3 Scientific highlights

Towards the unearthing of terrestrial mass planets

The Anglo-Australian Planet Search (AAPS) team, which includes Chris Tinney of the University of New South Wales, Hugh Jones of the University of Hertfordshire and Paul Butler of the University of California, has been using the AAT and the 'Doppler Wobble' technique since 1998 to search for extra-solar planets orbiting almost 250 nearby Sun-like stars.

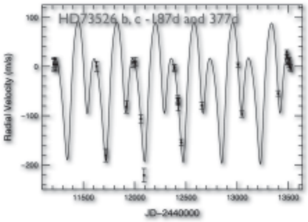

Figure 3.1 The radial velocity curve of the solar-like dwarf HD73526 reveals it is orbited by at least two planets, each with a mass comparable to Jupiter.

The AAPS has now detected twenty-five of the more than two hundred known extra-solar planets orbiting nearby stars. When the amount of telescope time that this program has used (ranging from 16 nights per year in 1999 to 32 nights per year in 2006) on the 3.9m AAT is compared with the telescope time available to AAPS' competitors elsewhere, this turns out to be a very favourable 'return' on telescope time invested. Indeed, when measured in 'planets detected per star monitored' the AAPS is by far the world's most efficient planet search.

Along the way the astronomers of the AAPS team have achieved a number of notable results – the first gas-giant planet found in a near-circular Earth-like orbit; the first gas-giant planet orbiting in a near-circular orbit beyond 3au (i.e. beyond where the asteroid belt lies in our Solar System) to also have no interior gas-giant planets (HD70642b), making it at the time the most 'Solar System-like' system; and the detection of a pair of planets in 2:1 resonance around the star HD73526 (see Figure 3.1).

The primary scientific goal of the AAPS is to achieve the best possible long-term Doppler precisions over periods up to, and beyond, that of Jupiter, in order to discover Solar System analogues orbiting other stars. AAPS has demonstrated the ability to achieve 2–3m/s velocity precisions, for stars with suitable intrinsic stability, extending back to 1998. So the next few years will see the program in a position to say whether Jupiter-like planets in Jupiter-like orbits are common or rare.

In the last few years the team has been pushing to even better precision limits. For the brightest and most stable host stars being monitored, longer observations have been shown to deliver Doppler precisions of 1m/s or better. As a result, these stars are now being targeted in dedicated 48 night observing campaigns in the AAPS 'Rocky Planet Search'. The improved precisions and longer time blocks of the Rocky Planet Search make the AAPS sensitive to planets as small as a few Earth masses in orbits of less than 10 days, placing the AAT in prime position to answer critical questions about the formation mechanisms for terrestrial-mass planets.

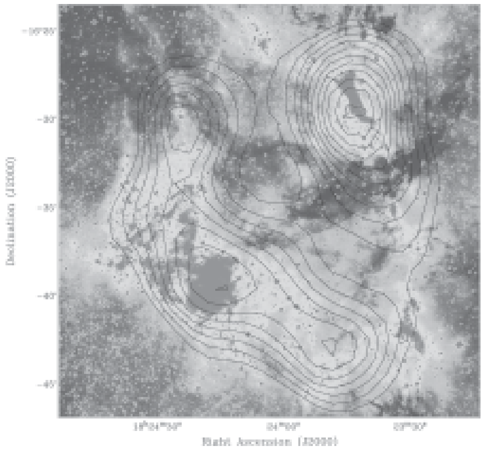

Figure 3.2 The known Galactic SNR G15.1-1.6 seen for the first time on an image from the AAO/UKST H-alpha Survey of the Southern Galactic Plane. There is an excellent match between the optical emission and overlaid PMN 4850 MHz radio contours (from 0.1 and 0.37 Jy/beam).

Exciting results from the AAO/UKST H-alpha Survey

The AAO/UKST H-alpha Survey, led by Quentin Parker of the AAO and Macquarie University, (Parker et al., 2005) has continued to produce exciting science results and further discoveries. The survey itself was carried out from 1997 to 2000 and the results have been available on-line since 2003 from the Wide Field Astronomy Unit at the Royal Observatory Edinburgh. The following projects exploit this survey. Parker and students have used 2dF/AAOmega at the AAT as well as other telescopes, for some of the follow-up spectroscopy.

PhD student Milorad Stupar and Parker have uncovered a significant number of new Galactic supernova remnants, based on the detection of filamentary nebulosities (elongated clouds of gas) from the AAO/UKST H-alpha survey. Furthermore they have also detected optical emission from many known radio Galactic remnants for the first time, offering fresh opportunities to study the evolution and interaction of these important sources of interstellar medium enrichment and energy injection. A catalogue of 21 new Galactic supernova remnants has been produced.

PhD student David Frew (now at Perth Observatory) and Parker have developed a powerful distance estimator for planetary nebulae (PNe) based on a new H-alpha surface brightness radius relation (SB-r). The technique uses precise H-alpha fluxes for calibrating PNe with accurate distances from primary techniques like trigonometric parallax. We have also shown that 20% of objects currently accepted as nearby PNe are actually Strömgren spheres in the interstellar medium surrounding hot white dwarf or subdwarf stars. Removing such contaminants produces a much tighter, cleaner distribution in our new SB-r relation. The SB-r relation can provide distances for PNe once an accurate surface brightness is obtained, enabling a robuse estimate of the number of PNe within the local Galactic volume within 2Kpc. This leads to improved estimates of the total space density and birthrate of PNe in our Galaxy. Crucially, the Galactic production rate for PNe, now, for the first time, agrees with the best estimates for the White Dwarf formation rate from other studies. Whether binarity is essential for PNe formation is currently a hot question but PNe in close binary systems form a distinct lower trend in the new SB-r relation (see Figure 3.3) so binarity can, at most, account for only 33% of all PNe, another exciting new result.

PhD student Brent Miszalski, AAO vacation scholar Jayne Birkby and Parker have uncovered an additional 300 new Galactic PNe to add to the approximately 900 in the Macquarie/AAO/Strasbourg H-alpha planetary nebula project: MASH. These were uncovered using special processing techniques applied to the data of the AAO/UK Schmidt H-alpha Survey (SHS) which we dub MASH-II. A significant number of very extended, low surface brightness, highly evolved examples have been found which can be applied directly to the Frew-Parker SB-r relation and improve the integrity of the local volume PNe number density. Additionally a sample of highly compact PNe has been found in the Galactic bulge which can be used to unravel the properties of this important component of our Galaxy.

PhD student Warren Reid and Parker have constructed the most complete and homogeneous census of a PNe population ever compiled for a single galaxy. This has been done through discoveries from the AAO/UKST H-alpha Survey of the central area of the Large Magellanic Cloud. PNe were confirmed by the AAO's 2dF spectroscopy, which gave 460 new PNe and independently recovered all 169 previously known PNe in the area. A large fraction of new LMC PNe are considerably fainter than the faintest previously known and we have tripled the number accrued from all sources over the last 80 years. These data have already led to significant advances in our understanding of the sub-structure of the central LMC, such as rotation, inclinations and transverse velocity as well as the distribution of the old stellar population, the PN luminosity function (PNLF) and PNe physical parameters such as temperatures, densities, nebulae masses and abundances. Importantly, because the LMC has a precisely known distance, meaningful PNe physical parameters can also be derived.

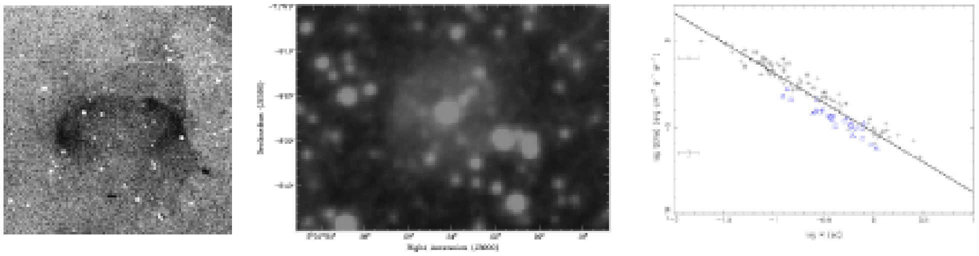

Figure. 3.3
Left: Plot of a new, large, low-surface brightness evolved PN from MASH-II: BMP0733-3108, 8 arcminutes across.
Centre: Plot of RP609 - a new LMC PN with an extremely faint AGB halo
Right: New Surface-brightness versus radius relation for PNe.

Using the pulse of a star to constrain its fundamental parameters

The measurement of stellar oscillations is a very elegant experiment in physics. A star is a gaseous sphere that oscillates in many different modes when excited. The oscillation frequencies depend on the sound speed inside the star, which in turn depends on properties such as density, temperature and composition. The Sun oscillates in many modes simultaneously and the comparison of the mode frequencies with the predictions of theoretical calculations has led to significant refinement of the solar model. The determination of the oscillation frequencies of other stars, known as asteroseismology, allows their interiors to be probed in exquisite detail, offering the chance to produce major advances in our understanding of stellar structure and evolution and in the underlying physical processes.

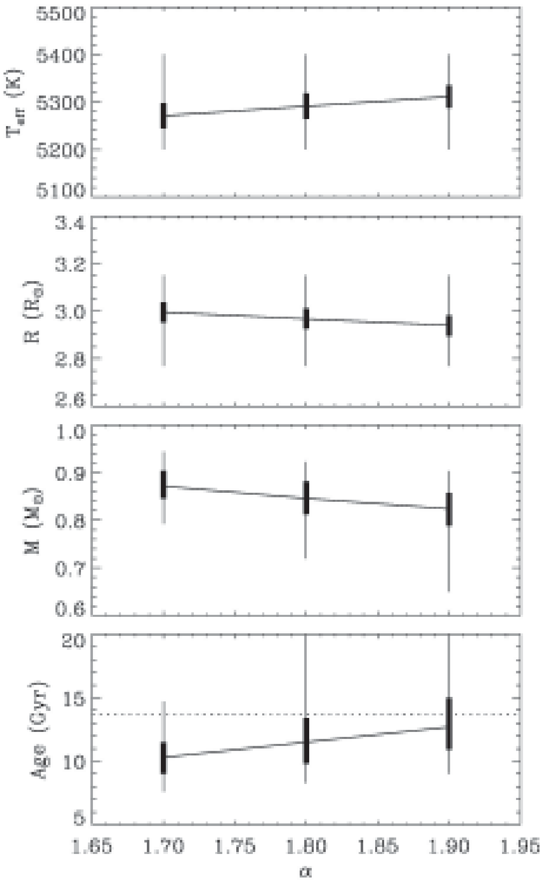

Figure 3.4 Paramaters of v Indi for three plausible choices of alpha, the mixing length parameter. The thin error bars show the range of each parameter based on classical measurements alone, while the thick bars include the constraint provided by astroseismology. The dashed line at an age of 13.7 Gyrs is the upper limit on the age of the Universe from cosmology.

Despite solar-like oscillations being a great challenge to observe due to their tiny amplitudes of less than one metre per second, thanks to the tremendous Doppler velocity precision developed during the last few years in the search for extrasolar planets with spectrographs such as UCLES, the field of asteroseismology is now able to deliver extremely impressive results.

A team of astronomers led by Timothy Bedding of the University of Sydney has recently performed a dual site observing campaign on each of the old metal poor; (1/25th solar) star *v* Ind and the subgiant β-Hyi. The difference in the longitudes of the AAT and telescopes at La Silla, Chile, permit more complete temporal coverage and help reduce the 1/day aliasing that is a big problem for single-site asteroseismological investigations.

Using their determination of the large frequency separation in the oscillation spectrum of v Ind, the stars' location in the Hertzsprung-Russell diagram and standard stellar evolutionary models, Bedding and colleagues have placed stringent constraints on the fundamental parameters of effective temperature, radius, mass and age. The thin error bars in Figure 3.4 represent the range of each parameter based on classical measurements alone (luminosity and temperature), while the thick bars, plotted for three different but reasonable choices of the convective mixing-length parameter, include the constraint provided by their measurement of the large frequency separation of the oscillations. The dashed line at an age of 13.7 billion years indicates the upper limit set by age of the universe from cosmology. Their results confirm that v-Ind has a low mass (0.85 ± 0.04 $M_{\odot}$) and is at least 9 billion years old.

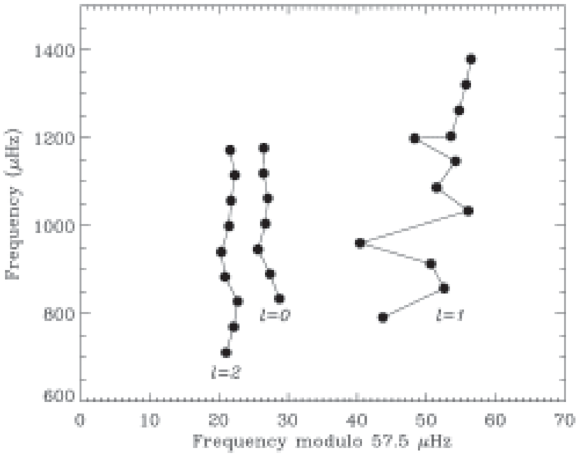

Figure 3.5 An echelle diagram of oscillations in β- Hydri, based on observations from UCLES at the AAT and HARPS at ESO in Chile. The measured frequencies are stacked modulo the large frequency separation and so form nearly vertical ridges. The strong deviations from vertical alignment in the l=1 modes indicate departures from a regular spacing that are due to mode bumping.

From their measurement of the large frequency separation of β-Hyi, the team has been able to infer the mean stellar density to an accuracy of just 0.6% (0.2538±0.0015 g cm^{-3}). Moreover, by combining this determination with the angular diameter of the star, as measured with the Sydney University Stellar Interferometer, they have obtained a direct estimate of the stellar mass, to an accuracy of 2.7% (1.07± 0.03$M_{\odot}$). This is probably the most precise mass determination of a solar-type star that is not in a binary system, illustrating the immense power of combining asteroseismology and interferometry.

In addition, the dual site observing campaign on β-Hyi has led to the identification of oscillation modes which show the clear effect of mode bumping (Figure 3.5). Mode bumping is an important complication with subgiants in which some oscillation frequencies are shifted from their usual almost-regular spacing as a result of the strong abundance gradient in the hydrogen-burning shell, just outside the helium core. The quantification of such effects has the potential to provide information about the properties of the convective core, including any mixing beyond the region that is convectively unstable (so-called core overshoot). Indeed, modelling of the full set of oscillation frequencies in β-Hyi should permit constraints on two important convective parameters: the mixing length and the amount of core overshoot, and thus provide a crucial test of stellar evolution models in a regime beyond that of the Sun and other main-sequence stars.

Unveiling dark energy with the WiggleZ Survey

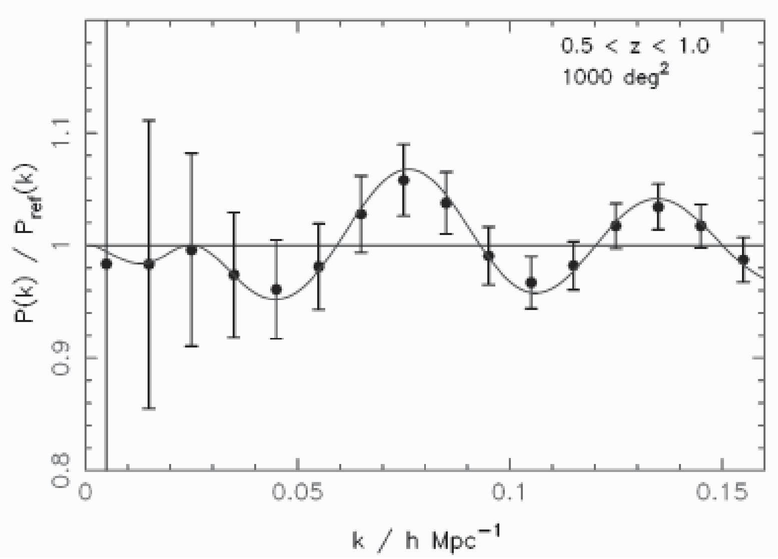

Figure 3.6 Any dark energy present in the Universe will affect the distribution of galaxies. This figure shows a simulation of the expected variation of galaxy numbers as a function of spatial frequency (i.e. wave number, or inverse distance). The amount of dark energy and its nature can change the scale of the observed oscillations. Directly measuring these oscillations (or wiggles - hence the project name) therefore allows us to measure dark energy.

Towards the end of the last century a major upheaval of our understanding of cosmology began. Separate teams, using different techniques, found that the expansion of the Universe is accelerating, with profound consequences. Prior to this discovery it was believed that the expansion should be slowing down as the attractive effects of gravity counteracted the expansion. The fact that this is not the case is of enormous importance to our understanding of the Universe. The most likely explanations are either that the theory of gravity, as developed by Einstein, is flawed and must be revised, or the content of the Universe is dominated by an exotic form of dark energy, which has the peculiar property of repelling matter, like a sort of anti-gravity. In either case, the result would be a major change in our understanding of the Universe, and solving this problem is regarded as one of the most pressing issues in physics.

A team of scientists, led by Michael Drinkwater of the University of Queensland and Warrick Couch of Swinburne University of Technology, working with the AAOmega spectrograph on the AAT, has begun to tackle this challenge. The key to the solution lies in the way the distribution of galaxies is related to conditions in the early Universe. Very early in the history of the Universe, the distribution of matter was very smooth. Over time, small seed fluctuations in the density began to grow via accretion of matter through gravitation. The manner in which these grow depends on the energy content of the Universe, including both gravity and any dark energy present. The fluctuations eventually collapse to become galaxies. The link between seed fluctuations at early times, imprinted on the cosmic microwave background (the heat glow from the Big Bang), has already been explicitly linked to the present day distribution of galaxies, by scientists working on data from the AAO's 2dF Galaxy Redshift Survey. However, to see the effects of dark energy we must look to galaxies at earlier times, i.e. higher redshifts. Figure 3.6 shows the expected signal of galaxy clustering. The scale of the oscillations depends on the physics of dark energy.

Using the AAOmega spectrograph at the AAT, Drinkwater, Couch and colleagues on the WiggleZ team are the first in the world to begin measuring the link between galaxies and dark energy. The project has just completed its first year of observations, making use of over 50 nights of AAT time (Figure 3.7) to observe a large sample of emission-line galaxies out to redshift z~1. The assessment after this first year is that the team is on track to meet their goal of measuring the dark energy 'equation of state' parameter to a precision of 10%. The team has already found that the strength of the clustering for their sample of emission line galaxies is much higher than expected, which improves the final measurements possible from the survey. Even before the final dark energy results are announced, this unprecedented galaxy sample will make breakthroughs in a number of other areas, including the understanding of how local environment affects star formation and nuclear activity in galaxies.

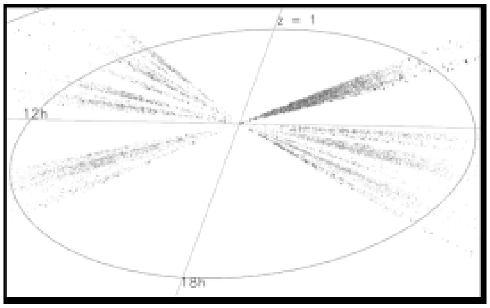

Figure 3.7. The distribution of WiggleZ galaxies measured from the first year of observations. Our location is in the middle of the plot, with more distant galaxies further towards the edge. The WiggleZ survey targets areas all around the sky to allow them to be observed at all times of the year.

Studying stellar magnetic activity with SEMELPOL

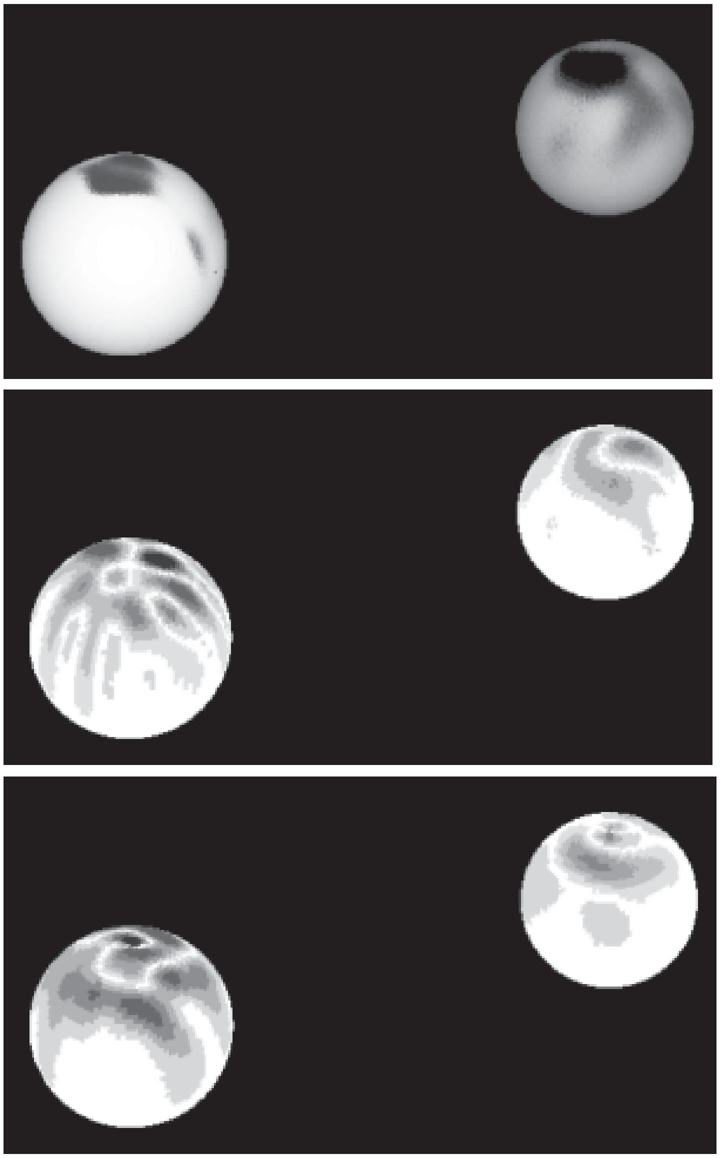

Figure 3.8 Reconstructions of the spot (upper), radial magnetic field (middle) and azimuthal magnetic field (lower) reconstructions of the binary star system HD155555 with the primary star on the left and the secondary on the right. The light and dark shading correspond to positive and negative magnetic polarity.

One of the most important processes in young solar-type stars is the generation of magnetic fields. This affects everything from the star's activity to its angular momentum loss. The magnetic field of the Sun is generated by a magnetic dynamo which operates in an interface-layer between the differentially rotating outer convective zone (the equator of the Sun rotates faster than the poles) and the underlying rigidly rotating radiative zone, where strong shears occur in the motion of the gas. It is still not clear if the magnetic fields of other stars are generated by this same mechanism. In particular, young solar-type stars show levels of magnetic activity orders of magnitude higher than the Sun. It is widely believed that this enhanced activity is driven by more powerful magnetic dynamos but the details of how these operate remain elusive.

A large multi-national collaboration of astronomers, including Brad Carter of the University of Southern Queensland, Stephen Marsden of the AAO and Andrew Collier-Cameron of the University of St. Andrews have been utilising the AAT and the visitor instrument SEMELPOL to investigate the magnetic field structure of a number of stars other than the Sun. SEMELPOL is a polarimeter designed by Meir Semel, at the University of Paris, which, in conjunction with the UCLES spectrograph, allows the observation of polarised light from a star. As the presence of magnetic fields polarises light, these observations, combined with a technique called Zeeman Doppler imaging, can be used to reconstruct the distribution of magnetic fields on the surface of the young stars. This information provides a unique insight into the nature of magnetic field generation within these stars.

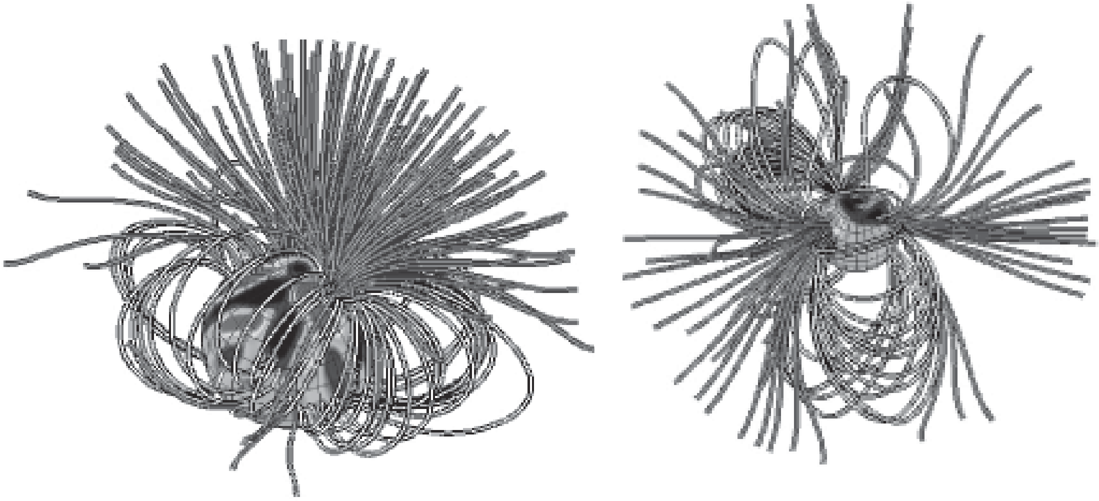

Figure 3.9 Coronal magnetic field reconstruction of the primary (left) and secondary (right) stars of the binary HD155555. The light lines indicate closed magnetic field lines (connecting back to the stellar surface) while the dark lines represent open field lines.

The Zeeman Doppler imaging program has been running on the AAT for several years and there have been a number of highlights during the last 12 months. For example, new SEMELPOL observations have recently been obtained of an extremely active young binary star, HD155555. This star is somewhat unusual in that both components exhibit magnetic activity, which has has allowed the scientists to study the effect of binarity on each component of the system. These observations (when compared to data obtained in previous years) have revealed that the spot features on the surfaces of both stars (Figure 3.8, top) are stable over a number of years. As this stability has not been observed in single stars it may be linked to the tidal forces the two stars exert on each other as they orbit.

Furthermore, both components of the binary show large regions of azimuthal magnetic field (field lines wrapping around the rotational axis of the star, as shown in Figure 3.8, bottom). Where this has previously been observed in single stars it has been argued that a non-solar dynamo must operate since with a solar-like magnetic field generation mechanism azimuthal field is not expected to appear near the surface. These observations have also led to the first ever reconstruction of the coronal (tenuous outer atmosphere) magnetic field of an active binary system. This has shown that these two stars have significantly different coronal field geometries (see Figure 3.9).

The SEMELPOL has recently utilised the instrument to create detailed maps of the magnetic fields of T Tauri stars. These infant stars are still accreting material from the disks of gas from which they formed and were traditionally believed to harbour only simple dipole magnetic field structures. However, the new AAT observations show that their magnetic field structures are complex and resemble those of older stars that are no longer surrounded by disks.

UnRAVElling the secrets of the Galaxy from the motions of its stars.

RAVE (RAdial Velocity Experiment) is a large international collaboration using the 6dF multi-fibre spectroscopic system on the UKST to obtain spectra for a very large sample of Galactic stars. During the last year, the RAVE consortium obtained their 200,000th spectrum and preparations are now well under way for the second public data release (DR2). The validation of the data to be included in DR2 has taken somewhat longer than expected since several sets of calibration data have been obtained.

Nevertheless, members of the consortium are already extracting important new results from the existing data. For example, a team of astronomers led by Lionel Veltz of the University of Strasbourg have analysed the distribution of G and K type stars towards the Galactic poles using radial velocities from RAVE, together with additional data from ELODIE (a fixed-configuration, cross-dispersed échelle spectrograph), the 2-micron All Sky-Survey (2MASS) and proper motions from United States Naval Observatory CCD Astrographic Catalogue 2. The combination of photometric and 3D kinematic data has allowed the vertical distribution of dwarfs, subgiants and giants to be determined and their kinematics to be explored. Discontinuities within the frequency distributions of stars as a function of velocity and brightness are identified that separate the thin disc, thick disc and halo components of the Galaxy. This has allowed the astronomers to estimate the respective scale heights of the thin disc and thick disc to be 225 ± 10 pc and 1048 ± 36 pc.

In addition, a team headed by Martin Smith of the University of Groningen have used a sample of high velocity stars from the RAVE survey and previously published datasets to place new constraints on the local gravitational escape speed of our Galaxy. Their use of cosmological simulations of disc galaxy formation allows for a more precise determination of the escape velocity than in previous studies. The escape velocity is found to lie in the range 498 km/s to 608 km/s (90% confidence), with a median likelihood of 544 km/s. Their result convincingly demonstrates the presence of a dark matter halo. Moreover, using a variety of halo models, they estimate a virial mass of $1.42 \text{x} 10^{12}$M.

A number of ongoing RAVE projects are exploring the local kinematics, the chemical abundances and the chemo-dynamical evolution of the Galactic disc, distance determinations and the local star formation history.

Integral field spectroscopy with SPIRAL and AAOmega

An upgraded Segmented Pupil/Image Reformatting Array Lens Integral Field Unit (SPIRAL IFU) has been in operation at the telescope since commissioning in June 2006. SPIRAL consists of a head unit with a 32x16 element array of microlenses which cover a rectangular area on sky of 22.4x11.2arcsecs. Light incident on each microlens is fed down an optical fibre and is now directed into the AAOmega spectrographs. The improvements permit an observer to record 512 spectra simulataneously, over a greater range of wavelengths than was previously possible, from a spatially extended astronomical source. Thus SPIRAL offers significant advantages over traditional long slit spectrographs, which can sample extended sources in only one dimension per exposure.

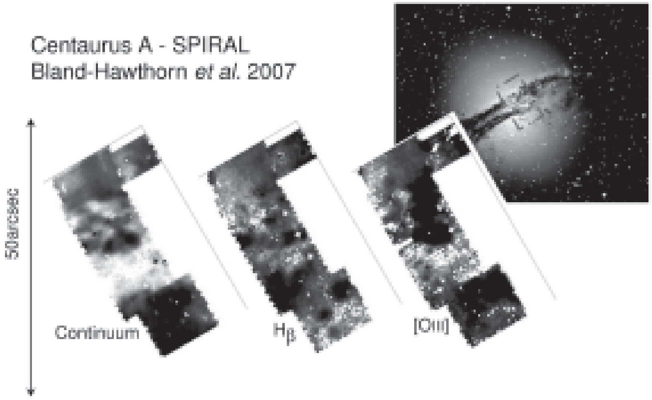

Figure 3.10 The nuclear region of Centaurus A, the closest giant elliptical galaxy. It harbours a massive black hole that gives rise to powerful emission features. A mosaic of 9 telescope pointings with SPIRAL covering an area of approximately 50x25 arc seconds and centred on the nucleus of Centaurus A is shown. The three mosaics are the result of spectral line fitting to the SPIRAL data cube (continuum, and integrated line flux for H-beta and [OIII] ë5007A) which contains some 4000 individual optical spectra. Kinematic and line ratio diagnostics are being used to interpret the complex AGN/star formation and jet/wind interactions in the nuclear region.

The relatively large 0.7 arcsec spatial pixel scale of SPIRAL is particularly well matched to the typical optical seeing at the Siding Spring Observatory site and also retains sensitivity to low surface brightness sources, provided they are extended on the few arcsecond scale. Some IFU systems with smaller pixels are detector read-noise limited, even on 8-metre class telescopes. The smaller fibres in the IFU feed (in comparison to the multi-object fibre feed from prime focus) mean that the spectrograph delivers a higher spectral resolution (by a factor of 1.5) with SPIRAL than with 2dF. Nevertheless, a wide range of AAOmega configurations can be used with SPIRAL including the Poisson noise limited Nod-and-Shuffle observing technique, which offers the potential to reach great depth. SPIRAL is particularly well suited to the study of the structure of local galaxies and, an example of this work is shown in Figure 3.10.