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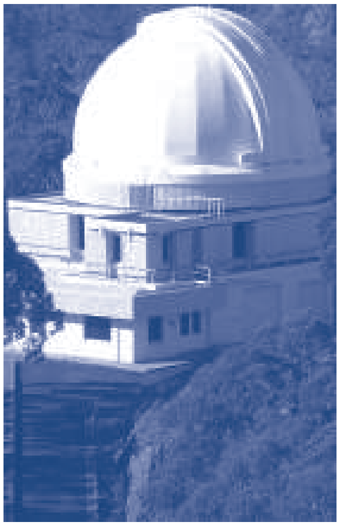
Scientific Highlights



Galaxy patterns reveal missing link to Big Bang

A large consortium of astronomers from the AAO, RSAA, ATNF, UNSW and the UK have been involved in a 10-year effort to map the 3D distribution in space of 220,000 galaxies using 2dF on the AAT. This 2dF Galaxy Redshift Survey (2dFGRS) has been carried out by a team led by AAO Director Dr Matthew Colless and Prof. John Peacock of the University of Edinburgh. The survey is almost ten times larger than any previous such study. Observations for the survey ended in 2002, and the survey is already the richest source of AAO scientific papers to date.

In January, 2005, the 2dFGRS consortium announced that it had found the ‘missing link’ that directly relates modern galaxies like our own Milky Way to the hot Big Bang that created our Universe about 13.7 billion years ago. The survey measured in detail patterns in the distribution of galaxies, on scales from 10 million to 1 billion light-years. Subtle features in these patterns were set by physical processes that operated when the Universe was very young, and reveal the ‘missing link’ between present-day galaxies and the Big Bang. The 2dFGRS result has been independently corroborated by the US-led Sloan Digital Sky Survey (SDSS), which made use of a different method to obtain a consistent result.

Matching ripples

Theorists in the 1960s suggested that the primordial seeds of galaxies should be seen as ‘ripples’ – a pattern of hotter and cooler spots – in the cosmic microwave background (CMB). This CMB is heat radiation left over from the Big Bang. We see the CMB as it was when the Universe was only about 300,000 years old. The ripples in the CMB were first seen in 1992 by NASA’s COBE satellite, and revealed in greater detail by the WMAP satellite (see below). Until now, however, no-one had been able to definitely show how they were connected to galaxy formation. Astronomers use a statistic called the ‘power spectrum’ to mathematically describe the pattern of spots in the CMB. A plot of the power spectrum has peaks and troughs in it, and describes how the spots are clustered on different scales. The 2dFGRS team has produced the same kind of power spectrum for the galaxies that it mapped out, and for the first time found a high-confidence match between the galaxies and CMB power spectra. This confirms that gravity was the driving force that created today’s galaxies.

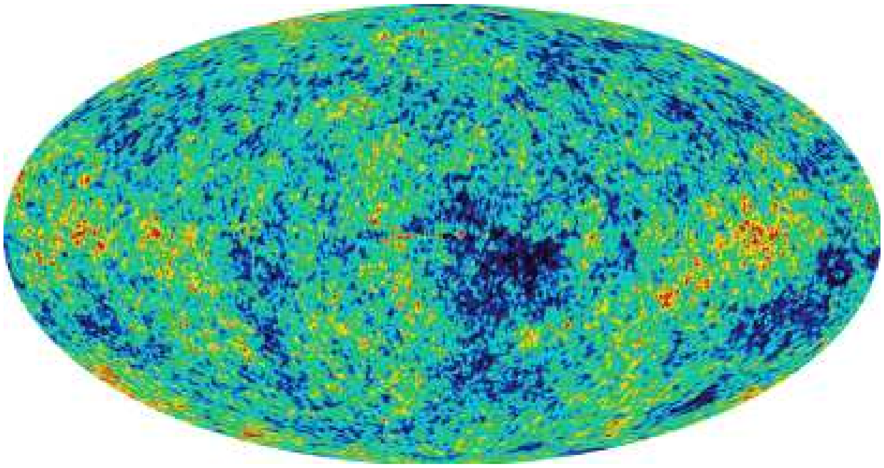
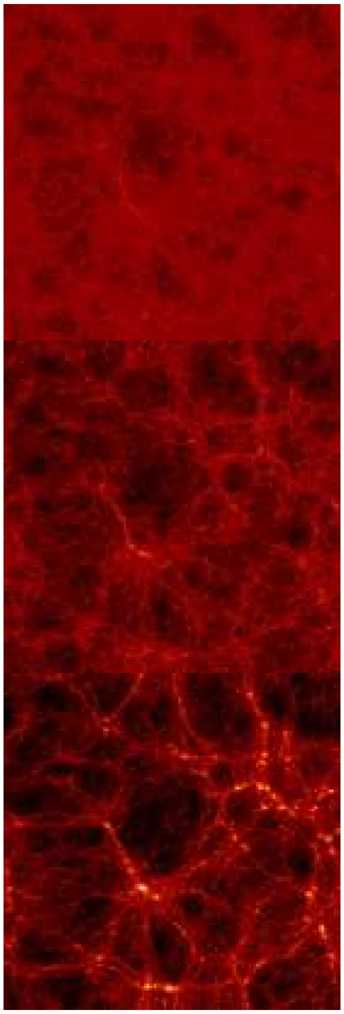


Image of the Cosmic Microwave Background, emitted 380,000 years after the Big Bang, (photo: WMAP Science Team / NASA)



Above: Computer simulation of matter forming into galaxies. The top picture is the furthest point back in time, redshift 3, the middle picture is a mid-point and the bottom picture simulates the structure at redshift zero, the present day. (photo: (c) Virgo Consortium)

Weighing the Universe

The same features in the power spectrum have also allowed the 2dFGRS team to 'weigh' the Universe with unprecedented accuracy. These features – called the "baryonic wiggles" – contain information about the contents of the Universe; in particular about the amount of ordinary matter – particles called baryons – that makes up stars, planets and people. The 2dFGRS has shown that baryons are a small component of our Universe, making up a mere 18% of the total mass. The remaining 82% is dark matter. For the first time, the 2dFGRS team has measured the density of matter in the Universe with an uncertainty of less than 10%.

Furthermore, the 2dFGRS has also shown that all the mass in the Universe (both luminous and dark) is outweighed 4:1 by an even more exotic component called "vacuum energy" or "dark energy". This opposes gravity, causing the expansion of the Universe to speed up. This conclusion comes from combining 2dFGRS results with data on the cosmic microwave background radiation. The origin and identity of the dark energy remains one of the deepest mysteries of modern science. Astronomers believe they could find clues to the identity of dark energy by identifying baryon wiggles in the pattern of galaxies that existed when the Universe was half its present age. They are now planning huge galaxy surveys to do this.

The 6dF Galaxy Survey

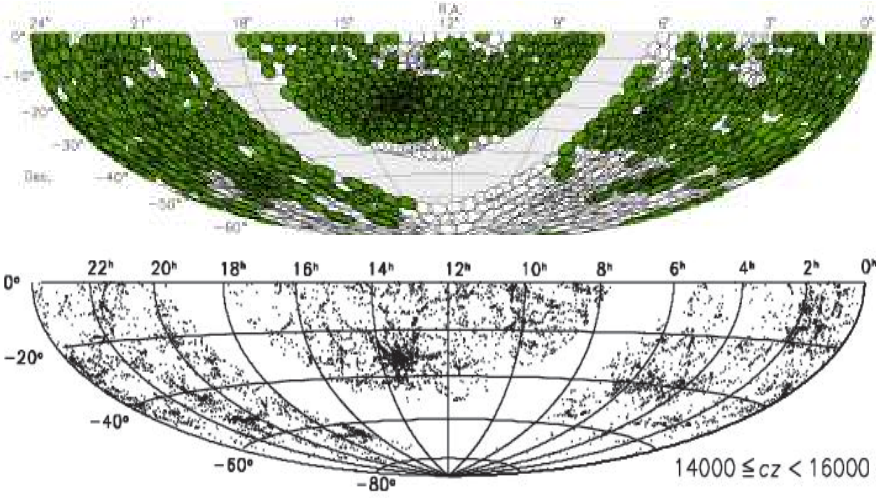
The measured velocity of a galaxy is a combination of the velocity due to the expansion of the universe (redshift), and its local motion due to the gravitational pull of neighbouring galaxies (peculiar velocity). The two facets of the 6dF Galaxy Survey (6dFGS) are a redshift survey of around 150,000 galaxies over the southern sky, and a peculiar velocity survey of a subset of 15,000 of these galaxies. When complete, it will be the largest survey of its kind by more than an order of magnitude. In terms of sky coverage, the 6dFGS will ultimately cover 8 times the area of the 2dF Galaxy Redshift Survey and twice that of the Sloan Digital Sky Survey.

Local mapping, galaxy formation and cosmology

The aims of the redshift survey are to investigate how galaxies are distributed by mass, luminosity, galaxy type and environment; to measure the clustering of galaxies on both small and large scales; and to further investigate cosmological measures of the universe like the power spectrum, and the large-scale structure of dark matter.

The peculiar velocity survey requires higher sensitivity measurements, and will provide a detailed mapping of galaxy velocities over a much larger area than ever before, covering about half of the local universe. The histories and properties of elliptical galaxies can be derived, spanning the smallest (dwarfs) to the most massive, which will be of key interest to modellers of galaxy formation. Finally, the “bias” of galaxies, or their number distribution compared to the distribution of total mass, can be measured to see how it varies with galaxy properties and environment.

Left: The Hydra cluster of galaxies, (photo: D. F. Malin, (c) AAO)



Top: The Second Data Release (DR2) takes its data from 936 fields. This figure shows that their distribution is true to the observing strategy adopted by 6dFGS from the outset: mid-latitude fields were tackled first, followed by those nearest the equator and finished with the polar targets. Bottom: Shows the distribution of DR2 redshifts on the sky for a small fraction of the total sample in the redshift slice indicated. Many local large-scale structures (such as the Shapley Supercluster) can be seen in what is the most detailed and comprehensive view of the southern local universe to date.

Public data release

In 2004 the 6dFGS team continued into the third year of this survey, which uses the fibre spectrograph 6dF on the UKST. Observing for the 6dFGS nominally finished on 31 July 2005, although some clean-up observations will take place during the remainder of 2005.

The 6dFGS data are made public at approximately yearly intervals, with Early and First Data Releases (DR1) having taken place in December 2002 and March 2004 respectively. Most recently, the Second Data Release (DR2) spans observations during the period January 2002 to October 2004, including and superseding DR1. It contains 89211 spectra that have yielded 83014 unique galaxy redshifts over roughly two-thirds of the southern sky. A total of 71627 sources now have their spectra, redshifts, near-infrared and optical photometry available online and searchable through a database at http://www-wfau.roe.ac.uk/6dFGS/. A third and final data release will be made in 2006.

RAVEing with the UK Schmidt

The largest catalogue of star velocities

RAVE is a major international project to measure the radial velocities (line-of-sight speed) and metallicities (chemical composition, linked to age) of up to a million stars in our Galaxy. The acronym stands for RAdial Velocity Experiment, and its end product will be new knowledge about the composition and history of our Galaxy, and a greater understanding of how other galaxies form.

The task is being accomplished with the AAO's 1.2 metre UK Schmidt Telescope. It will result in the largest catalogue of star velocities ever produced. Since the start of the project in April 2003, some 70,000 stars have been measured, more than twice the total number of measurements that existed before RAVE started.

A new direction for the UK Schmidt Telescope

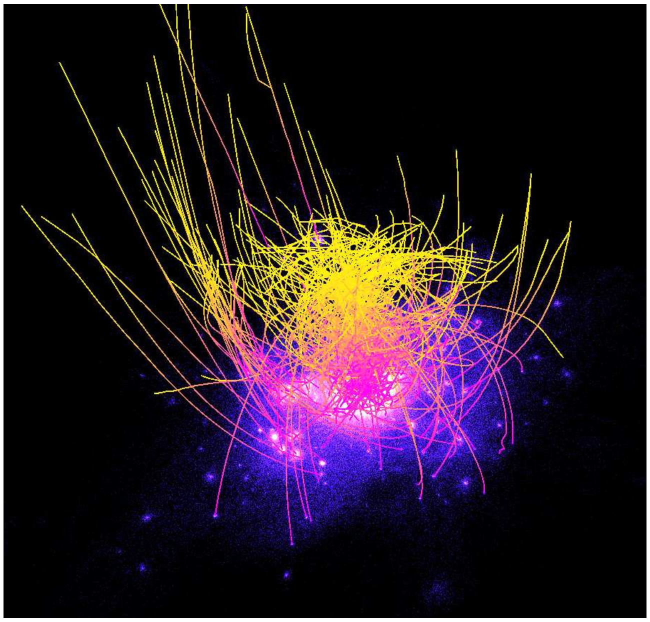
The recent completion of the UK Schmidt Telescope's other major project, the 6dF Galaxy Survey, has brought to an end the telescope's funding by the Australian and British governments. It now receives its operational funding entirely from the RAVE project, although the instrument will continue to be run by the AAO. RAVE observations now occupy the telescope full-time, and we expect to measure up to 130,000 stars per year. The project is supported by scientists from ten participating nations: Australia, Canada, France, Germany, Italy, the Netherlands, Slovenia, Switzerland, the UK and the USA.

The history of our Galaxy to be revealed

The scientific questions that RAVE scientists want to answer are centred on the dynamical history of our Galaxy – how the large-scale motions of stars have evolved to become the way we see them today. For example, the halo of our Galaxy (a spheroidal mass of stars, globular clusters and dark matter) is thought to have been formed by the disruption and accumulation of many small satellite galaxies. The stars that came from these devoured satellites still carry a memory of their origin with them in their orbits through space. Thus, analysis of the velocities of very large numbers of stars allows a kind of galactic archaeology to be carried out: stars with a common origin can be disentangled from the mass by their common velocities, and also their similar chemical signatures.

Weigh a spiral arm

In the broadest sense, RAVE is designed to allow a comparison of what we see in our Galaxy today with what simulations of galaxy formation predict. Other questions the survey will address include the chemical history of the Galaxy, the origin of the so-called ‘thick disk’ (a rarefied layer of stars above and below the main disk), and the origin of the bulge at the Galaxy’s nucleus. The idea of ‘weighing a spiral arm’ (by analysing the motions of stars within it) is also one that has caught the imagination of RAVErs, and will probably be one of the first significant results to come from the survey.



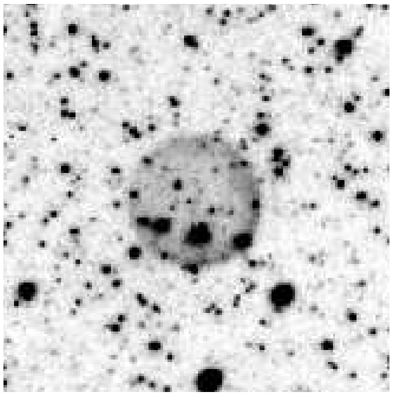
During its early history, dozens, if not hundreds, of satellite galaxies were in orbit around the Milky Way. As they are absorbed by our Galaxy, the satellites are torn apart by tidal effects. However, their member stars still retain the fossil memory of their original motion, shown here by the spaghetti-like flight paths of the satellites.

The AAO/UKST H-alpha Survey: A Rich Source of New Discoveries

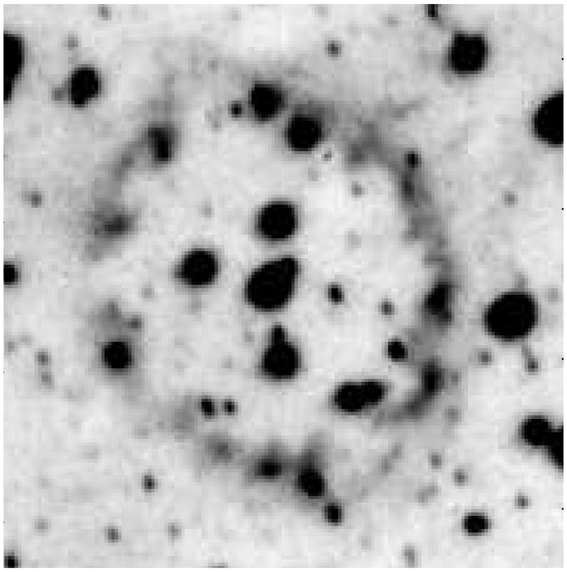
The AAO's UK Schmidt Telescope (UKST) completed the H-alpha Survey of the Southern Galactic Plane and Magellanic Clouds in late 2003. A narrow-band filter was used to target hydrogen and nitrogen emission associated with hot gas and stars. This filter is the world's largest interference filter in use in astronomy. The survey was the last UKST wide-field photographic survey and the only one undertaken in a narrow-band. The survey covers a very large area of the sky (4000 square degrees) at high resolution and sensitivity. The original survey films were scanned by the SuperCOSMOS measuring machine at the Royal Observatory, Edinburgh (ROE), to provide the online digital atlas called the SuperCOSMOS H-alpha Survey (SHS), which is now an online digital data product of the Wide-Field Astronomy Unit of the ROE. A variety of programs are now underway to exploit the scientific potential of this new resource.

Greater understanding of Planetary Nebulae

The largest project arising from the AAO/UKST H-alpha survey has been the Macquarie/AAO/Strasbourg H-alpha planetary nebula project, led by Quentin Parker (AAO/Macquarie), which has uncovered about 1000 new Galactic planetary nebulae, nearly doubling the sample accrued from all sources over the last century. A planetary nebula is the end product of a low – to moderate-mass star, which expels its outer gas envelope to form a gaseous nebula around the star. Eventually the remaining star becomes a white dwarf. Other



Above: A newly discovered planetary nebula (PHR1706-3544) from the 3-hour – H-alpha survey data. This nebula is not visible in the standard broad-band surveys.



Right: The highly unusual ring nebula (PCG11) around a newly-discovered WN star. The ring has a regular scalloped appearance, with fingers of gas pointing towards the center. This is the pattern expected for a shell of gas which has undergone gravitational instability. This is the clearest and most complete example yet known.

discoveries of planetary nebulae (PNe) include: a possible new phase of PNe evolution; a very large PN in an early stage of interaction with the interstellar medium; two very large bipolar PNe previously misidentified as HII regions; and a new sample of old, highly evolved PNe which have spread out over a large area and are now very faint and difficult to find.

A wind-speed record and a scalloped shell

The SHS atlas has also been used to search for HII regions, or hot gas clouds, and the remnants of supernova explosions. Most recently, groups of astronomers have searched for emission line stars detected in the survey. Other methods of observation, such as spectroscopy, are used to classify and study these new objects. One particularly interesting object is just the fourth known massive WO star in the Milky Way Galaxy. These exceedingly rare stars are the most chemically extreme Wolf-Rayet stars, and they may explode as unusually powerful supernovae or even gamma-ray bursts. WO stars lose material in fast stellar winds, and the new star is estimated to hold the current wind-speed record for a non-degenerate star. Another interesting find is a WN star with a scalloped shell around it (see above). This highly regular pattern is due to gravitational instabilities, and while the effect is seen in other objects, the WN star is the only example of a *complete* shell of these instabilities, on any observable spatial scale.

Eclipsing binary stars in the Small Magellanic Cloud

The fuzzy patches of light in the night sky of the far Southern Hemisphere called the Magellanic Clouds are well known to be companion galaxies to the Milky Way Galaxy. The Large Magellanic Cloud (LMC), at a distance of about 50 kpc, and the Small Magellanic Cloud (SMC), at about 60 kpc, are sufficiently close to us to allow our present-day technology to provide separated images of stars in most parts of both galaxies. These satellite galaxies are important first steps in establishing the cosmological distance scale, because they allow us to use stellar distance calibrators that are well understood in our own Galaxy (e.g. Cepheid variable stars, red-giant stars, star clusters, eclipsing binaries) to determine their distances from us. Unfortunately, the various methods have not exactly agreed in the past, revealing systematic differences at the 10% level which most astronomers consider to be unsatisfactory.

Technological advances improve accuracy

Two technological advances of the past decade have allowed eclipsing binaries to be used as distance calibrators to nearby galaxies where the stars are faint because of their large distances from us. The MACHO and OGLE projects used arrays of CCD detectors mounted on small telescopes in Australia and Chile to obtain direct photometric images of the LMC and SMC. The by-product of both surveys was the discovery of large numbers of variable stars in both galaxies, including thousands of eclipsing binaries. The quality of the photometry was so good, and the MACHO and OGLE research teams so efficient, that the orbital periods of these binary stars were determined to 1 part in 100,000, and the resultant light curves were

Right: A photograph of the Small Magellanic Cloud (SMC) taken with the UKST (photo: AAO/ROE) defined to uncertainties of 1-2%. The second technological advance was the development of the multi-object spectrograph on the AAT known as 2dF. This instrument uses 400 optical fibres that may be positioned over a two-degree field of view (2dF) to receive the light from up to 400 individual stars and feed it through a spectrograph to record their separated spectra simultaneously, vastly increasing the observing efficiency.

Astrophysical properties found for 50 binaries

Ron Hilditch (St Andrews), Ian Howarth (UCL), and Tim Harries (Exeter) have carried out a project on eclipsing binaries in the SMC using the OGLE light-curve database and 2dF instrument to record thousands of spectra of more than 150 eclipsing binaries with orbital periods less than 5 days (that is, the two stars in each binary are close together, separated by only 1-2 stellar radii). They obtained enough spectroscopic observations on 50 eclipsing binaries to determine the orbital velocities of both stars in each binary. These results were combined with analyses of the binaries' OGLE light curves to determine the complete astrophysical parameters for each binary: that is, the masses, radii, temperatures and luminosities of both stars in each binary. The result is the largest single survey of the properties of intrinsically luminous high-mass binary stars ever achieved in any galaxy. These data are now being used as tests of the theories for the interactive evolution of stars in close binary systems in a galaxy with low heavy-element abundances and a different star formation history from our Galaxy.

Independent measures of distance to the SMC

The survey has also provided 50 independent measures of distance to the SMC, as the distance to each binary can be calculated directly from the binary parameters, with the usual correction for extinction. The SMC is a three-dimensional object which, from studies of Cepheid variables, may be approximated as a tilted rugby football shape with one end of the long axis about 14 kpc nearer to us than the other end. The eclipsing binaries were concentrated nearer the central parts of the galaxy where the line-of-sight depth is ~3 kpc according to the binary results and those of Cepheids. Hilditch, Howarth and Harries find a mean distance to the SMC of 60.6 +/- (1.0, 2.8) kpc (internal and external uncertainties), one of the most precise determinations to date. AAOmega, the new AAO instrument that supersedes 2dF, should allow the group to extend this work to many more eclipsing binaries in both the SMC and the LMC in the near future.

Sniffing out brown dwarfs

The discovery over the last ten years of over 150 planets orbiting other stars has excited astronomers and revolutionised our understanding of how planets form. Unfortunately, almost every single one of these planets has been detected by indirect means – that is, astronomers have not observed light coming from the planets themselves, but rather the effects those planets have on the light coming from their host star. As a result, although astronomers can estimate masses and orbital parameters for these planets, they can't study the planets themselves in the same way that they can study solar system planets.

Brown dwarfs the key to studying extrasolar planets

The best proxy for studying these "indirect" gas giant planets, with masses ranging from one-tenth to ten times that of Jupiter, are the objects known as "brown dwarfs". Brown dwarfs are failed stars – objects formed in the same way as stars, but with masses between 10 and 80 Jupiter masses, making them too small to ignite the nuclear reactions seen in stars. As a result they share many properties with gas giant planets. They are relatively cool (surface temperatures of 500-1500 degrees), very faint, and have highly complex atmospheres containing rich mixtures of molecules (e.g. water and methane) and dust.

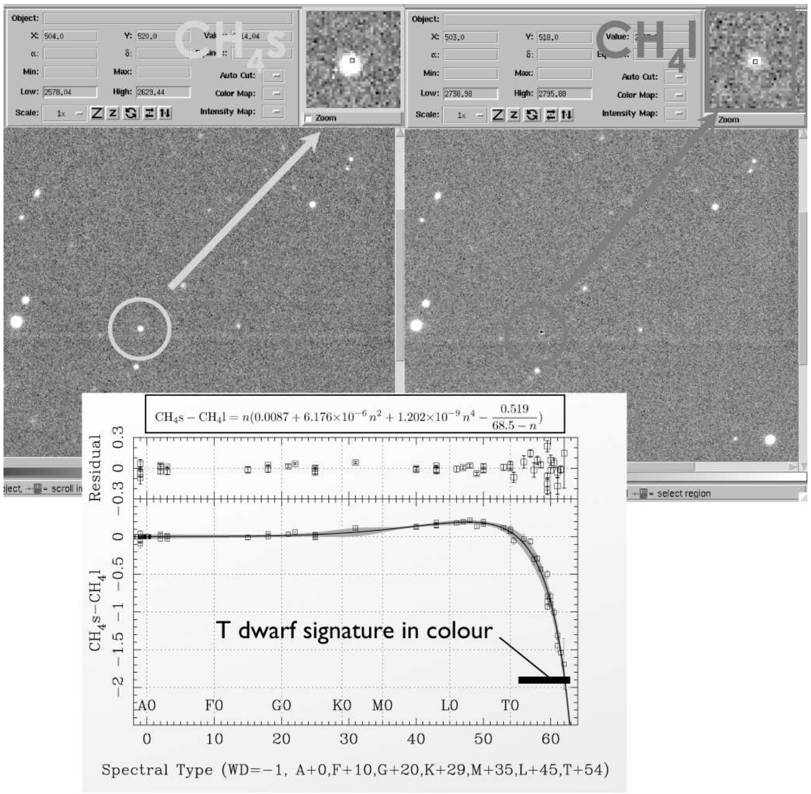
Unfortunately, finding brown dwarfs is almost as hard as finding extrasolar planets – they too only started to be discovered in the last decade, and there are now just a few hundred brown dwarfs known. The coolest and most interesting brown dwarfs are the hardest to find, and a lot of large telescope time has been used in the search for new examples.

Left: an artist's impression of how one of the new gas giant planets might look from one of its moons, (photo: (c) David A. Hardy / www.astroart.org)

Methane filters on IRIS2 reveal new T-dwarfs

Astronomers using the AAT have developed an entirely new way in which to hunt out these rare objects, using a dedicated set of methane filters installed in the IRIS2 instrument. These filters isolate the strong methane absorption bands seen in the coolest "T-type" brown dwarfs, allowing them to be readily separated from the rich background of much more numerous non-brown dwarfs. Moreover, not only do these filters identify these brown dwarfs, but the calibration system developed for the filters with IRIS2 allows their location within the sequence of T dwarfs to be immediately calculated. Using this new system, Chris Tinney and Simon Ellis of the AAO, together with collaborators Adam Burgasser (AMNH), Michael McElwain (UCLA) and Davy Kirkpatrick (IPAC), have identified and studied eleven new T-dwarfs, several of which lie in a new and potentially extremely important class of "K-band suppressed" T dwarfs.

Below: A section of sky observed through two different methane filters. While other stars stay much the same, the T-dwarf is much fainter in the right image, so it is easy to identify. (Inset): The graph panel shows how the difference between filters (or colours) can then be used to estimate the spectral type of the T dwarf from the hottest (T0) to the coolest (T8).



Asteroseismology of alpha Cen A

Asteroseismology, the measurement of stellar oscillations, is a beautiful physics experiment. A star is a gaseous sphere and can oscillate in many different modes. The frequencies of these oscillations depend on the sound speed inside the star, which in turn depends on density, temperature, rotation and chemical composition of the stellar interior. The five-minute oscillations in the Sun have provided a wealth of information about the solar interior. The Sun oscillates in many modes simultaneously and comparing the mode frequencies with theoretical calculations has led to significant revisions to solar models. It is widely expected that measuring oscillation frequencies in other stars will produce similar advances. Indeed, it is fair to say that theorists have been waiting eagerly - and with some frustration - for the first oscillation data to appear. The difficulty lies in the tiny amplitudes: only about 20 cm/s for the strongest modes in the Sun.

Oscillations observed in Sun's twin

T. Bedding (U. Sydney), R. P. Butler (Carnegie), H. C. Kjeldsen (Aarhus), C. McCarthy (Carnegie), G. W. Marcy (Berkeley), S. J. O'Toole (Erlangen), C. G. Tinney (AAO), and J. T. Wright (Berkeley) have observed oscillations in the star alpha Centauri A. This star is a near twin of the Sun but is slightly more massive, making it an excellent test for asteroseismology. Oscillations of alpha Cen A were first measured by Bouchy and Carrier using the CORALIE spectrograph in Chile. They were able to measure some of the oscillation frequencies, but with only one telescope they were limited by the ambiguities inherent in single-site data. Continuous coverage is important for disentangling the beating between different oscillation modes.

Most precise velocities ever measured

The new observations were made with both UCLES at the AAT and UVES at the VLT and were the most precise stellar velocities ever measured. This high velocity precision was obtained by using an iodine cell as a wavelength reference, the same technique that has been so successful in finding planets around other stars. It proved possible to extract frequencies for 42 separate oscillation modes and determine their amplitudes (most around 20-30 cm/s) and also to make the first estimate of mode lifetimes (slightly shorter than in the Sun). The group have since gone on to measure oscillations in the B component of this system, again with UCLES and UVES, and are now making detailed comparisons with theoretical models.