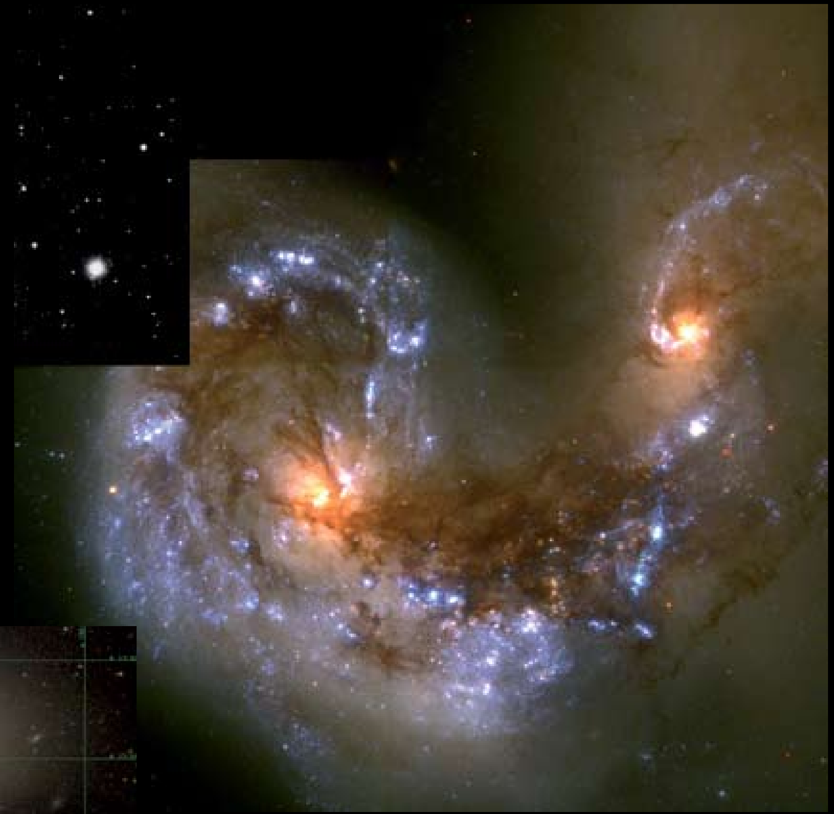
COSMIC ARCHAEOLOGY

NASA, ESA, S BECKWITH /STSCI, THE HUDF TEAM

The Hubble Ultra Deep Field. An image taken by a ground-based telescope would find this a blank region of the sky. However, when the Hubble Space Telescope exposed its Advanced Camera for Surveys for over 11 days a swarm of galaxies appeared. The colours give valuable information about both their distance and their formation process.

Dr Ignacio Ferreras, Lecturer in Astrophysics in the Department of Physics, ponders the question of how galaxies are formed.

Encounter and merging of two galaxies.
The larger image shows two disrupted progenitors 'dancing' around each other, leaving behind a trail of dust (dark red patches) and young stars formed by the interaction (blue clumps). A few billion years later, this system will look like an inconspicuous elliptical galaxy as shown in the smaller image (below). Galactic archaeology focuses on extracting the past history of a galaxy from observable clues left behind.



The dark side of galaxies.
A large fraction of the matter in a galaxy is in a component we cannot see directly with telescopes. We have to use indirect techniques to determine how much there is of this dark matter. The two figures above right show how gravitational lensing can be used for this purpose. Light from a far away background bright source is bent by the gravitational pull of the galaxy (the extended central source in the Hubble Space Telescope infrared images). This light-bending effect is similar to what a lens does. In this case multiple images of the background source are generated (the circular white dots). We can use these images to 'weigh' galaxies. The graphs below show that two galaxies with a similar content of stars and luminous matter have a very different contribution from dark matter.

Figure A

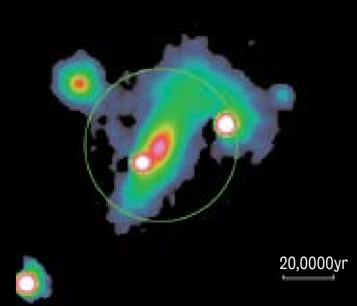


Figure B

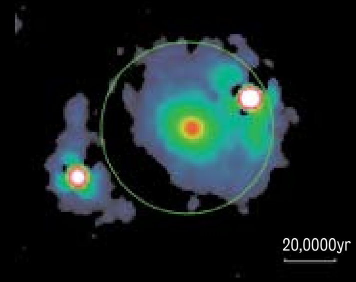


Figure C

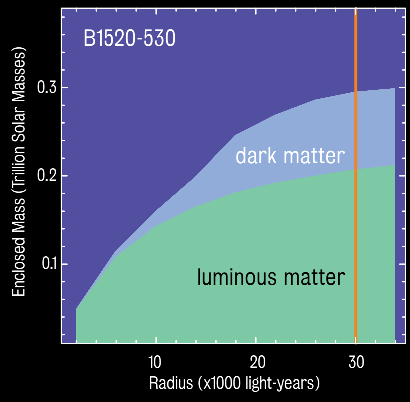
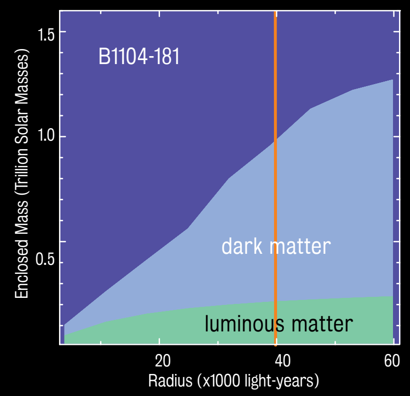


Figure D



Galaxies are the building blocks of the Universe. Like our own home galaxy – the Milky Way – galaxies are island universes mostly made up of gas (hydrogen and helium), dust and billions of stars. Understanding the formation and evolution of galaxies is one of the key questions of modern science.

Before the 1920s, it was not clear to astronomers what galaxies were. Through the telescope they looked like blurry smudges of light, comparable to other nebulous objects such as the Orion nebula, which is a cloud of gas within our own galaxy. It was the giant strides of astronomers such as Edwin Hubble and Allan Sandage that put galaxies in their proper perspective: showing them to be island universes as big as our own galaxy, living in a huge, ever expanding universe. In recent decades, developments in optics and solid-state physics have given us instrumentation capable of detecting galaxies so far away that the light we receive from them corresponds to an epoch when the Universe was just one tenth of its current age. The image on page 60 shows a picture of the deepest image of the sky: the Hubble Ultra Deep Field. There are ongoing as well as projected surveys that will gather a vast amount of information from millions of galaxies. Extragalactic astrophysics has flourished as a science at the frontier of our knowledge, bridging the gap between the very large and the very small. We now study the large-scale distribution of galaxies to find out about the properties of particles and fundamental physics.

Stars and galaxy formation

Because of the vast distances that separate galaxies, light is the only information we can gather from them. In order to study their formation process we use our knowledge of the theory of stellar evolution to determine the age of a stellar population by observing its spectral energy distribution (ie the distribution of light with respect to wavelength, or roughly speaking, its 'colours'). A recent burst of star formation generates stars over a wide range of masses: from very massive stars – 10 times that of the Sun – down to the smallest stars that can burn hydrogen to stay active – with masses around one tenth of the solar mass. The lifetimes of stars depend strongly on their mass. The very massive ones burn their fuel very quickly and die in a few million years, a much shorter interval than the life of a star like the Sun, which can live for 10 billion years. After a recent episode of star formation the light from a galaxy is dominated by the very massive stars. These stars have very hot atmospheres, appearing blue. A few million years later, these massive stars die, leaving behind the longer-lived lower mass stars which are cooler and therefore redder. Hence, we expect red and blue galaxies to represent old and young stellar populations respectively.

Galactic archaeology

Finding out the formation process of a galaxy from the light we receive from its stellar populations is the goal of galactic archæology. For nearby systems – like our own Milky Way and its galaxy satellites such as the Magellanic clouds – we can observe individual stars. By performing an analysis of these stars with respect to their age, velocity, and position in the galaxy, we can decipher the formation process. Distant galaxies are more complicated to study because the light we receive from them comes from unresolved stellar populations comprising millions, if not billions of stars. It's as if we tried to determine the history of London by observing a blurred image combining all its historical landmarks as well as modern buildings. Analogously to the invasions, revolutions and quiescent periods that shaped the present structure of London, one can also explore the episodes of formation of a galaxy that led to their actual spectral energy distribution. Of course one could not make an accurate estimate of the formation history of a single galaxy (or a single city). However, it is when we work with large samples that we can statistically determine the way galaxies form.

Recent projects such as the Sloan Digital Sky Survey (SDSS) have allowed such a study of galaxy formation. SDSS uses a dedicated, 2.5-meter telescope at Apache Point, New Mexico, to perform both photometry and spectroscopy of galaxies. In the first phase – recently finished – SDSS has mapped about 8,000 square degrees and obtained spectra from nearly 700,000 galaxies.

Late type

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Early type

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A tale of two galaxies. Even though galaxies come in many possible morphologies or forms, they can be generally classified into two general types. Late-type galaxies (above left) are blue galaxies with a significant ongoing process of star formation. In contrast, the light from early-type galaxies (below left) is dominated by old stars. Our goal at King's is to extract star formation histories such as those sketched in figure E from the spectroscopic data we can collect from telescopes shown in figure F. The shaded areas in figure F show characteristic spectral regions which are most sensitive to the ages of stars.

Figure E

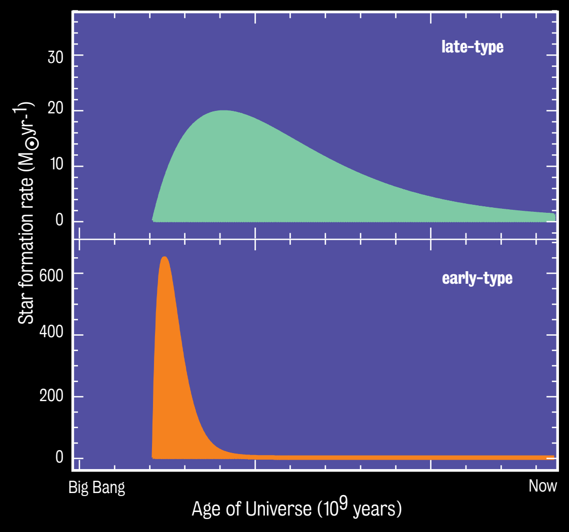
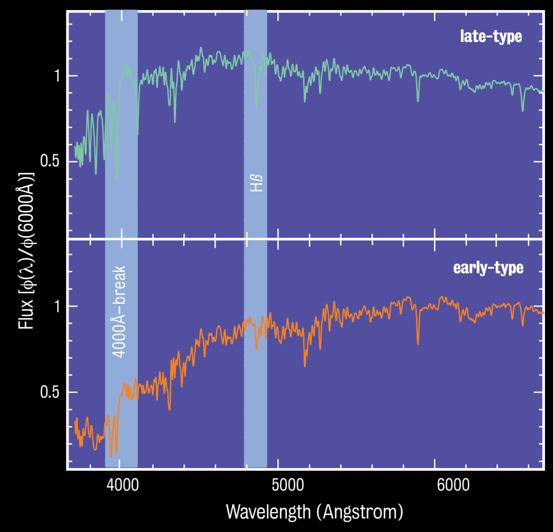


Figure F



Another way to perform galactic archæology is looking into the past. The light we detect from very distant galaxies corresponds to an epoch when the Universe was a fraction of its current age. SDSS is a wide-area survey but it cannot probe deep enough to look for distant galaxies. There are other surveys which follow a different approach, targeting smaller regions of the sky at a much deeper level. These so-called pencil-beam surveys, such as the Great Observatories Origins Deep Survey (GOODS), make use of NASA's Hubble Space Telescope in order to be able to resolve the shapes of distant galaxies. These galaxies represent the early stages of those seen by SDSS. Light from some of the distant GOODS galaxies left their 'home' when the Universe was just one tenth of its current age.

Formation

At King's we are currently working on subsamples both from SDSS and GOODS in order to explore the star formation history of galaxies. Our findings suggest that galaxies form their stars in two different models: a quiescent mode (like the current status of our Milky Way) and a runaway bursting mode, which is the way massive giant ellipticals were formed. The emergent picture is that of a Universe in which by the present time most of the stars in galaxies have been already formed. We live in an epoch in which only the cosmic leftovers are being transformed from gas into stars. Some galaxies are seen to be forming stars at a faster rate, but these so-called local starburst galaxies in no way compare with the formation process that took place eight to 10 billion years ago.

Telescopes can only show us the components of a galaxy that emit light. Hence, only stars, gas and dust are visible. Planets are much fainter, but in principle they could be seen using a powerful enough telescope. However, about 80 per cent of the total matter content in the Universe is of an exotic form – which has not been discovered yet. This dark matter neither emits nor reflects light. It is truly invisible matter that nevertheless exerts a gravitational force in galaxies, clusters of galaxies and the whole Universe. Unfortunately, its density is not high enough for detection in a laboratory. Only when vast, galaxy-sized regions are considered can one feel its effect. If it were not for dark matter, galaxies could not have been formed. Hence, a galaxy is made up of two main components: luminous (ordinary) matter and a tenuous dark matter halo that extends over much larger distances than the luminous component.

Elusive halo

In order to detect this elusive halo we probe indirectly its effect on the properties of the visible galaxy. At King's we are exploring the dark matter content of elliptical galaxies by using gravitational lensing. A ray of light only follows a straight path if there is no matter along its trajectory. However, matter curves spacetime, thereby bending (and delaying) the motion of light. Some galaxies happen to lie very close to the line of sight of very bright, far-away sources of light called quasars. These interloper galaxies act as 'lenses', curving light rays and often generating multiple images of these background quasars. By studying the multiple images of these systems we can determine the mass (ordinary plus dark matter) that is responsible for this gravitational lensing. Using the same images we can also determine the content in luminous matter. Along with collaborators at Queen Mary, University of London and the University of Minnesota, we have found that more massive galaxies have a much higher contribution from dark matter (see Figures C and D on page 63). The puzzle of galaxy formation is being slowly resolved, resulting in a complex mixture of dark and luminous matter; star formation and galaxy mergers, from local galaxies out to the very primordial density fluctuations left soon after the Big Bang. Edwin Hubble himself would be surprised at the enormous advances made by extragalactic astrophysics in the recent decades – and in the decades to come.

● *Dr Ferreras was one of 60 new staff appointed by King's in 2005-6 following a thorough strategic review of the College's research profile. A new strategic investment fund was agreed to enable the College to build upon areas of strength and comparative advantage, to help make King's a truly global player in many areas. Particular emphasis was placed on reinforcing King's ability to work across traditional academic boundaries and exploit the practical applications of research.*