NUAP - Diffuse Matter and Star and Planet Formation

Introduction

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 < 0.1 pc 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. 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.

Big Question 1 - Triggering of and Feedback in Star Formation

Triggering of and feedback in star formation 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 clusters demonstrates that feedback is sometimes positive. We do not even know why feedback can have such contrasting effects in different regions. 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.

1a) 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 the properties of a multiphase interstellar medium (ISM) affect triggering and feedback.

1b) 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 environments.

1c) Detailed high spatial and spectral resolution radio, millimetre, submillimetre, 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.

Big Question 2 - The Path to Life

Star formation can lead to the existence of planets that lie in circumstellar habitable zones and possess chemical initial conditions that lead to life. This is the consequence of:

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

2b) The masses that stars have. - Though we observe young stars with discs, we have only a rudimentary understanding of the collapse of dense cores (sizes $\sim$ 0.1 pc, particle densities $\geq 10^5$ 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.

2c) 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 modes by which planetary systems form, and the influence of migration processes that determine the final planetary system architecture.

2d) The gas phase and surface chemistry of interstellar clouds and protoplanetary discs. - The most ambitious effort through May 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 Strengths in Triggering and Feedback

In this and the following section, **each general area and technique in which the UK is especially strong is highlighted in bold face at least once**. *Italics are used similarly for key facilities.*

1a) Triggering and feedback involve scales ranging from kpcs (spiral arms) and 100 pc (Giant Molecular Clouds - GMCs) to pcs (translucent CO clumps in GMCs) and 0.1 pc (dense cores in which stars form).

Exeter and St. Andrews scientists have developed **numerical hydromagnetic models** that give insight into the triggering of GMC formation by galactic spiral arms. Leeds and Liverpool JMU researchers 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 Leeds 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 at Oxford on **CR acceleration and magnetic field amplification** in SNR shocks will prove key to understanding SNR evolution and how global ISM properties are established.

The Cardiff group has made important computational contributions to the understanding of triggering on GMC- and smaller scales. Cardiff, Exeter, Kent, Leeds, and St. Andrews groups are elucidating theoretically and computationally how dense cores form. Cambridge, Exeter, and St. Andrews scientists have incorporated continuum **radiative transfer in hydrodynamic models** to study radiative feedback in cluster formation. *High Performance Computing (HPC)* is vital for the type of work described in this and the previous paragraph.

1b) Star formation occurs under very diverse conditions. The achievement of an understanding of triggering and feedback requires observations of similarly diverse environments. Manchester, Birmingham, and UCL 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. Exeter and Leeds scientists collaborate with Penn State colleagues on the interpretation of X-ray data for young Milky Way stellar clusters to study feedback due to the winds.

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 the dense core from which 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 submillimetre to infrared and optical, probing the full span of star formation and early stellar evolution. These include: the CORNISH (Leeds) and MMB (Manchester) radio; the *JCMT*-GBS (Cardiff), JCMT-JPS (Liverpool JMU), and JCMT-SLS (Manchester) submillimetre; the RMS (Leeds) mid-IR; the *UKIRT*-GCS (Edinburgh) and UKIRT-GPS (Hertfordshire) and *VISTA*-VHS (Cambridge) and VISTA-VVV (Hertfordshire) near-IR; the IPHAS (Hertfordshire) and *VST*-VPHAS+ (Hertfordshire) optical surveys. The institutions of the researchers leading the various surveys are indicated. Such a large number of surveys is essential, because each survey is particularly sensitive to different types of stars or regions or gives unique information about sources also studied in other surveys.

1c) 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 acting in star forming regions, rather than probe the stellar kinematics that arise as important consequences of those processes. 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. If ALMA were not equipped with detectors operating at the higher frequencies potentially accessible with that facility, *C-CAT* and ALMA data would have to be combined to allow reliable measurements of the temperatures and masses of structures. C-CAT would also enable wide field surveys with about four times higher spatial resolution than obtained with SCUBA2 on the JCMT.

UK Strengths in the Path to Life

2a) Meteoretic isotopic abundances are consistent with a supernova having triggered the formation of the Solar System. The origins of some types of Solar System material can be associated with specific types of stars. The development of **3-D Monte Carlo radiative transfer codes** in UCL and applications of them to the **analysis of optical and infrared data for mass loss outflows, nebulae, and SN ejecta** can enable the determination of the specific elemental and dust contributions from these sources to the proto-Solar System.

2b) 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. Scientists in Belfast, Cambridge, Cardiff, Exeter, Hertfordshire, Leeds, Manchester, the OU, RAL, and UCL constitute a **millimetre and submillimetre observational star formation** community that is one of the strongest in the world. They interpret dust continuum emission and molecular line data to diagnose dense cores ranging from those that are starless to those containing young high mass stars. These same scientists will play key roles in the use of the *ALMA* and *SKA* interferometers to study protoplanetary discs. Leeds and UCL scientists lead international teams with guaranteed *Herschel* time for the study of dense cores.

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). The Belfast, Manchester, and UCL groups have contributed greatly to the development of chemical kinetic models used, by themselves and some of the other groups mentioned in the previous paragraph, to exploit diagnostic spectral line observations. The Belfast group contributed significantly to the identification of 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. Groups with strong laboratory efforts exist in Heriot-Watt, Strathclyde, and UCL. Complementary efforts are developing in the OU. Theoretical spectral line identification efforts in UCL are world leading and have resulted in the detection of water in an exoplanet. Future studies by the UCL group will be important in the search for potential signatures of biological activity on exoplanets (and for studies of brown dwarfs and low metallicity stars).

Dense cores are magnetised and weakly ionised and contain charged submicron dust grains that play significant roles in coupling magnetic fields to the flow of neutral material. Computational models of disc formation will have to be 3-D multifluid hydromagnetic models including grains. 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 Leeds group published the first paper on **AMR multidimensional multifluid hydromagnetic models including ambipolar diffusion** (the relative motion of charged particles and neutrals). A Cardiff group has a strong record in **numerical innovation within the SPH approach**. Cardiff and Sheffield researchers collaborate on 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.

2c) 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**. Cambridge researchers 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, Cardiff and Edinburgh 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. Cambridge and Queen Mary 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. They and the Edinburgh group have independently made great strides in understanding the transport and concentration of dust and small bodies in turbulent and self-gravitating discs, which are key issues given our current inability to explain the growth of small bodies to sizes greater than one metre. Cambridge scientists study the final clearing of gas from discs via photoevaporation, which is potentially important for halting migration.

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. 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 Leeds 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. Cambridge 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.

Edinburgh and Leeds scientists are using 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.

Efforts to use **radio interferometers** to study dust in protoplanetary discs are led by a St. Andrews group. 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. The St. Andrews group will use *e-MERLIN* to investigate the population of centimetre-sized solids. *SKA* will allow a huge extension of such work.

2d) *SKA* will also be important for searches for gas phase prebiotic molecules, which are detectable at centimetre but not millimetre 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. Manchester hosts the international **Program Development Office for SKA**. Leeds is particularly involved in defining the SKA scientific objectives associated with the search for prebiotic molecules. With the strong efforts in millimetre 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 and interstellar dust particles impinging on the Earth's atmosphere will benefit all three communities.

Summary Lists of Relevant Facilities and Resources

Current: Grants; Herschel; High Performance Computing; JCMT; UKIRT surveys; VLT; VLTI

Becoming available in the next 5 years: ALMA (full array 2012); e-Merlin (2010); Gaia (2012); JWST (2013); MROI (2014); VISTA surveys (2010); VST surveys (2010)

Becoming available more than 5 years from now: C-CAT (2016); ELT (2017+); FIRI (2025?); SKA (fully operational 2020?); SPICA (2017+)

Knowledge Transfer

The numerical fluid and N-body techniques being developed for star and planet formation are applicable in many areas including turbulent combustion and molecular dynamics and protein folding.

Many problems in astrochemistry concern questions about reaction kinetics that are fundamental to a wide range of disciplines, including atmospheric and environmental sciences. For instance, work on the master equation approach to treating surface astrochemical kinetics has influenced work on modelling negative autoregulated genetic networks in single cells. Future laboratory studies of relevance to surface astrochemistry will reveal considerable insight into surface catalysis of general applicability.

The development of instrumentation has considerable potential for generating spin-off activities. For example, the advances enabling the rapid transfer of petabytes of data from the antennae of SKA will be applicable for the efficient communication of large quantities of many types of information.

Complete and efficient exploitation of the vast datasets generated by the surveys will require the development of approaches to data visualisation and data mining techniques appropriate for large, heterogeneous data warehouses.