

# F. Staff research

This section describes the research activities of staff at the Anglo-Australian Observatory, where not already covered in Chapter 3. In addition to providing support for the Observatory, the scientific staff pursue their own research programs. Staff make extensive use of the Anglo-Australian Telescope (AAT) and UK Schmidt (UKST) facilities and also use many other research facilities such as the radio telescopes operated by the Australia Telescope National Facility, the Hubble Space Telescope and the telescopes of the European Southern Observatory.

## The Keck, Lick, and Anglo–Australian Extrasolar Planet Surveys

Within the last three years, planets have been discovered around 12 nearby Sun-like stars. All of these planets have been revealed by small periodic Doppler variations in the spectra of their host stars. The planets detected to date have profoundly challenged the theories of planet formation, with the discoveries of Jupiter-mass planets in very small (four-day) orbits, and Jupiter-mass planets in extremely eccentric orbits. Only the 47 Ursae Majoris system, with a Jupiter-mass companion in a circular orbit with a period of several years, reminds us of the Solar System.

Now that planets have been detected, we would like to know what fraction of stars have planets, what fraction of planetary systems are similar to the Solar System, and how many other types of planetary systems exist. Toward this goal, Butler and Tinney (AAO), and their collaborators are carrying out surveys of all 800 of the nearest, brightest Sun-like stars using the Lick 3-m (California), Keck 10-m (Hawaii), and the Anglo-Australian 4-m telescopes. The precision of their velocity measurements, of 3 metres per second, is sufficient to detect Saturn-mass planets within five astronomical units, and Neptune-mass planets within one astronomical unit. During the year, three further planets were detected, bringing the total discovered in this program to nine.

This research project was awarded the International Astronomical Union Bioastronomy Medal.

## Studies of Brown Dwarfs and very low mass stars

Tinney (AAO), Forveille and Delfosse (Grenoble), have continued their study of brown dwarf candidates from the DEep Near Infrared Survey (DENIS) being carried out at La Silla, Chile. Using the AAT, they have obtained optical and infrared spectra of a sample of brown dwarf candidates from the first one per cent of the DENIS data. They have not only used this data to discover the first isolated field brown dwarfs, but have shown that an entirely new spectral class needs to be created for the faintest objects found in this survey. These objects — the L dwarfs — fit into none of the canonical OBAFGKM spectral types usually used. Their atmospheres are dominated by the production of perovskite ( $\text{CaTiO}_3$ ) and vanadium oxide dust, leaving only caesium and chromium hydride features behind in their spectra. This means that the material which is responsible for the features usually seen in cool stars is being depleted into dust. Consequently, radically different spectra of a type never seen before are produced.

Tinney (AAO), Reid (Palomar) and Hawthorn (AAO) have continued using the AAO's Taurus Tunable Filter (TTF) facility to search for brown dwarfs in nearby young star clusters. The TTF is ideal for selecting brown dwarf candidates in these crowded regions, because it can efficiently identify stars emitting in the Balmer hydrogen-alpha line. This line is present in young stars and brown dwarfs, but not in the majority of field stars. So the TTF selects only the members of interest in the cluster. Two nearby clusters (IC 2391 and IC 2602) have now been surveyed in this way, producing a list of possible brown dwarf members. The next step in this program is to use the two-degree field

facility (2dF), to confirm the success of this new selection technique. Successful confirmation with 2dF would give enough confidence in the new selection process to do away with the need for follow-up spectroscopy.

Tinney (AAO) and Reid (Caltech) have completed a study of the kinematics of the lowest mass stars. They were trying to see if they could confirm the suggestion by numerous authors that there exists a population of young brown dwarfs near the sun, which are masquerading as M-dwarfs. They found no kinematic difference between the population of the lowest mass stars, and more massive M-dwarfs. In the course of this study, they acquired a set of quality high-resolution spectra for the lowest mass stars near the sun. They were able to analyse this data to produce two interesting results. First they found that the 'star' LP944–20, previously thought to be an ordinary M-dwarf, is in fact a brown dwarf with a mass of  $0.060 \pm 0.004$  solar masses, and age about  $560 \pm 90$  million years. Secondly, they found that the same object shows an extremely rapid rate of rotation. This makes it the second of a growing class of objects at, or below, the bottom of the hydrogen burning main sequence which show very rapid rotation, and very little signature of dynamo activity.

Tinney (AAO) has begun a study of brown dwarfs, almost of all of which are now known to be quite rapidly rotating. To date, rotation signatures have been based on the observed broadening of spectra. However, this only tells us how rapidly the star is spinning to within an unknown inclination factor — the so-called  $v \sin i$  factor, where  $v$  is the rotation velocity and  $i$  is the unknown inclination angle. A photometric study looking for signatures of rotation offers the possibility of measuring the period, and deriving  $\sin i$ . Tinney has therefore pioneered using the TTF in a time-series mode to seek the signatures of cool patches (either dust clouds or star spots) traversing the disk of several nearby brown dwarfs. As dust clouds are now known to play an important role in brown dwarf atmospheres, this offers the tantalising prospect of the study of 'weather' on other stars.

## Magnetic White Dwarfs

Ferrario, Vennes, Wickramasinghe (ANUATC), Bailey (AAO) and Christian (Berkeley) have obtained spectropolarimetric observations for the source EUVE J0317–855. This is a rapidly rotating white dwarf with a strong magnetic field which was first detected as an extreme ultra-violet source by the EUVE and ROSAT satellites. A strongly structured, circular polarization spectrum with polarizations of up to about 8 percent is observed. The data can be modeled as the result of a dipole field of strength 450 million Gauss displaced from the center of the star by 35 percent of the stellar radius. The high mass and rapid rotation suggest that this star may be the result of a double degenerate merger.

Ferrario, Wickramasinghe (ANUATC), Bailey (AAO) and Buckley (SAAO) have continued to work on magnetic cataclysmic variable stars found by the X-ray satellite ROSAT. Spectropolarimetry of the intermediate polar RX J1712–2414 shows circular polarization of several percent and was taken with sufficient time resolution to study variations during the white dwarf rotation period of 927 seconds. Polarimetry of the eclipsing polar RX J0929.1–2404 has been used to derive a model for the emission regions on two poles, and determine a magnetic field of 20 million Gauss.

## Pre-main-sequence stars

Bailey (AAO) has continued his program of studying pre-main-sequence stars using the technique of spectro-astrometry as a way of detecting close binaries and studying the outflows around these sources. The method has shown itself capable of detecting close binary systems with separations larger than around 100 milli-arcsec. This is the resolution limit of infrared speckle interferometry which has been the technique most widely used to resolve close binary systems in the past. Using spectro-astrometry, Bailey should be capable of detecting even closer binaries. The pre-main-sequence star T CrA has been confirmed as a new binary and may have a short enough period for orbital motion to be detected. A program of radial velocity measurements has been started to provide further observation on binaries discovered using this technique.

## Chemistry in molecular outflows

Bourke (AAO/ATNF), in collaboration with Garay (Chile), Bergin (SAO) and Caselli (Arcetri), has begun an intensive study of the chemistry within the molecular outflow from the low mass protostellar source IRAS 11590–6452 using the SEST telescope. This outflow is one of only a few to show significant abundance enhancements of SiO and CH<sub>3</sub>OH. These are due to the destruction of dust grain mantles and the wearing away of grain cores through shock activity. The ongoing study includes observing a large number of molecular species and transitions at millimetre wavelengths to determine abundances, temperatures and densities within the outflow, and the development of shock chemistry models to explain the observations.

Bourke, with McGregor (MSSSO), Robinson (ADFA), Hyland (SCU), have imaged the full length of the molecular outflow from the source IRAS 11590–6452 in the 1–0 S(1) and 2–1 S(1) molecular hydrogen transitions at 2 microns with CASPIR (MSSSO) and IRIS at the AAT, to determine if this emission is in fact solely due to shocks and to investigate whether the excitation conditions vary throughout the outflow. This data, together with previous H and K spectroscopic data obtained with IRIS, will also be used to investigate temperature variations at the shock locations. Modelling of these data will allow the group to determine whether C- or J-type shocks, or some combination of the two, are present.

## Magnetic field strengths in molecular clouds

The extent to which magnetic fields play a part in the evolution of molecular clouds and star formation is possibly the greatest outstanding question in star formation studies. Observationally, the difficulty is measuring magnetic field strengths in the dense molecular cloud cores in regions of direct interest to star formation studies. So far a few molecular clouds have been studied in detail with the VLA (e.g. W3(OH), S106, Orion) and their magnetic field strengths imply that they are in an approximate critical balance between gravity and magnetic energies. However, there is a sufficient number of upper limit measurements to imply that the magnetic fields are not important in the support against gravity in many, if not most, molecular clouds.

Bourke, with Myers (SAO), Robinson (ADFA) and Hyland (SCU) have undertaken a program to measure the large scale magnetic field strengths in a sample of southern and northern molecular clouds with the Parkes radio telescope and the NRAO 140-foot telescope. By measuring the Zeeman effect in the thermal-ground state OH transitions at 1.6 GHz, the magnetic field strength in the molecular gas can be determined. For a sample of about 20 clouds, they have detected the Zeeman effect in only 1 or 2 sources. The upper limits for the remaining sources imply that the magnetic fields certainly do not dominate the cloud physics, and in some cases cannot be important in long term cloud support. Follow-up observations with the ATCA and VLA are planned to examine the small-scale field structure within the sample.

## Asteroseismology

The analysis of stellar oscillations provides a powerful method for studying stellar interiors. Stars are gaseous spheres which, in some circumstances, may be excited into many different radial and non-radial oscillation modes. Asteroseismology uses the analysis of stellar oscillations to provide information on stellar interiors, such as their composition, mixing properties, ages and internal rotation. Medupe, Kurtz (SAAO), Chapman (AAO/ATNF), Bedding and Baldry (Sydney) have begun a program in which the AAT high resolution echelle spectrograph (UCLES) has been used to observe two rapidly oscillating A-type (roAp) stars, HR3831 and  $\alpha$  Circinus, which have pulsation periods of approximately 10 minutes. Several thousand high signal-to-noise UCLES spectra were obtained at the AAT. These data are being analysed to look for radial velocity and line profile variations in the stellar absorption lines. Line profile variations have not previously been detected

from rapidly oscillating stars. Their detection would not only enable pulsation mode identification, but would also provide information on the stellar magnetic fields and the interaction between the magnetic fields and the stellar pulsations.

## Mass-loss from evolved stars

Chapman (AAO/ATNF), Cohen (Jodrell Bank), Habing and Bouter (Leiden) have used the Australia Telescope Compact Array (ATCA) to search for OH maser emission in 40 fields in the Galactic bulge. Each field covered a region of  $15 \times 15$  arcminutes. A total of 30 maser sources were detected above a threshold of 0.25 Jy. All the maser sources are identified as evolved stars with strong circumstellar winds. The data have been used to study the detection statistics for OH maser emission from evolved stars. A long-standing issue has been to explain the low detection rates for OH masers from highly evolved stars which have infrared colours that indicate high mass-loss rates. For the bulge sample, the sources detected in OH have redder infrared colours and stronger far-infrared flux densities than the non-detections. The OH masers are pumped by far-infrared photons emitted by dust grains. Chapman et al. find that the efficiency of the pumping process varies over a large range and this is the likely reason for the low detection rates of stellar masers.

Chapman (AAO/ATNF), Leitherer (STScI), Bouter (Leiden), Koribalski (ATNF) and Storey (RCfTA) are studying the stellar winds from Wolf-Rayet stars. They have used the ATCA to measure the radio continuum flux densities at 3, 6, 13 and 20 cm from a sample of 36 southern Wolf-Rayet stars within three thousand parsecs of the Sun. A key result from this study is that at least 40 percent of Wolf-Rayet stars have non-thermal radio continuum emission. Comparison of the radio data with recent high resolution HST images show that 80 percent of the non-thermal sources have an identified massive binary companion star which also has a strong stellar wind. In most, if not all cases, the non-thermal emission arises from an interaction zone where the winds from the two stars collide with each other, producing high temperature shocked gas and synchrotron radio emission. The non-thermal emission may be variable and partially absorbed as it passes back through the ionised stellar wind of the nearer star. Wind-wind interactions appear to occur for binary systems with a large range of separations. Indeed, the strength of the non-thermal emission appears to be largely independent of the separation of the two stars.

## X-ray emission from stars

Johnston (AAO), Fender (Amsterdam) and Wu (Sydney) observed the bizarre X-ray binary Cir X-1 at optical and infrared wavelengths. This binary system contains a neutron star in a highly eccentric 16-day orbit, the longest known orbital period for a low-mass X-ray binary. Both the infrared and optical spectra show complex emission lines, with several components which originate in different parts of the binary. They have determined the best position for the optical counterpart of Cir X-1, using HST images and SuperCOSMOS scans of UK Schmidt plates.

Johnston (AAO) and Verbunt (Utrecht) have used the High-Resolution Imager of the ROSAT X-ray satellite to study several globular clusters known to contain faint X-ray sources. The nature of these faint sources is unclear, in contrast to the bright sources, whose identification as low-mass X-ray binaries is fairly secure. The X-ray observations put further constraints on the number, luminosity, and X-ray spectral shape of these sources.

## Supernova studies

Cannon and Stathakis (AAO) continued the long-term spectroscopic monitoring of SN 1987A. No time was allocated this year for observations with the RGO Cassegrain spectrograph, but an opportunity arose to obtain data during commissioning tests of the prototype SPIRAL fibre-feed imaging spectrograph. With Kenworthy (IoA/Cambridge), Lee and Taylor (AAO), spectra were

taken of a field a few arcseconds in diameter around the supernova. In good seeing, it was immediately apparent that there were significant differences between the spectra from adjacent half-arcsecond pixels. These differences presumably correspond to different proportions of light coming from the central supernova remnant, the circumstellar ring, hot ambient interstellar gas in the Large Magellanic Cloud and two nearby, relatively bright stars. Similar data were subsequently obtained in the near-infrared spectral region, using the 3-D instrument from the MPIE (Munich) in collaboration with Meikle and Fassia (ICSTM), again in sub-arcsecond seeing.

Considerable effort has gone into trying to monitor the spectroscopic development of SN 1998bw, a bright Type Ic supernova first discovered because it appears to be the origin of a burst of  $\gamma$ -rays detected on 25 April 1998. In addition to the monitoring observations, Cannon, Malin and Tinney (AAO), in collaboration with Hambly and MacGillivray (ROE), obtained an accurate optical position for SN 1998bw by combining SuperCOSMOS measurements of a Schmidt Sky Survey photograph of the field with some recent CCD images of the supernova. The resultant position agreed with that of the radio source, measured at the ATNF, to within 0.2 arcseconds. Inspection of the UKST photographs shows that SN 1998bw is located within an HII region lying on one of the spiral arms of its parent galaxy.

## Abundances of globular cluster stars

Cannon (AAO), with Da Costa, Norris and Gibson (MSSSO) and Croke (Crete), used 2dF to obtain spectra for a sample of upper main-sequence stars in the giant globular cluster  $\omega$  Centauri. This cluster is unique in that its evolved red giants display a large spread in iron-group abundances, in addition to the CNO variations seen in the evolved stars in many clusters. The objective is to determine to what extent the abundance spread seen in  $\omega$  Cen is primordial, or perhaps due to a self-enrichment process early in the life of the cluster, and how much can be attributed to internal processes of stellar evolution.

## Astrometry from Schmidt plates

Continuing a project begun last year, Cannon (AAO) is working with Hambly and MacGillivray (ROE), and other members of the UKST and SuperCOSMOS teams at Siding Spring and in Edinburgh, to improve the accuracy of astrometry obtainable from UKST photographs. Steps taken so far include the use of a better reference catalogue (the ACT, made by the US Naval Observatory by combining Tycho-Hipparcos positions with proper motions derived from the old Astrographic Catalogue); the use of an empirical 'mask' to remove the distortions caused by the curvature of the photographs in the Schmidt Telescope; and some improvements to the data analysis code. The result is that positions accurate to better than 0.25 arcsec can now be derived over entire Schmidt plates.

## Advanced imaging

Bland-Hawthorn (AAO) continues to develop new methods for advanced imaging. He has investigated the possibility of a double cavity scanned with a synchronised capacitance bridge in order to 'square off' the Lorentzian profile of the etalon cavity. He has also performed simulations to demonstrate the feasibility of a tunable filter with curved plates and graded index coatings. The technology has important applications for removing phase effects over a wide field, and achieving a monochromatic field in fast beams, for example at the AAT f/3.3 prime focus.

As well, Bland-Hawthorn and PhD student Cianci are investigating Rugate beam splitters to identify specific classes of sources, including brown dwarfs at different temperatures and quasars beyond the redshift of reionization.

Bland-Hawthorn (AAO) and MacKenzie (Sydney), are producing a simple optical Rugate filter in preparation for more sophisticated OH suppressing filters in the near infrared, designed in collaboration with Offer (AAO).

## Sky subtraction with fibre systems

Watson, Offer, Lewis, Bailey and Glazebrook (AAO) have reviewed the techniques used for sky subtraction with multi-fibre spectroscopy systems. The concern is that sky subtraction with fibres does not in general compare favourably with that using multi-slits for the faintest classes of objects. While it is true that fibres demand much greater care in sky subtraction, there is no fundamental reason why the two techniques should not produce similar results. With the 2dF facility, high-quality sky subtraction must be carried out on a routine basis, and techniques for further improving the existing performance are being explored. Examples include improved profile-fitting for extraction of the spectra, and elimination of optical effects causing occasional fibre-to-fibre spectral transmission differences. In designing new fibre instruments, it is possible to incorporate novel methods of sky subtraction, and one such technique using the optical properties of fibres is being investigated. For this method, the same fibre is used to transmit both the object signal and a local sky sample, and may approximate better to slit sky subtraction than conventional fibre techniques.

## Proper Motions of the Nearest Galaxies

Tinney (AAO) has commenced a program of astrometric observations of the nearby satellite galaxies of the Milky Way, using the ESO 3.5-m telescope. This program will exploit the excellent astrometric properties of CCDs, and the excellent seeing of the ESO site to obtain positions of these galaxies (relative to quasars discovered by Tinney and collaborators) to a precision of one milli-arcsecond per epoch. This should produce a firm detection of the proper motions of these galaxies within five years.

## Gas in nearby galaxies

Bland-Hawthorn (AAO), Veilleux (KPNO), Carignan (Montreal) and Freeman (MSSSO) have continued to study ionized gas in nearby galaxies. They have measured the hydrogen-alpha rotation curves beyond the extent of the neutral hydrogen disk, for a further four galaxies. Dark haloes extend considerably further than the hydrogen disks in most cases. A continuing puzzle is the source of the outer warm gas, since the cosmic ionizing flux appears to be too weak by an order of magnitude. Since all spirals have warped outer disks, they are presently investigating a model in which the central blue disk irradiates the gas exposed to the inner disk. An early indication is that warps in spirals may be far more severe than observed in HI surveys.

## Galaxy clusters

Bland-Hawthorn and Malin (AAO) have continued their work to understand very extended, extremely faint, diffuse structures in rich clusters identified in stacked photographic plates. In collaboration with Weil (Columbia), they have shown that in the Virgo cluster, the galaxy M87 exhibits a stellar fan-like structure which arises from a dwarf galaxy that has been scattered by the compact stellar core of M87. As much as half the mass of the interloper is retained by M87's core, and this may explain the counter-rotation observed there. In collaboration with Moore (Durham), Calcaneo-Roldan (Durham) and Sadler (Sydney), they have studied extraordinary linear features in the Centaurus and Coma clusters. These features appear to require a low-surface brightness galaxy to have been disrupted along its orbit more than two billion years ago. In support of this picture, they identify a standing wave at the point of closest approach to the cluster centre. The observed features have broadband colours which are consistent with two billion years of stellar ageing.

Bland-Hawthorn and Jones (MSSSO) have made extensive progress with the TTF in measuring variations in star formation rate density between galaxy clusters and the field over the redshift interval  $z = 0.2$  to  $0.6$ . Using the TTF, a hundred emission-line sources can be identified in a rich cluster over

a 10 arcminute field, in a time of around four hours, considerably quicker than with more traditional observing techniques. A powerful demonstration of the technique was recently made in conjunction with Zaritsky (UCSC). His group identify compact clusters from surface brightness fluctuations in drift scan surveys. From only three hours of observation, Bland-Hawthorn and his collaborators have identified a peak in the number of emission-line objects at a slightly higher cluster redshift, compared to the number of objects seen at a lower cluster redshift or in the surrounding field population.

Phillipps (Bristol), Parker (AAO) and Jones (Bristol) are continuing a study of the Virgo and Fornax galaxy clusters which involves digitally stacking multiple exposures on Tech Pan film of the clusters. The high sensitivity of Tech Pan film, together with the addition of multiple exposures makes the survey well suited to the detection of low surface brightness objects. A new catalogue of the low surface brightness galaxies in the two clusters is in preparation. The search has led to the detection of many thousands of previously unknown low surface brightness galaxies within a region of nine square degrees within the Virgo cluster. These have been used to study the luminosity function for galaxies within the Virgo cluster.

Drinkwater (NSW), Phillipps (Bristol), Gregg (LLNL), Jones (Bristol), Smith (Cardiff), Parker (AAO), and Sadler (Sydney) are using the 2dF facility to obtain redshifts for 14 000 objects within the Fornax galaxy cluster. They aim to obtain redshifts for all objects within the cluster with blue magnitudes brighter than  $B = 19.7$ . The redshifts obtained so far have revealed a population of unresolved compact emission-line galaxies. These galaxies are missing from existing galaxy catalogues but may amount to one to two percent of all galaxies. From their hydrogen-alpha emission lines it is evident that the galaxies have high star-formation rates.

## FLAIR redshift surveys

Shanks (Durham), Parker (AAO), Fong and Metcalfe (Durham) have continued with the extension of a large redshift survey for galaxies included in the Edinburgh/Durham Southern Galaxy Catalogue. The redshift survey has been extended to cover an additional 90 UK Schmidt fields. The large homogeneous survey will result in a powerful cosmological resource for detailed statistical analyses of galaxy clustering on large spatial scales.

Wakamatsu (Gifu), Malkan (UCLA), Parker (AAO) and Hasegawa (Gifu) have finished obtaining redshifts for heavily-obscured galaxies in crowded fields between the Ophiucus and Hercules clusters of galaxies. The data have been taken to look for a possible connection between the two clusters. Evidence was found for a wall-like structure that links the two galaxy clusters, and for a possible additional galaxy cluster located in the constellation of Libra, between the Ophiucus and Hercules clusters. The observed wall of galaxies appears to be extremely large, extending over 70 degrees on the sky, with a linear size estimated to be up to one million parsecs.

Colless (MSSSO), Parker (AAO), Hola (MSSSO) and Raychaudhury (IUCAA) have started a project in which FLAIR is used to measure integrated linewidths for galaxies for which redshifts were previously obtained in a magnitude-limited redshift survey by Colless and Hola. The linewidths will be used to investigate the dependence of the Tully-Fisher relationship on galaxy properties and to provide a low redshift comparison sample for studies of the evolution of the Tully-Fisher relationship.

Proust (Meudon), Parker (AAO) and Drinkwater (NSW) are continuing a programme to obtain redshifts for galaxies in four relatively nearby, rich X-ray galaxy clusters. These will be used to analyse the structure, dynamical evolution and sub-clustering properties of the clusters and to investigate correlations between the optical and X-ray properties of the clusters. This may shed new light on the current discrepancy that exists between X-ray and optical estimates for the mass of galaxy clusters.

## Gamma Ray Burst follow-up

Tinney (AAO), Galama (Amsterdam) and Palazzi (BeppoSAX) have been co-ordinating a program of follow-up over-ride observations on the AAT for over 12 months now. This program has shown some success, with the AAT being able to contribute to the identification of at least two (GRB 980326 and GRB 980425) Gamma Ray Burst optical counterparts within the last 12 months.

## Infrared emission from active galactic nuclei

Wolstencroft (ROE), Parker (AAO) and Lonsdale (Caltech) are using FLAIR and the ATCA to study several hundred sources included in the IRAS far-infrared catalogue which show a peak of emission at 25  $\mu\text{m}$ . They have found that spectroscopic observations of IRAS sources, selected to have strongest emission at 25  $\mu\text{m}$ , provide an efficient method for identifying active galactic nuclei where the far-infrared emission occurs from dust grains that are heated by a central source. The far-infrared properties are being used to test recent models in which the dusty material is located within a toroidal shaped region which absorbs and reddens light from the central regions. The study has led to the identification of three highly reddened quasars. Approximately one-quarter of the selected IRAS sources have been identified as active galactic nuclei.

## Quasar studies

With Shanks, Croom (Durham), Smith (MSSSO), Miller and Loaring (Oxford), Boyle has continued to obtain redshifts for the 2dF QSO Redshift Survey. The overall aim of the survey is to obtain 25 000 quasar redshifts with which to measure large-scale structure in the Universe. So far, over 1200 redshifts have been obtained, making it already the largest single quasar redshift survey in existence. Initial results indicate a mean clustering scale length of quasars close to 4 million parsecs (for a Hubble constant = 100).

Together with Brotherton and van Breugel (IGPP/LLNL), the quasar redshift survey team have created a unique catalogue of radio-selected active galactic nuclei by cross-correlating the NVSS VLA radio catalogue with the 2dF quasar survey input catalogue. Over 100 of the 600 radio sources have been spectroscopically identified with the Keck telescope, resulting in the discovery of a new class of radio-loud broad absorption-line quasars. Other interesting rare objects have also been found as part of the survey, including a unique starburst-AGN.

Boyle (AAO), Aretxaga (ESO) and Terlevich (RGO) have also continued to work on the imaging of luminous quasars at high redshifts. This includes the first unambiguous detection in the near-infrared K-band of a host galaxy around a normal radio-quiet quasar at  $z = 2$ . The host galaxy comprises some 35 percent of the light of the system, corresponding to a galaxy five magnitudes brighter than a passively-evolved elliptical galaxy at  $z = 2$ .

Boyle and Terlevich (RGO) have also shown that the luminosity evolution of quasars closely mirrors the evolution of the star formation rate in the Universe recently derived from deep galaxy redshift surveys and the Hubble Deep Field data. They argue that this provides circumstantial evidence that star formation and the quasar phenomenon must be closely linked.

With Smith (MSSSO), Boyle has been working on the environments of intermediate redshift ( $0.3 < z < 0.7$ ) radio-quiet quasars. They find that the redshift evolution in the environment of radio-quiet quasars is consistent with that of field galaxies over the same range in redshift. This is in marked contrast to the cluster galaxy environments observed for radio-loud quasars over these redshifts.