ASTROPHYSICS

Professor Roger Davies and Professor Joseph Silk

Research in this sub-department spans almost the whole range of astronomy, from the largest scales in the Universe to observational work on stars and the interstellar medium. There are, therefore, ample opportunities for students wishing to pursue research leading to the DPhil degree. The Sub-Department of Astrophysics consists of over 50 research-active staff, of whom 10 are established university appointments (permanent), 18 are post-doctoral researchers and 20 are research students. There are two statutory Professorships, the Savilian Professorship (held by J. Silk since 1/1/99) the newly created Philip Wetton Chair in Astrophysics, to which R. L. Davies has recently been appointed. In addition, there are several astrophysicists in the Sub-Department of Theoretical Physics; those involved are flagged with an asterisk and further details of their work can be found in the Theoretical Physics Section of this booklet.

The Astrophysics Sub-Department is situated in the Denys Wilkinson Building which is close to the centre of Oxford and the extensive University Parks. The Laboratory has excellent library, teaching and workshop facilities. The Sub-Department has grown steadily in recent years. J. Silk, Head of Astrophysics, has established a theoretical research group studying cosmology, galaxy formation and dark matter. We are also fortunate in having excellent access to a powerful complement of computer systems for data analysis, modelling and simulations.

Oxford Astrophysics has been successful in attracting long-term Royal Society, PPARC Advanced and other Senior Research Fellows funded by a grant from the Leverhulme Trust. A PPARC rolling grant supports research into observational cosmology. We are taking a major role in the construction of the UK-Japan near-infrared, fibre-fed, multi-object spectrograph, FMOS, for the 8m Subaru telescope. Oxford is also a partner in consortia designing and building second generation instruments for the European Southern Observatory's VLT and the Gemini telescopes, notably KMOS, MUSE, WFMOS and ExAOC. We have also won a Marie Curie Excellence Grant from the European Commission for realising SWIFT, a novel integral field spectrograph. Oxford is the coordinating node for CMBNET, a European network for collaborative research into the cosmic microwave background, and for the Early Universe European network for particle cosmology. Oxford also is a node in two other European networks on Type 1a Supernovae (theory and observation), and SISCO: Spectroscopic and Imaging Surveys for Cosmology.

Members of the sub-department have been very successful in gaining observing time on most of the large aperture ground-based telescopes, including the Anglo-Australian Telescope (AAT), the William Herschel Telescope (WHT), the United Kingdom Infrared Telescope (UKIRT), and the new generation of 8m class telescopes (Gemini, Subaru, and VLT) for optical and infrared observations, as well as the James Clerk-Maxwell Telescope (JCMT) for sub-millimeter imaging. Many hours have been awarded to Oxford astronomers on the Very Large Array (VLA) at radio wavelengths and recently we have been using Very Long Baseline Interferometry (VLBI) techniques with the Multi-Element Radio-Linked Interferometer Network (MERLIN) and the Very Long Baseline Array (VLBA). Members of the sub-department are involved in observations from space over a very wide range of wavelengths, with ASCA, XMM and Chandra (for X-ray observations), the Hubble Space Telescope (HST) (for infrared, optical and ultraviolet astronomy), and in the preparations for the PLANCK mission to study the cosmic microwave background. The UK Gemini Support Group is located at Oxford. In theoretical astrophysics, there are strong programmes in the area of galaxy dynamics, cosmology, galaxy formation, dark matter and the cosmic microwave background radiation. The recent appointment of R.L.Davies will lead to an expansion in extragalactic astronomy and astronomical instrumentation.

1. Observational cosmology and galaxies

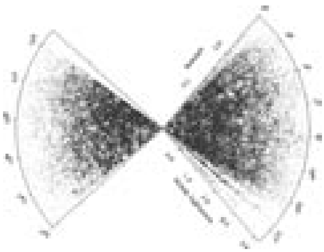
J Baker, K Blundell, G Cotter, G Dalton, R Davies, I Hook ,R. Johnson, L Miller, S Rawlings, N Thatte, S Yi.

1.1 Motivation

Theory provides predictions of the spectrum of fluctuations in the matter distribution of the Universe, but testing these predictions by making observations is by no means straightforward. The matter fluctuations may be traced by making surveys of galaxies, clusters of galaxies, quasars or radio sources. Determination of the three-dimensional structure of the Universe requires surveys covering a large fraction of the observable Universe, and these surveys must account for a variety of biases and projection effects. Problems encountered range from those that are conceptually simple but observationally challenging - such as the requirement of redshift information for a large number of objects - to those that are subtle such as the distortions due to gravitational lensing of distant objects by the intervening matter distribution. At Oxford we are, for example, studying the structure of the Universe using Type 1a Supernovae. The present paradigm for galaxy formation and evolution has galaxies assembling in their dark matter halos as these merge to form ever more massive objects over cosmic time. The Hubble Space Telescope (HST) has shown us that galaxy interactions and mergers were more common in the distant past and that these events are frequently associated with star formation episodes. How the luminous components of galaxies come to have their present appearance, why some have disks and others do not and when the major star forming episodes occurred are some of the central goals of our observational work on galaxy evolution. In addition to using normal and active galaxies as cosmological probes, there are a number of programmes at Oxford which aim to improve our understanding of how active galaxies work. Key questions include: why do only some active galaxies develop powerful radio-emission; what is the link between extranuclear star formation and nuclear activity; is there a link between the mass and structure of the host galaxy and the type of nuclear activity; why were there large changes in the space density of active galaxies with cosmic time? These programmes require observations at all wavebands, and often at the high angular resolution offered by Very Long Baseline Interferometry at radio wavelengths or the HST in the infrared, optical and ultraviolet wavebands.

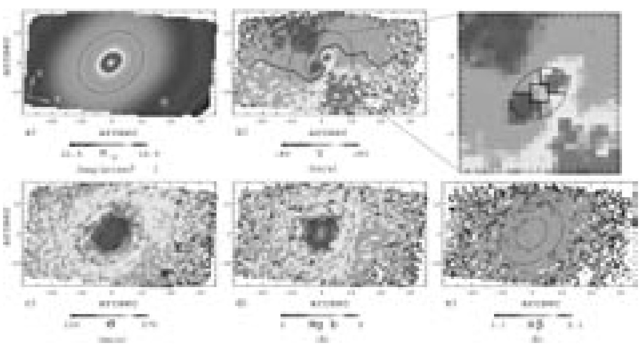
1.1.1 Galaxy surveys

Our group is working on a number of surveys of large-scale structure as traced by galaxies and clusters of galaxies, both nearby and distant. The aim of this research is to study the formation and evolution of galaxies and their large-scale distribution. One of these surveys uses the two-degree field (2dF) facility at the Anglo-Australian Telescope, which allows simultaneous measurement of the spectra of several hundred galaxies over that field. The Anglo-Australian 2dF Redshift Survey aims to measure redshifts for at least 250,000 galaxies; this will provide the first three-dimensional measurements of galaxy clustering on the large scales that may be studied at early cosmic epochs by measuring fluctuations in the microwave background. As we probe the galaxy distribution to fainter magnitude limits, the study of galaxy clustering is affected by the evolutionary histories of the galaxies themselves, as we see more distant objects at earlier times. The combined effects of cosmological redshift and galaxy evolution imply that multicolour surveys of faint galaxies are required to trace the evolution of galaxy clustering. We are in the process of constructing a deep wide-field optical and infra-red survey of faint galaxies. This will be used to identify candidate clusters of galaxies at a range of cosmological epochs, which will be followed up using the new generation of 8 m telescopes to study the evolution of galaxies and galaxy clustering.



A slice of the Universe showing nearly 200,000 galaxies from the 2dF Galaxy Redshift Survey. In addition to the three dimensional positions of galaxies, the survey contains a wealth of information on the nature of each galaxy, including luminosity and star-formation history. The survey represents a comprehensive snapshot of the local Universe to which future surveys can be compared to study the evolution of galaxies.

Local galaxies can be studied with greater precision and linear resolution than high redshift galaxies allowing us to make connections between their structure, dynamics and star-formation history. Our work seeks to characterise and model local galaxies as a function of luminosity, environment and Hubble type. In this work we apply the latest instrumental techniques that allow us to take a spectrum at every point in a galaxy simultaneously (using Integral Field Spectrographs, IFS) to produce a map of the velocity field and composition of the gas and stars. We are also able to estimate the age of the stars that dominate the integrated light. A few galaxies have core regions with stellar kinematics that are completely decoupled from those of the rest of the galaxy and this is taken as an indication of a past merger, but when did it occur? NGC4365, shown in the figure, is a good example. The velocity map shows that, this otherwise ordinary galaxy is rolling around its long axis but the central regions are rotating roughly perpendicular to this! The lower right panel shows that the strength of the Hβ Balmer absorption line is constant across the entire galaxy, both the decoupled core and main body. This shows that the stars in both components are the same age. It is very likely that the decoupled kinematics arose from a merger but character of the stars tells us this happened 12-14 Gyrs ago in the initial star forming event and that the galaxy has been quiescent since. The core is a remnant of the formation process, not the result of a late merger. Thus by measuring both the kinematics and the ages of the stellar population we are able to deduce the evolutionary history of galaxies. That work used the purpose built {SAURON} spectrograph on the William Herschel Telescope with which we



NGC 4365 - A good example of a galaxy having a core region with stellar kinematics that are completely decoupled from those of the rest of the galaxy.

are pursuing an extensive survey. We plan to use IFS on the 8m Gemini and VLT telescopes to extend this work to higher redshift galaxies and into the infrared allowing us to "age" and "weigh" distant galaxies to test the assembly paradigm directly. Through this work we have developed precise techniques for determining the mass-to-light ratio of galaxies, their ages and compositions all of which can be adapted to measure the evolution of galaxies directly by studying the galaxy population in groups and clusters at high redshift. We know that the galaxy population in dense regions of the universe is quite different from that in regions of average density but we do not know why. Through statistical studies of galaxies in different environments over a range of redshift we can eliminate candidate mechanisms. We use the luminosity in X-rays to signal the presence of a true physical association at high redshift and to determine the local density of the intergalactic medium. By using multiple object spectroscopy at both optical and infrared wavelengths we can assemble large galaxy samples for this work.

1.1.2 Quasar surveys

Quasars are the most luminous objects known. They are the most extreme form of active galaxy in which a galaxy's nuclear region can generate 1000 times more light than all the stars in that galaxy. Some of them are the most distant objects yet discovered, making them useful probes of changes in the Universe with time. Quasar surveys at optical, radio and X-ray wavelengths are being revolutionised in size: e.g. the collaborative 2dF quasar survey will eventually produce a sample of 24,000 optically-selected quasars. This large number is needed so that we can study how the clustering of quasars changes with cosmic epoch, which can be used to compare with theoretical predictions, as well as placing quantitative limits on the parameters that describe the geometry of the Universe and allowing greatly improved determination of the cosmological evolution of the population of quasars.

1.1.3 Radio source surveys

Like quasars and other active galaxies, luminous radio sources are also concentrated in the younger Universe. Oxford workers are pursuing programmes to study the most distant examples of these objects. These are seen at times when the Universe was only about one billion years old, and are thus important for studying the earliest observable phases of galaxy formation. We study these objects across the electromagnetic spectrum using the largest ground-based optical and radio telescopes, and space-based facilities such as the HST, Chandra and XMM satellites, as well as infra-red and sub-mm imaging. We aim to disentangle the effects of the radio activity, and the active nuclei which power them, from the underlying starlight. In particular, we have made the first redshift surveys of faint radio galaxies. These have yielded high-redshift radio galaxies whose host-galaxy light should be less affected by the active nucleus, and whose properties give direct information on the formation and early evolution of elliptical galaxies. We are also determining how the entropy injected into the intergalactic medium by jets influences galaxy formation and evolution. We are also using the new generation of high-frequency surveys to identify sources whose radio jets have very recently been triggered.

1.1.4 Physical models of quasar and radio source evolution

It has been recognised for 30 years that the space density of quasars was much higher in the past than at the present day. When the Universe was about one-third of its present age there were about 100 times more quasars of a given luminosity than there are today, after allowing for the expansion of the Universe since that time.

The quasar and radio source surveys described above give us quantitative information on the amount of that evolution but tell us little about how and why it occurs. To tackle this problem we need both a physical model for the evolution of quasars, radio sources and active galaxies, and also we need new observational information. Key to our understanding are the links between host galaxy type, mass and environment, nuclear activity and starburst activity. New ground-based infrared and submillimetre observations are shedding new light on this problem, together with Hubble Space Telescope infrared imaging of quasar host galaxies.

1.1.5 Radio galaxy and quasar companions at high redshift and distant clusters

Active galaxies are frequently found with normal galaxy companions or in clusters of galaxies, and Oxford workers are leading projects aimed at identifying and studying companion galaxies over a large range in redshift. At moderate redshifts, clusters can be imaged directly in the optical and we have found many quasars and radio sources in clusters of galaxies. This may provide an important clue to the origin of the rapid rise in number density of quasar activity with redshift, for example it might pinpoint the epoch at which rich clusters first formed. At higher redshifts clusters can be detected by multi-colour near-infrared imaging, and star-forming companion galaxies may be detected using narrow-band imaging techniques to isolate strong emission lines. We are also involved in the study of high-redshift clusters selected by their imprint on the Cosmic Microwave Background.

1.1.6 The nuclear environment of nearby active galaxies.

Active galactic nuclei are thought to be powered by massive black holes. However, star formation can sometimes play a major role in the energetics of the nuclear region. By conducting high resolution observations using adaptive optics at near infrared wavelengths, Oxford researchers are studying the close-in nuclear environment of active galaxies. Besides measuring the fraction of nuclear luminosity attributable to star formation, these observations also address the issue of fuelling of the active nucleus. The mechanism for transporting gas from ~100 pc scales to the immediate vicinity of the black hole is not well understood, although bars and Linblad resonances do play a vital role. Spectra of the close nuclear environment also provide kinematic information about gas in the narrow line region, and allow us to probe the physical conditions and excitation mechanisms of the circumnuclear environment.

1.1.7 Demographics of supermassive black holes in ngalaxy nuclei.

Super-massive black holes (with masses from a few million to a few billion solar masses) are thought to lurk in the nuclei of all present day galaxies. A recently established empirical relationship shows a tight correlation between the mass of the super-massive nuclear dark mass and the total mass of the galaxy bulge. Yet it is unclear as to what physical processes collude to link two quantities whose size scales differ by a factor of more than a million. Oxford researchers are carrying out a co-ordinated program to build up a larger sample of black hole mass measurements, especially at the low and high mass ends, to explore the dependence of black hole mass on galaxy morphology, level of activity, radio properties etc. Integral field and long slit data at near infrared wavelengths, where dust extinction is less significant, are being used to probe the nuclei of spiral galaxies, thus complementing present work that has concentrated on early-type galaxies. The program is being extended to use adaptive optics techniques to substantially improve the spatial resolution of the observations. By probing the stellar dynamics of galaxy nuclei at spatial scales corresponding to the sphere of influence of the central black hole, we hope to unravel the physics that underlies the observed correlation.

1.1.8 Weak and strong gravitational lensing

The observation that high luminosity, high redshift active galaxies seem to have more foreground galaxies projected close to their line of sight than expected by chance has been a long-standing puzzle. One possibility is that gravitational lensing of background quasars and radio galaxies by foreground groups and clusters of galaxies may magnify their flux. If this is true, we would expect to be able to identify the presence of such mass concentrations using X-ray observations, observations of decrements in the microwave background or through their distorting effect on the images of other background galaxies in the field. Oxford workers are pursuing all these possibilities. If foreground galaxies are close enough to the line of sight then strong gravitational lensing effects come into play. There are several examples of strong lensing in the Oxford quasar and radio galaxy surveys, and these are being used to measure the mass-to-light ratio in distant galaxies and clusters.

1.1.9 Measuring cosmological parameters using type Ia Supernovae

In the last five years the use of Type Ia supernovae as standard candles has provided evidence that the expansion of the Universe is accelerating. This initially unexpected result hinges on the observation that distant supernovae appear fainter than would be expected in a non-accelerating universe. Work is now underway to understand and extend this result by studying supernovae in detail at high redshift. One of the most important issues to understand is the extent to which dimming by dust may be affecting the results. Researchers in Oxford are working in collaboration with colleagues around the world on major surveys to find and study distant supernovae, using the world's leading observational facilities.

1.1.10 Galaxy evolution using GALEX UV space telescope

NASA's space UV telescope satellite, GALEX, is performing an unprecedented all-sky UV survey. Since its launch in April 2003, it has been collecting the UV spectra and images of hundreds of thousands of galaxies and stars. Its main science topics include the star formation history of the universe and of individual galaxies. Our team in Oxford led by Yi is working on the star formation history of early-type galaxies which have been believed to be quiescent (no recent star formation). Surprisingly, we found at least 15% of bright early-type galaxies show unambiguous signs of recent starbursts; this very interesting result is stimulating us to make various further tests and investigations.

1.2 Theoretical astrophysics and cosmology

J Binney, G Bryan, J Magorrian*, P Ferreira, J Silk, S Yi*

This group's research concerns the dynamics under gravity of all astrophysical systems that are not extremely relativistic. It includes the formation of large scale structure in the Universe, the formation of galaxies, galaxy evolution, the dynamics of the Milky Way and other galaxies, gravitational lensing and the long term evolution of the Solar System. Much of this research is driven by observations from the new generation of telescopes and instruments, including the HST and preparation for future missions, such as ALMA, PLANCK, NGST, and the new generation of cosmic microwave background experiments. The modelling involves both analytical and numerical work, with modern theories of non-linear dynamics playing a unifying role.

1.2.1 Cosmic microwave background

The origin of large-scale structure may be probed by studying trace fluctuations in the cosmic microwave background. These are imprinted by primordial irregularities in density that grew by gravitational instability in the early Universe. The increasingly refined measurements of anisotropies that have been detected over a range of angular scales are beginning to constrain and even challenge theoretical models. Planned radio and submillimetre wavelength experiments using telescopes on balloons (the recent BOOMERANG experiments), satellites (MAP in 2001 and Planck in 2007) and ground-based interferometer arrays will approach a level of sensitivity that will definitively measure many, if not all, cosmological parameters with unprecedented precision. One of the major uncertainties is that of foregrounds, both galactic and extragalactic, which need to be evaluated in order to enhance the precision of such measurements. Simulations of sky maps will be one of the activities that will be undertaken at Oxford. In a complementary attack on large-scale structure, the deep galaxy redshift surveys now underway and which will obtain of order a million redshifts have the sensitivity to probe large-scale power in density fluctuations in the nearby Universe. The physical scales that are studied in this way overlap with the power spectrum inferred at high redshift from mapping of the cosmic microwave background, and combination of the two approaches will provide new insights into models for large-scale structure. On small angular scales, early formation of galaxy clusters, radio galaxies and quasars inevitably provide energy input into the intergalactic medium and generate fine-scale temperature anisotropies. Understanding the detailed nature of such signatures will help define a goal for new generations of experiments and satellite missions.

1.2.2 Galaxy formation

Understanding how galaxies form and unravelling the nature of the origin of the large-scale structure of the Universe are key unresolved issues in cosmology. A focus of our research includes the study of galaxy formation and evolution. The challenge of galaxy formation theory is to account for the fossilised properties of galaxies, such as morphologies, scaling relations, and chemical abundances, as well as the evolution of these properties with redshift. The star formation histories of disk and elliptical galaxies and their high redshift counterparts provide vital clues to galactic evolution. Semi-analytical techniques can be applied to yield global star formation rates in disk galaxies and evolve nearby galaxies backwards in time. Galaxy mergers induce ultraluminous starbursts, and study of such phenomena, including the roles of infall, galactic winds and active nuclei, provides insight into spheroid formation. An improved understanding of protogalaxy evolution will have profound implications for understanding chemical evolution and for interpreting far infrared and submillimetre observations of star-forming galaxies in the distant Universe.

1.2.3 Dark matter

The frontier of particle physics is beyond the TeV energy range of current generations of accelerators but in the realm of the energy scales of supersymmetry or grand unification, or even quantum gravity. The interface of cosmology and particle physics plays a critical role in motivating such research. These seemingly diverse realms coincide in the Big Bang cosmology, which provides a unique particle accelerator that operates up to energies of 10^{19} GeV. The study of the early Universe thus provides a unique laboratory for searching for relics from very early epochs for testing ideas from such theories as grand unification and supergravity. Perhaps the most important development has been that of the inflationary cosmology, which may solve a number of outstanding problems that have puzzled cosmologists for over half a century. These include the isotropy of the Universe, its size, its homogeneity on large scales and its lack of homogeneity on small scales, and the paucity of bizarre relics such as monopoles. Predictions of inflationary cosmology, such as the origin and spectrum of density fluctuations and the distribution and composition of dark matter, are important to the understanding of galaxy formation and sensitively depend on the details of the correct particle theory. The particle relics from the beginning of the Universe may surround us today in the form of dark matter in galaxy halos. One current study explores the hypothesis that the dark matter in our galactic halo and in the halos of nearby galaxies consists of massive stable relic particles which occasionally annihilate to produce a substantial flux of sub-GeV cosmic ray antiprotons, high energy gamma-rays and neutrinos with unique spectral signatures.

1.2.4 External galaxies

In recent years, galactic astronomers have become more aware of the importance of cusps in the centres of galaxies. First, computer simulations of halo formation in hierarchical clustering cosmogonies have revealed the existence of a universal, cusped profile for galactic haloes. Secondly, there is an extensive data-set of images of galactic nuclei taken with the HST. The brilliance of the central nuclei is a consequence of a power-law rise in the light distribution right down to the very limits of the resolution. Researchers in Oxford have been actively involved in the understanding and the modelling of dynamics in the cusp. There are several suggestions as to the origin of galactic cusps; perhaps some are caused by the presence of black holes, while some may be the result of the engulfment of gas-rich, small disk galaxies. Another intriguing possibility is that the cusps are a natural end-point of the process of merging and accretion that built the galaxies. The shapes of external galaxies depend on their orbital populations. These populations change through capture into and escape from resonance. Resonances are important in both galactic and Solar System dynamics, as small disturbances can have a dramatic effect on orbital shape at resonance. For example, tidal resonant forcing of highly inclined orbits around a central black hole can cause a substantial increase in the likelihood of collision. This may be an important means of fuelling the black holes that are believed to reside in galactic nuclei. Workers in Oxford have developed a new pictorial form of non-linear perturbation theory that enables us to study motion close to a resonance and to make predictions of dynamical behaviour that can be compared with numerical simulations. Why are some galaxies barred, and some are not? Why are some galaxies lop-sided, and others not? The question of the origin of non-axisymmetric structures has led us to undertake detailed stability analyses of models of stellar systems. These include normal mode studies of the linear stability problem, as well as brute force N-body calculations.

1.2.5 The Milky Way

The Oxford workers are engaged in a long term project towards a comprehensive understanding of the Milky Way. Over the last decade, Binney and co-workers have been developing a new method (the Oxford Torus Project) to analyse the stellar kinematics of nearby stars. When stellar motion is viewed in a six-dimensional phase space of positions and momenta, it is particularly simple. The stars move on three-dimensional tori. This feature is preserved under slow adiabatic perturbations. By adjusting the distributions of stars on tori, models are obtained for the interpretation of the kinematics of stars in the Milky Way. Another area undergoing rapid development is the study of the Bulge of the Milky Way. The DIRBE instrument that flew on the COBE satellite provided the most detailed picture to date of the Galactic Bulge. This is evidently asymmetric; for example, the infrared light distribution is brighter towards positive longitudes than negative longitudes. This was striking confirmation of a viewpoint earlier advanced in Oxford and elsewhere that the Milky Way galaxy is barred, with the near-side of the bar lying towards positive longitudes. A major effort (the Oxford Bar Project) aims at developing a series of stellar dynamical models of the inner Galaxy and using them to interpret the radial velocity and proper motion data towards the Galactic Centre. The microlensing surveys are a very new and important source of information on the Milky Way. So far the dynamical implications for our galaxy are not well understood, and Binney has been in the forefront of the struggle to understand these data using models developed both for the dark halo and the Bulge.

1.2.6 Galaxy Spectral Evolution

At Oxford, we also have a group (with one lecturer and two PDRAs) that focuses on constructing the spectral evolution models of galaxies. The main technique is the evolutionary population synthesis (EPS) which numerically computes the integrated spectrum of a galaxy as a function of time, following star formation history, initial mass function, and individual stellar evolution. The predicted synthetic spectra are currently the most powerful tools to study galaxy evolution. Outstanding tasks include age estimation of old galaxies near and far. The spectra trace visible matter, whereas the mass distribution may be dominated by dark matter. Therefore, comparing the knowledge obtained from galaxy spectral analyses to that from dynamical modelling and kinematic observational data may allow us to find the link between luminous matter and dark matter.

2 Stellar Astrophysics

A Lynas-Gray, P Podsiadlowski, S Yi.

2.1 The evolution of single and binary stars

We have several projects studying the various phases in the evolution of stars, starting with the basic formation process to their final phase, the planetary-nebula or supernova stage. We are particularly interested in applying stellar evolution theory to stars in binaries to see how binary interactions can affect the structure and evolution of stars, for example, to explain the origin of stars with chemical anomalies (e.g. barium stars) or to explain the non-spherical, often bipolar morphologies of many planetary nebulae. In these studies, we use a variety of analytical and numerical tools (specially modified stellar structure codes, hydrodynamical codes in one to three dimensions) and maintain active collaborations with various theoretical and observational groups around the world. At present, the two major applications of this work are the study of pre-supernova evolution in interacting binaries and X-ray binaries.

2.1.1 Supernovae

There are two fundamentally different types of supernovae: thermonuclear explosions which occur when a white dwarf is pushed above its maximum mass of 1.4 solar masses (the Chandrasekhar limit) and which leads to the complete disruption of the star (referred to as a 'Type Ia supernova'), and core-collapse supernovae which take place when the core of a massive star has exhausted all of its nuclear fuel. In the latter case, the core of the star collapses to leave a compact remnant, a neutron star or in some cases a black hole. A small fraction of the energy released in the collapse is deposited in the envelope, leading to an explosion and the bright, spectacular display we refer to as a supernova. The appearance of the supernova, however, depends sensitively on the pre-supernova structure of the envelope and hence the star's evolutionary history in a binary. The various binary interactions (mass loss, mass accretion and merging) can fundamentally change the structure of a massive star and may thereby account for many of the observational supernova sub-classes.

We are particularly interested in applying this theory to two of the most interesting nearby supernovae of our generation, SN 1987A and SN 1993J. SN 1987A was the first naked-eye supernova since Kepler's supernova in 1604 and is a highly anomalous supernova. Contrary to what had been predicted, the progenitor was a blue supergiant instead of a red supergiant, and is surrounded by a spectacular, but very complex, nebula consisting of three bright rings (seen most clearly with recent HST images) and has various chemical anomalies in its envelope. At the moment, these anomalies can be best explained if the progenitor originally was in a binary and has merged with its companion in the not-too-distant past. We are actively modelling all the detailed physical processes involved in the merging of two massive stars, in particular the dynamical evolution of the system in the merger phase, the associated anomalous nucleosynthesis and the dynamical ejection of part of the envelope, presumably producing the triple-ring nebula around the supernova.

The progenitor of SN 1993J on the other hand seems to have been a star mainly consisting of helium and heavier elements with a very small hydrogen-rich envelope. This again suggests that it was a member of a binary and that it lost most of its hydrogen-rich envelope by mass transfer. In both cases, future observations and theoretical calculations will be required to confirm or refute the suggested binary connections.

Type Ia supernovae have recently been used as cosmological distance candles (See Section 1.1.9) to measure the curvature of the Universe. At face value, the results suggest an accelerating Universe, a dramatic break from the previous picture. However, these results do not take into account possible evolutionary changes in the population of Type Ia supernova progenitors. Considering that there is no agreement on what the progenitor systems of these supernovae actually are, this seriously weakens the cosmological argument. We are presently studying various types of binary systems proposed as progenitors for Type Ia supernovae and model the evolution of the population of these progenitors since the early Universe, using binary population synthesis methods.

Hypernovae are a rare, new supernova type, first identified in 1998, which are much more energetic than a normal supernova and are probably caused by the collapse of a rapidly rotating helium star to a stellar-mass black hole. Some hypernovae are observationally known to be related to gamma-ray bursts, the most violent and most energetic events known in the Universe. Again our main interest is in understanding what type of stellar system can produce the progenitors of these spectacular events.

2.1.2 The formation and evolution of X-ray binaries and millisecond pulsars

Recent observations of the space velocities of pulsars (rapidly rotating neutron stars) have shown that when neutron stars are born in a supernova they receive very large kicks (presumably due to an asymmetry in the supernova explosion). This has important effects on the orbital parameters and the Galactic distribution of neutron stars in binaries. We are particularly interested in so-called low-mass X-ray binaries (LMXB), where a low-mass star with the mass of the Sun or less transfers matter to a neutron star, which as a result becomes a luminous X-ray source. While supernova kicks are important for understanding the formation of LMXBs in the Galactic disc, in dense stellar environments like globular clusters, other processes may be more important. For example, in globular clusters, LMXBs may form as a result of the tidal capture of a neutron star by a normal star. However, whether this is a viable process depends on the response of the normal star when the tidal energy is deposited inside the star (the tidal energy can be a large fraction of the binding energy of the star). During the LMXB phase, it is generally believed that the neutron star is spun up by accretion of matter, leaving a millisecond pulsar once the X-ray phase has ended. However, statistical comparisons between millisecond pulsars and LMXBs suggest that there are either too many millisecond pulsars relative to the number of LMXBs or that the duration of the LMXB phase has been overestimated by a large factor. This latter, more likely, possibility may be understood by irradiation effects which can dramatically change the structure of the irradiated normal star. In particular, the secondary may become inflated which leads to accelerated evolution and a shorter duration of the LMXB phase. The details of this process depend, however, on the circulation inside the secondary caused by the one-sidedness of the irradiation in a binary. This is an important problem which we are actively studying at the moment, developing both the theoretical framework and the numerical tools to tackle this problem.

One of the most important recent discoveries in this field, which indeed may challenge the above paradigm for LMXBs, is the realization that many stars in so-called “low-mass” X-ray binaries originate from much more massive progenitors (e.g., Cyg X-2, Cyg X-3). Based on our recent calculations, it now seems that a large fraction, if not the majority, of low-mass X-ray binaries may actually belong to a much more massive, previously largely ignored class of intermediate-mass X-ray binaries, and that standard textbooks on the subject need to be rewritten. Apart from modelling individual systems, we use binary populations synthesis techniques to model the population of X-ray binaries (with US collaborators) and keep active collaborations with observational groups to test our predictions and improve our modelling efforts.

The formation of planets around pulsars (indeed, the first planets outside the solar system were discovered around pulsars) is a related problem of much current interest. Many massive X-ray binaries are predicted to merge in the near future. As a result of a complete merger, the neutron star sinks to the centre of the massive star forming a new hybrid object, generally referred to as a Thorne-Zytkow object (TZO). While no such TZO has yet been discovered, recent theoretical calculations predict that these objects should show anomalous surface abundances of many chemical elements which should be easily detectable spectroscopically. We are planning to use these predicted anomalies to search for these objects observationally.

2.1.3 Isochrone Project

One of the world’s most popular stellar isochrones (The Yale-Yonsei Isochrones) is in fact generated at Oxford at the moment as Yi moved to Oxford in 2001. Isochrones are defined as the locus of coeval (equal age) points on the evolutionary tracks of stars of different masses in the Temperature-Luminosity plane. Once accurate isochrones are constructed, one can use them to match the observed data of various populations to derive their ages. Most notably, isochrones are used to derive the ages of globular clusters in the Milky Way. Because globular clusters are often considered as the oldest populations in the universe, this allows us to set the lower limit on the age of the Universe. Not to mention the beauty of the stellar evolution theory behind the isochrones, there are numerous applications of isochrones, including isochrone synthesis for galaxy evolution modelling.

2.2 Stellar atmospheres

A knowledge of stellar abundances is crucial to our understanding of stellar and galactic evolution. While most stars have solar abundances or are metal-deficient with respect to the Sun, more pronounced abundance anomalies are also found. A few stars, for instance, have photospheres composed of 99% helium and 1% carbon (by numbers) with all other elements (including hydrogen) present only in trace amounts. Detailed abundance studies of stars in external galaxies (beyond the Magellanic Clouds) are becoming feasible using the HST and 10 metre class ground-based facilities. Improved techniques for the analysis of stellar spectra are under development; these take advantage of better computer hardware, numerical methods and (most important of all) recent advances in atomic and molecular physics. Synthesis of whole spectral regions with inclusion of all likely spectral features is now a viable method of approach.

Subdwarf-B (sdB) star research is of interest to investigations of stellar mass-loss, as these stars appear to represent extreme cases of near complete envelope loss during the later stages of stellar evolution. If most stars evolve through the sdB star stage, following evolution up the giant branch, understanding the envelope loss which results in sdB star formation is crucial to understanding the late stages of stellar evolution; it would also be the key to understanding chemical evolution of a galaxy or star cluster over several stellar generations. A recently published better understanding of sdB star evolution should help determine the contribution of sdB stars to the observed ultraviolet upturn in giant elliptical galaxies, with the view to its calibration as an age indicator. Following the exciting discovery of low-amplitude pulsation in seventeen sdB stars, the techniques of asteroseismology are being used to constrain stellar evolution models through a determination of envelope structure. The intention is to establish sdB star envelope structure by determining the dispersion relation of acoustic or gravity waves in surface layers, where wave scattering can be accurately computed.

3 Interstellar medium

P Roche

Tiny particles of cosmic dust permeate interstellar space and profoundly alter our view of many astronomical objects through the effects of interstellar extinction. However, the dust is not just a nuisance; the particles bear within them a record of the prevailing conditions where the dust was formed, ranging from the circumstellar shells of red giant stars to the cold molecular clouds where many complex molecules are synthesised. These species make important but poorly-understood contributions to interstellar chemistry and the energy balance of the interstellar medium. We are currently using the properties of the molecules and dust in planetary nebulae as probes of the processes and mechanisms which occur in intermediate mass stars at the end of their lives.

With the advent of sensitive infrared instruments, it has become possible to probe the chemical and physical structure of cosmic dust, and to investigate the sources lying within dust clouds, tracing the spatial extent and spectral properties of these dusty regions. These observations are particularly important in regions which are totally obscured at visible wavelengths such as the centre of our Galaxy, regions of star-formation in molecular clouds and the nuclei of dusty galaxies. Spectroscopy, imaging and polarimetry are employed to characterize these dusty environments and to investigate the objects lying in their cores. High resolution images obtained with the infrared cameras in Hawaii and La Palma are used to probe the nearest star forming regions on the scale of our own solar system. Models and Monte Carlo simulations of the effects of scattering by dust particles are developed to interpret the observations and provide information on the structures and geometry of the envelopes and disks around newly-formed stars.

4 Astronomical instrumentation

4.1 Infrared and visible wavelength instrumentation

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The astronomical instrumentation group at Oxford has expanded rapidly in the last year, with a strong influx of new personnel and new projects. We are now involved in designing, fabricating and deploying second generation instruments at three different 8-meter class telescopes - the European Southern Observatory's Very Large Telescope (VLT), the Gemini telescopes and the Japanese Subaru telescope. In addition, Oxford hosts the UK's Gemini Support Group which seeks to assist UK observers with preparation and exploitation of their Gemini programmes, putting us in an ideal position to exploit these facilities. We are also involved in a joint OPTICON-PPARC effort to define and develop science programs for the next generation of 30 and 100 meter telescopes (ELTs). The Oxford instrumentation group have recently won a Marie Curie Excellence Grant from the European Commission for the design and realisation of SWIFT, a novel integral field spectrograph. SWIFT will provide integral field capability covering the wavelength range 0.7 to 1.0 μm. SWIFT's novelty stems from the combination of a very high throughput image slicer based integral field unit, a CCD detector with very high sensitivity at red wavelengths, and the enhanced sensitivity and resolution afforded by an adaptive optics system. It is a fast track project, to be realised over a four year timescale. A dedicated team of 5 researchers has already begun working on the project. SWIFT will explore the kinematics and dynamics of galaxies at moderate and high redshift, using emission lines shifted into its bandpass. Additional financial support is also available from the University.

We are the principal UK partners with Japan in the construction of a wide-field, multi-object, infrared spectrograph project (FMOS). This will be fed by a robotic fibre-optic positioning system at the prime focus of Japan's 8.3m Subaru telescope. FMOS will see first-light in early 2005, and provides an excellent opportunity for a D.Phil student to become involved in the laboratory testing and science verification phase of the instrument which will address a wide range of science programmes from brown-dwarf stars to the evolution of galaxies at high redshifts.

Together with consortium partners in Germany (MPE, Garching and USM, Munich) and the UK (Univ. of Durham, UKATC) we have won a competitive bid to design and construct KMOS, the cryogenic, multi-object, near-infrared spectrometer for the ESO VLT. KMOS will be one of the VLT's second generation instruments, and will represent UK's major contribution to VLT instrumentation. KMOS will be equipped with deployable mini integral field units, thus providing spatially resolved information of over two dozen targets within a 7^{o} diameter field. Oxford will be responsible for the spectrograph module of KMOS, and for part of the data analysis and reduction software. KMOS is expected to be operational in 2009. We are also a major partner in MUSE, the Multi-Unit Spectroscopic Explorer, another second generation VLT instrument, led by R. Bacon (PI) in Lyon. MUSE will provide integral field coverage of $1' \times 1'$ field of view with $0.''2$ spatial sampling (almost 100,000 spatial elements!), whilst simultaneously covering the entire visible wavelength range in the spectral dimension (0.465 - 0.93 μm). The primary science driver for MUSE is to study emission line objects at high redshifts. These objects, with faint continua, are not easily detected in imaging surveys. MUSE also has a narrow field mode capable of observations close to the diffraction limit of the VLT, aided by its own adaptive optics system. Oxford is responsible for designing and developing the mechanical structure of MUSE. The project's instrument scientist is also at Oxford. Recently, our instrumentation group has been a partner in two successful bids for design and feasibility studies for Gemini second generation instruments. The first, termed ExAOC, is an instrument designed to perform direct imaging and spectroscopy of exo-solar planets using extreme adaptive optics, providing a contrast ratio exceeding 107 relative to the parent star. We will contribute an integral field unit to this instrument, which will allow simultaneous spectroscopy of all points within a couple of arc seconds of the parent star, at high spatial and moderate spectral resolution. The Phase A design study is on-going at the moment. We are also involved in a large consortium that will carry out a feasibility study for WFMOS, the most challenging of the Gemini second generation instruments. WFMOS will provide simultaneous spectra of ~5000 galaxies spread over a 1.5 degree field of view, in order to answer fundamental questions about the complexity of the Universe and to determine the equation of state of dark energy. It is a very ambitious project, as it will require major modifications to the Gemini telescope, and to the way in which the Observatory is run. At present, a feasibility study is being carried out.

Through a developing link with the CLRC's Rutherford Appleton Laboratory (also involved in the FMOS project) we are also contributing to the design and construction of a new 4m-class survey telescope (VISTA) which will be sited close to the VLT in Chile in 2006. VISTA hosts a uniqe wide field Infra Red camera which will be used to construct a deep survey of the entireSouthern sky to provide targets for the VLT, Gemini and the Next-Generation Space Telescope.

4.2 The UK Gemini Support Group

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The UK is a 25% partner in the international Gemini Observatory which operates two 8-m telescopes on the best observing sites in the world, Mauna Kea in Hawaii and Cerro Pachon in Chile. The UK Gemini Supportgroup is based in Oxford and provides user support for all UK users of Gemini as well as some specialist support for the international Gemini community. The group also coordinates the UK scientific perspectives on the telescopes, instruments and operations and represents these to our international partners.

The first-light image of M74 from Gemini's GMOS instrument provides a taste of the ease with which superb quality scientific data can be obtained as Gemini moves into the phase of full operations.