innovative data analysis, handling of large data sets, software development, and high-performance computing. At a broader level, astronomy is the work-horse in public outreach, inspiring interest in science across the full cross-section in age/gender/social background.