Science highlights

First millimetre light for upgraded Australia Telescope

First light at millimetre wavelengths for the upgraded Australia Telescope Compact Array occurred in November 2000, with a 3-mm observation of silicon monoxide maser emission from the Orion nebula.

On Thursday 30 November 2000, three years of designing, building, and testing for the Narrabri and Sydney engineering groups came to a climax at the Compact Array when two of the six dishes were fitted with the new 3-mm receiving systems and trained on a star-forming region within the Orion nebula containing silicon monoxide (SiO) masers. At 11.45 p.m. the telescope captured its first cosmic millimetre-wave photons, achieving "first light". Figure 8 shows the cross-power spectrum resulting from these first observations, at a frequency of 86.243 GHz. The millimetre photons from this source are produced by excited SiO molecules embedded within the star-forming clouds.

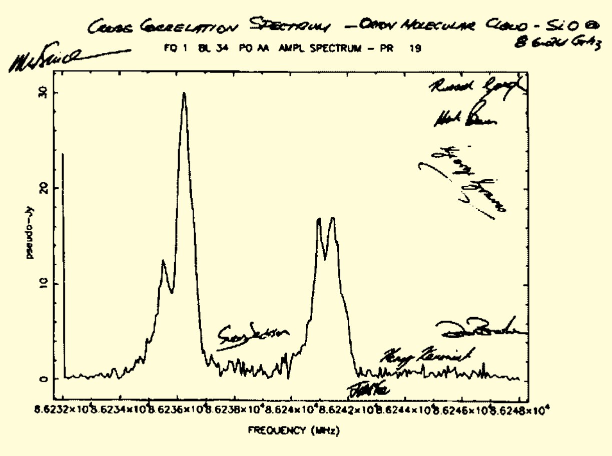

Figure 8 *"First light" – the Australia Telescope's first observation as an interferometer working in the 3-mm band with a single 31-m baseline, between antennas 3 and 4. The spectrum shows the SiO maser emission at 86.24 GHz from a star-forming region in the Orion nebula. The integration time was several minutes. No calibration has been applied.*

A project science team is now using the Compact Array in its 3-mm observing mode, looking at a variety of astronomical sources and investigating the performance of the system. Some of the first observations were of the SiO maser emission from the circumstellar envelopes of the evolved stars VX Sgr, R Dor, and R Aqr. The strong SiO emission from these stars can be detected easily in a single 10-second integration time. The team also observed HCO^+ absorption against the nuclear continuum source in the radio galaxy Centaurus A (Figure 9). Initial results are available on the Web at http://www.atnf.csiro.au/mnrf/3mm_details.html.

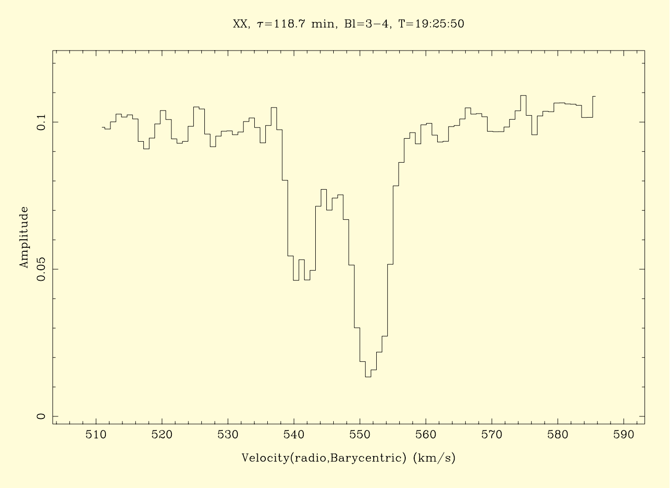

Figure 9 *This spectrum obtained with a single 31-m baseline shows HCO^+ absorption seen against the nucleus of the galaxy Centaurus A. A preliminary bandpass calibration has been applied and the spectrum is Hanning smoothed. The spectrum is centred on the velocity of the galaxy, at 552 km s^{-1}, where the strongest HCO^+ absorption occurs and also shows two narrower absorption features near 540 km s^{-1}. The velocity range shown does not include all of the absorption features known for Centaurus A.*

Science highlights

The prototype 3-mm receiving systems, installed on two of the Australia Telescope's six dishes, cover the frequency range 84–91 GHz. This current system will progressively be upgraded to the full array of six antennas with receivers covering a frequency range from 84 GHz to around 115 GHz. Routine millimetre observing is expected to start in mid-2003. In the meantime millimetre testing is under way whenever there is gap in the regular observing schedule.

At the heart of the new millimetre receivers are indium phosphide MMIC chips (page 64), cooled to -253° C, the product of a joint effort between the Australia Telescope National Facility (ATNF) and the CSIRO Division of Telecommunications and Industrial Physics (formerly the CSIRO Division of Radiophysics) under a special program established by former CSIRO Chief Executive Malcolm McIntosh to develop millimetre-wave integrated circuits for radio astronomy and telecommunications.

The upgrading of the Australia Telescope to work at millimetre wavelengths is funded by the Australian Federal Government under its Major National Research Facilities (MNRF) Program, and by CSIRO. More information on the MNRF projects is available on the Web at http://www.atnf.csiro.au/mnrf/mnrf_outline.html.

B. Koribalski and the MNRF science and engineering team (ATNF)

Photograph
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Massive proto-planetary disks detected at radio wavelengths

The giant HII region NGC 3603, located at a distance of about 20,000 light-years in the southern constellation of Carina, contains the Galaxy's most massive visible starburst region. The region has a large complex of molecular clouds and a dense concentration of massive stars in an early stage of evolution. The star cluster contains three Wolf-Rayet stars and around 70 O-type stars, of which an estimated 40–50 are located in a central region of approximately 13 x 13 arcseconds. These highly massive stars, which will eventually explode as supernovae, have an ionizing power about 100 times larger than that of the well-known Trapezium cluster in Orion.

Radio observations provide a means of detecting the individual stellar winds of some of the Galaxy's most luminous, massive hot stars located in the heart of NGC 3603. To study these stars, we obtained 12-hour observations at 3 and 6 cm with each of the 6-km configurations of the Australia Telescope Compact Array, giving a resolution of 1–2 arcseconds, high sensitivity and high dynamic range. This unique data set presents the first complete multifrequency study of this 2–3 million-year-old star-forming region.

The radio data reveal the presence of three sources recently identified as proto-planetary disks (ProPlyDs) on images from the Hubble Space Telescope and ESO Very Large Telescope (see Brandner et al. 2000, AJ 119, 292). The ProPlyDs are located 1–2 parsecs away from the stellar cluster core and roughly form a straight line from northwest to southeast. The radio images show cometary shapes, with a bright head and a faint tail consisting of diluted gas which points away from the cluster centre. These tear-shaped structures are probably formed by the influence of the radiation pressure and strong winds from the massive stars (Figures 10 and 11). Similar structures are also seen in the optical and infrared images of the ProPlyDs.

The ProPlyDs in NGC 3603 are several arcseconds in extent and are 20–30 times larger than their counterparts in Orion. Their radio flux densities are 10–20 times larger than expected, and are stronger towards longer wavelengths. This is a completely unexpected behaviour for these young objects, which are thought to emit optically-thin thermal radio emission. The spectral behaviour suggests optically-thin non-thermal (gyro-)synchrotron emission as the origin of the radiation, indicating that magnetic processes may be important in these ProPlyDs.

The "standard" ProPlyD model consists of a star, embedded in a neutral envelope which is surrounded by ionized material. Within the neutral material a circumstellar disk is presumed to exist and this plays a central role in the formation of stars and planets from interstellar matter. The circumstellar disks serve as a reservoir for accretion of matter and are responsible for angular momentum transport from the central star and the build-up of planetesimals. Such disks are expected to be photo-evaporated by external ultraviolet radiation from a massive star or star cluster. Bow shocks form in the vicinity of the ProPlyDs from an interaction between the evaporating ProPlyD gas and the winds from other massive stars. So far, no disks have been seen in the NGC 3603 ProPlyDs.

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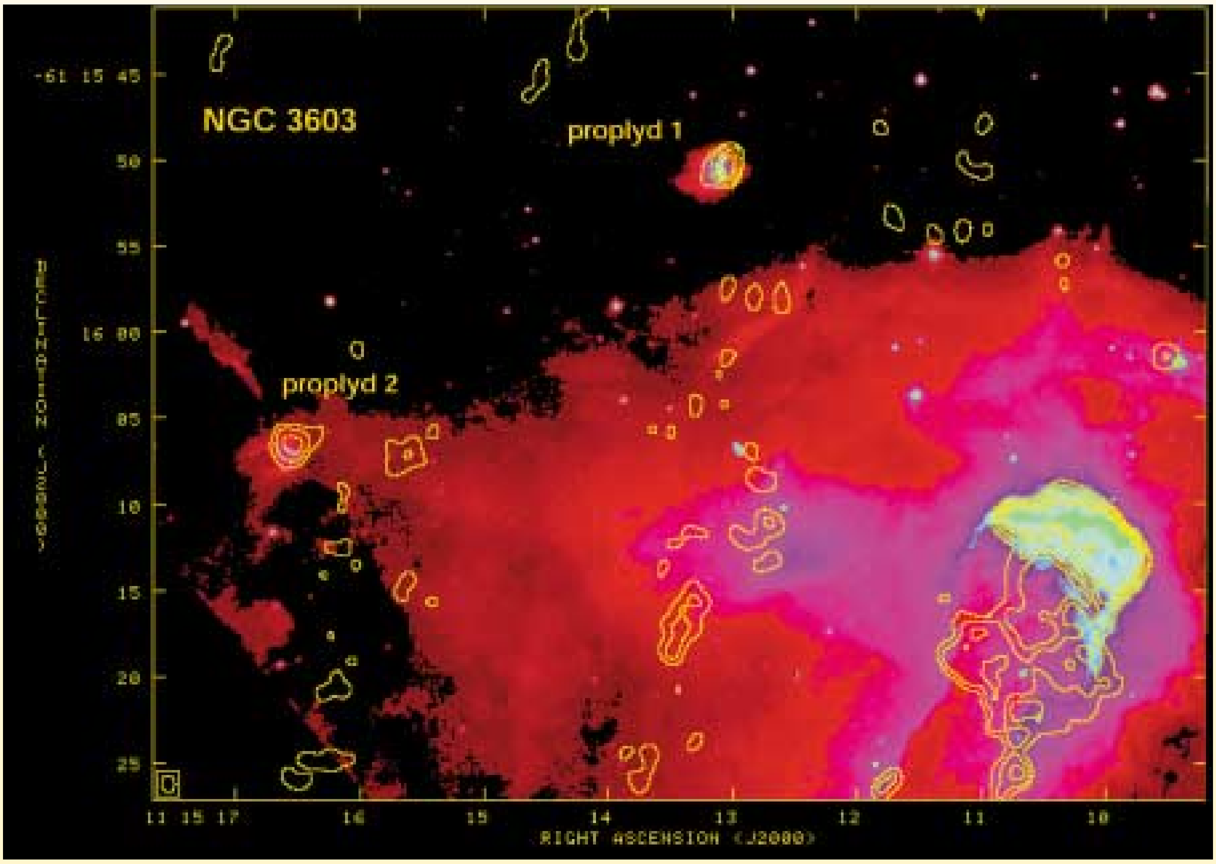

Figure 10 *Compact Array image showing the 3-cm radio continuum emission from the massive HII region NGC 3603 (contours) overlaid on a Hubble Space Telescope image by Brandner et al. (2000). Two of the three ProPlyDs are clearly visible to the north and east. The third ProPlyD is located to the northwest, outside this image. The brightest optical and radio emission is associated with giant gaseous pillars. North is to the top and east is to the left.*

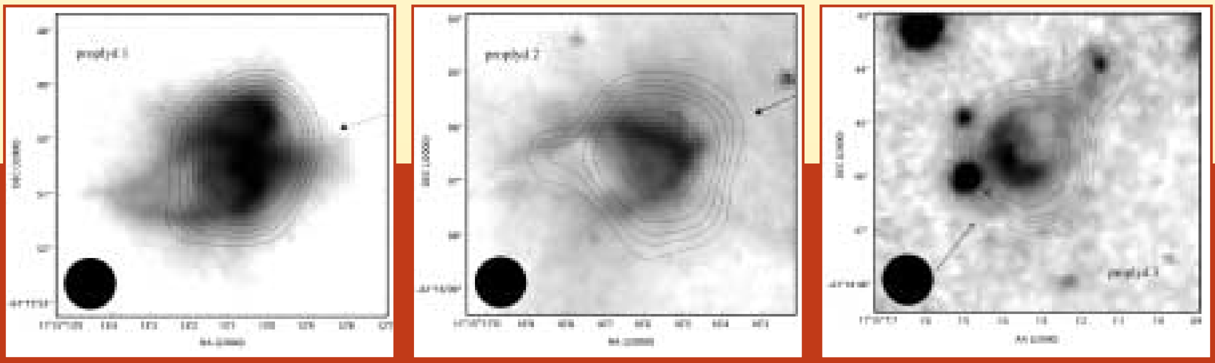

Figure 11 Compact Array images of the 3-cm radio continuum emission (contours) from the three NGC 3603 ProPlyDs overlaid on Hubble Space Telescope images of the ProPlyDs. The arrows indicate the ProPlyD ionization fronts resulting from the winds of the central star cluster.

New discoveries of millisecond pulsars in globular clusters

Globular clusters are a rich source of millisecond pulsars (MSPs). Exchange interactions in the core result in the formation of binary systems containing a neutron star which subsequently evolve, spinning up the neutron star through mass accretion. The MSPs formed in this way are among the most stable clocks in nature and are valuable for studies of the dynamics of clusters and the evolution of binaries embedded in them. However, they are quite difficult to find because the emission is weak and distorted by propagation through the interstellar medium, and the apparent pulse period may change rapidly because of binary motion.

About half of the 33 pulsars known in the Galactic globular clusters in 1994 were discovered at Parkes. From that time until recently, there have been no further discoveries of MSPs in globular clusters. With the advent of the new Parkes 20-cm receiver, we decided to mount a new attack on the globular clusters and attempt to break the long hiatus in such discoveries.

Extensive observations of the relatively nearby cluster 47 Tucanae, already known to be a rich storehouse of MSPs, resulted in the discovery of nine further MSPs, taking the total known in this cluster to 20, nearly a quarter of all MSPs known! Finding pulsars in more distant clusters for which there is no previous detection is more difficult.

In order to improve our search capability, we are using a new filterbank system built at Jodrell Bank and Bologna. This filterbank gives 512 x 0.5 MHz filter channels for each of the two polarizations making possible more effective removal of interstellar dispersion. It allows the detection of MSPs with dispersion measures of more than 200 $\mathrm{cm^{-3}}$ pc. The combination of this new equipment with the relatively high frequency of the multibeam receiver and its excellent sensitivity gives a unique opportunity to probe distant clusters.

Because globular clusters are known to contain binary MSPs with short orbital periods, we have implemented a new multi-dimensional code to search over a range of accelerations resulting from binary motion, in addition to the standard search over a range of dispersion measures requires huge computing resources. In Bologna, the new code runs on a local cluster of Alpha-500MHz processors and on the Cray-T3E 256-processor system at the CINECA Supercomputing Center. Data management and storage in this new experiment is also a non-trivial issue. A typical integration of 2.3 hours on a single target produces four Gbytes of data. But the results achieved so far amply justify the effort.

We have selected a sample of about 60 clusters, based on their central concentration and distance, and have so far discovered ten new MSPs in four

Photograph
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clusters which were not previously known to contain pulsars.

The first interesting case is NGC 6752 (Figure 12). This cluster is believed to have a collapsed core and was already known to possess a large proportion of binary systems and several dim X-ray sources suggesting that MSPs are likely to be formed in its core. In this cluster we first discovered a 3.26 millisecond pulsar, PSR J1910-59A, in a binary system with an orbital period of 21 hours. This pulsar was first seen in four consecutive data sets of length 2,100 seconds, showing a significant acceleration (~ -2.2 m s^{-2}) on each data set. A characteristic of this pulsar is that, because of the relatively low dispersion measure (34 cm^{-3} pc), it scintillates markedly, similar to the pulsars in 47 Tucanae, and so it is seen rarely. But, as we have already experienced with 47 Tucanae, the amplification due to scintillation might occasionally help in the detection of additional rather weak MSPs in the same cluster. By devoting a large amount of observing to this cluster, we have already found four additional MSPs. Even more interestingly, all of these four seem to be isolated. Such a large proportion of isolated/binaries (4/1) is not very common in globular clusters. It is possible that other hidden binaries might be present in this cluster.

Figure 12 *The globular cluster NGC 6752, now known to contain at least five millisecond pulsars. (Image from the Digital Sky Survey)*

Another interesting case is the MSP (so far the only one) discovered in NGC 6397. This cluster is close and has a very dense and probably collapsed core. It contains at least four X-ray sources which may be related to MSPs. Despite this, there was no known pulsar associated with NGC 6397 prior to this search. In this cluster we have found PSR J1740-53, a relatively weak pulsar with a spin period of 3.65 milliseconds and an orbital period of 1.35 days. This pulsar has been shown to be eclipsed for more than 40% of the orbital phase. Similar eclipses have been seen in other binary systems, for example, PSR B1957+20, PSR B1744-24A in the cluster Terzan 5 and PSR J2051-0827. However, all of these systems are very close binary systems with orbital periods of just a few hours and very light companions (minimum mass < 0.1 solar masses). In contrast, J1740-53 is in a rather wide binary orbit of period 1.35 days, and has a heavier companion, with a minimum mass of 0.18 solar masses. It seems unlikely that a wind of sufficient density to produce the observed eclipses could be driven off a degenerate companion. Follow-up observations of this pulsar will give insight into the eclipse mechanism in MSPs.

The third interesting case is represented by three millisecond binary pulsars found in another dense cluster, NGC 6266. The first one, PSR J1701-30A, has a pulse period of 5.24 milliseconds, an orbital period of 3.8 days, and the mass function gives a minimum companion mass of 0.19 solar masses. This system is typical of many low-mass binary pulsars, both associated with globular clusters and in the Galactic field. But the two other systems, PSR J1701-30B and PSR J1701-30C, belong to the class of short-period binaries. They have respectively a pulse period of 3.6 and 3.8 milliseconds and orbital periods of 3.8 and 5.2 hours. In particular, the detection of PSR J1701-30B was a challenge, because it shows acceleration peaks and significant acceleration derivatives.

The last, but not the least interesting, case is the ultra-short binary pulsar (and so far the only one) discovered in NGC 6544. This cluster is also one of the closest, densest and most concentrated globular clusters known. Although no X-ray sources are known in the cluster, a radio continuum source was discovered at its centre at the Very Large Array, but up to now, pulsar searches have been unsuccessful. PSR J1807-24 has a spin period of 3.06 milliseconds and is a relatively strong pulsar (Figure 13) with a mean flux density of 1.3 milliJansky. Follow-up observations made at Parkes and Jodrell Bank showed that it is binary, with an extremely short orbital period of 1.7 hours, the second shortest known. Even more interestingly, the projected semi-major axis of the orbit is tiny, only 12 light-milliseconds. The corresponding minimum companion mass is only 0.0089 solar masses or about 10 Jupiter masses.

We have proved that one of the key strategies in a search of the globular cluster system for MSPs, is to devote a large amount of observing to each target. MSPs in globular clusters are often difficult to detect: scintillation in clusters with low dispersion measures, abnormally long eclipses, and unfavourable orbital phases in the case of ultra-short binaries might easily prevent the detection during a single observation. On the other hand, the hidden systems are very often the most interesting ones.

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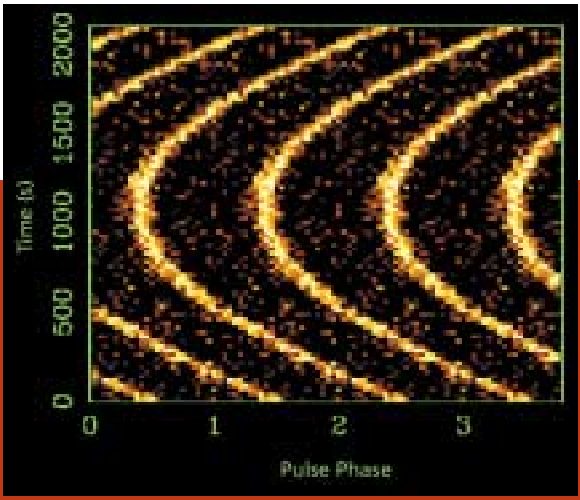

Figure 13 *Variation of observed pulse phase over the 2,100-seconds discovery observation for PSR J1807-24 in the cluster NGC 6544. Each horizontal line in the figure represents the mean pulse profile resulting from 16 seconds of data folded with a period of 3.059415 milliseconds. A pulsar with this apparent period would form a vertical trace in this diagram. The curvature shows that the apparent period varied significantly during the observation due to the pulsar's orbital motion. Although this pulsar is relatively strong (it was not detected in previous searches because of pulse smearing due to dispersion), weaker signals from such binary pulsars are difficult or impossible to detect with conventional "non-accelerated" search code.*

Science highlights

The Parkes radio telescope is the most successful telescope in the world at finding pulsars. Since the initial discovery of pulsars in 1967, over 850 pulsars have been discovered at Parkes. The pulsars can be divided into two main groups. The first group of "normal" pulsars have pulses which typically arrive once a second. The second group are known as the "millisecond pulsars". These stars rotate up to 600 times per second and represent a population of very old stars. These pulsars are believed to be "recycled" neutron stars which have been spun-up after accreting material from a binary companion star.

Photograph
© J Sarkissian

A very young pulsar discovered in the Parkes Multibeam Pulsar Survey

In the past four years, the Parkes telescope and its multibeam receiver have been used to scan the Milky Way for pulsars. Pulsars are ultra-dense rotating neutron stars that pack more mass than the Sun into a radius of a small city. The Parkes Multibeam Pulsar Survey has been phenomenally successful, nearly doubling the known population of these exotic objects.

Among the survey's booty is a pulsar that is among the very youngest known in our Galaxy. PSR J1119-6127 rotates just over twice per second, but is slowing down extremely rapidly owing to the tug of its enormous magnetic field. Its spin parameters can be used to deduce that it is only 1,600 years old, making it the fourth youngest pulsar known in the Milky Way. Young pulsars are exciting to find for a variety of reasons. The youngest of all are usually associated with gaseous nebulae, the result of the cataclysmic supernova explosion that formed them. These supernova remnants (SNRs) are interesting in their own right, teaching us about how the explosion energy is transferred into the surrounding regions of the Galaxy. In addition, young pulsars have a tendency to suddenly start rotating faster. This behavior is known as "glitching" and provides one of the few ways to learn about the interiors of neutron stars. Indeed, a small glitch of magnitude $\Delta P/P = -4.4 \times 10^{-9}$ was observed in the period of PSR J1119-6127 in August 1999. Finally, young pulsars often emit observable X-rays and gamma-rays. Such observations can be used to learn about how neutron stars cool off after their formation, as well as about pulsar emission mechanisms.

An associated supernova remnant

All known pulsars younger than 5,000 years are associated with supernova remnants. Although no supernova remnant was known at the position of PSR J1119-6127, we used the Australia Telescope Compact Array in the 13-cm and 20-cm bands to search for one. The resulting images clearly show a shell of emission of diameter 15 arcminutes centred on the pulsar (Figure 14). This shell shows all the hallmarks of being a previously uncatalogued supernova remnant and we designate it, from its Galactic coordinates, as SNR G292.2-0.5. The estimated ages of the supernova remnant and pulsar are comparable. This and the fact that the pulsar sits precisely at the geometric centre of the shell argues that they are indeed both the result of a supernova explosion that occurred some 1,600 years ago.

We have also observed this system at X-ray wavelengths. Data acquired with the ROSAT and ASCA X-ray satellites reveal extended emission coincident with the supernova remnant (Figure 15). We also detect an X-ray point source, offset approximately 1.5 arcminutes from the pulsar position. No X-ray pulsations are detected from this source, although the upper limit is quite high and does not rule out the source being the pulsar. Our team has requested time on the Chandra X-ray Observatory in order to continue the study of both the young supernova remnant and the point source.

The PSR J1119-6127/SNR G292.2-0.5 system is very different to the famous Crab pulsar and Nebula, which are often cited as being prototypical of young pulsar/supernova remnant systems. The Crab has a rapidly rotating (33 millisecond) pulsar that powers an extremely bright nebula, but shows no evidence for a surrounding shell emission. In contrast, the PSR J1119-6127/SNR G292.2-0.5 system contains a relatively slowly spinning pulsar, no evidence for a pulsar-powered nebula around the pulsar, but a clear shell.

In fact, for the past few years, evidence from a variety of lines of sources has indicated that the Crab pulsar is quite atypical of the young pulsar population. Our discovery of the PSR J1119-6127/SNR G292-0.5 system puts another nail in the coffin of the traditional view.

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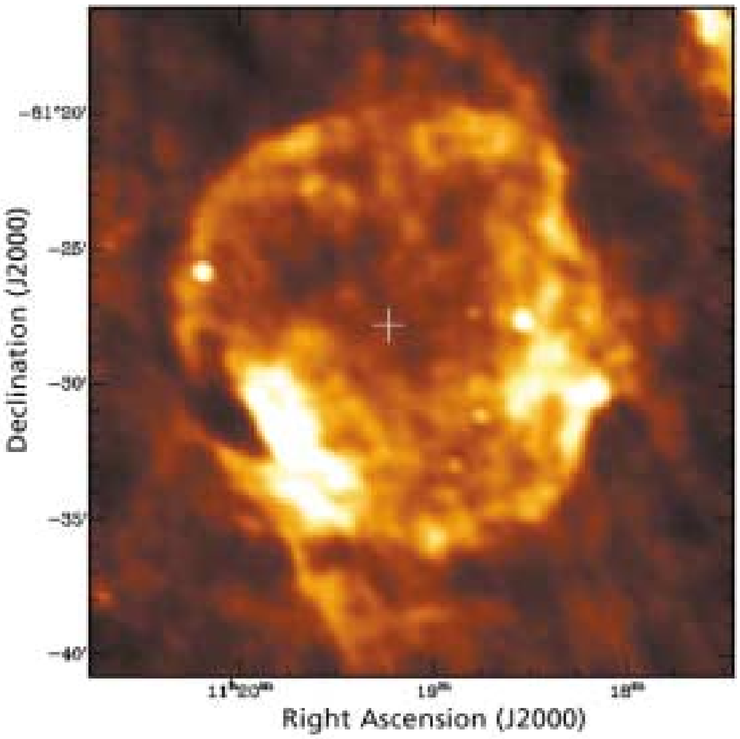

Figure 14 *Compact Array image of the radio continuum emission at 20 cm from a newly discovered young supernova remnant, G292.2-0.5. The cross marks the position of the pulsar.*

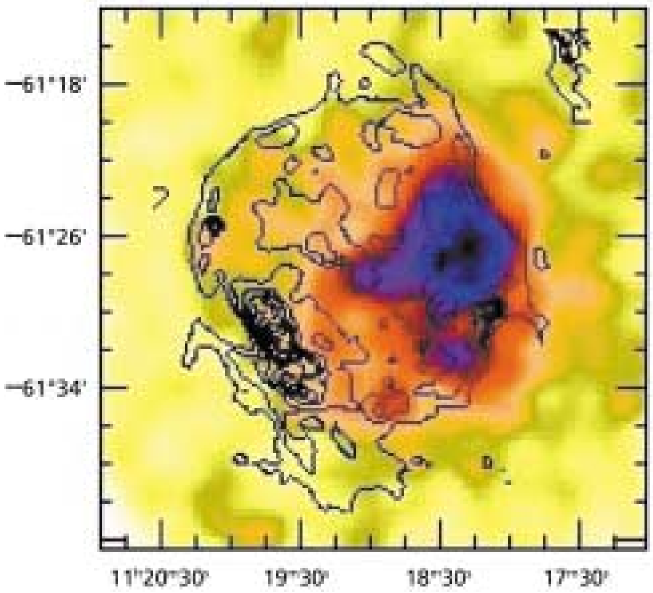

Figure 15 *False colour soft X-ray (0.8–3.0 keV) image of G292.2-0.5, obtained using the Japanese ASCA satellite observatory. The contours represent the 20-cm radio emission seen with Compact Array.*

A new test for General Relativity

A team with members from Swinburne, Caltech and the ATNF has seen General Relativity pass a new test using the very bright millisecond pulsar PSR J0437-4715.

In the early 1990s, the Parkes telescope commissioned an extremely large-scale survey for millisecond pulsars. The survey covered the entire sky south of the equator in 44,000 pointings, each of 2.5 minutes duration. Among the 100 or so pulsars discovered was PSR J0437-4715, a 5.7 millisecond pulsar in a near-circular orbit of 5.7 days around a white dwarf companion. Since then, PSR J0437-4715 has been at the forefront of pulsar timing experiments at the Parkes observatory because of its very close proximity to the Sun, and the range of experiments that are possible with it due to its very bright radio flux.

Early observations revealed that the pulsar was in a nearly-circular orbit and its dispersion suggested a distance of some 140 parsecs (Johnston et al. 1993). It was soon discovered that the pulsar was the source of pulsed X-rays, but notably absent in gamma-rays. PSR J0437-4715 was the first millisecond pulsar to have its white dwarf companion detected, and it soon became obvious that this pulsar had the potential to have its pulse arrival times determined to better than one microsecond accuracies.

Bell et al. discovered that the pulsar had a beautiful bow shock surrounding the pulsar, and after a couple of years the proper motion of the pulsar had been determined to high precision. The standard filterbanks used to observe the pulsar were proving unsatisfactory however, and a new collaboration was begun with Caltech to time the pulsar with a new auto-correlator.

This ultimately led to a determination of the pulsar's parallax. The measurements were so accurate that they permitted a new effect to be observed arising from the changing inclination angle of the system due to the proper motion of the binary. As the pulsar moves one arcsecond every seven–eight years, there is a very small change in the inclination angle of the orbit. Astoundingly, this change is now known to better than one per cent accuracy.

With the arrival of the Swinburne supercomputer in 1998, it became possible to attempt a new, more accurate form of pulsar timing through the method known as "coherent dedispersion". This technique uses a digitised form of the raw voltages and a filtering technique to undo the deleterious effect of dispersion in the interstellar medium. This presents a profile less affected by systematic errors than those induced by filters and other analogue devices but requires the recording of vast amounts of data and many months of supercomputer processing time.

Science highlights

A new instrument known as the CPSR (Caltech-Parkes-Swinburne Recorder) was commissioned in 1998. This can record 20 MBytes of data per second for up to ten hours. 47 Terabytes, or 47,000,000,000,000 bytes of information have now been recorded with this instrument on PSR J0437-4715 alone and the results processed on the Swinburne supercomputer. For every one hour of observing time, it is now possible to determine the arrival time to an accuracy of just 100 nanoseconds. This is the equivalent of a change in the Earth-pulsar distance of just 30 metres!

By accumulating over 600 of these one-hour observations it was possible to detect the annual “wobble” of the pulsar’s orbit as the Earth travelled around the Sun and changed the orbital orientation of the binary. This wobble accurately defined the pulsar’s 3D orientation, and the inclination angle was determined to an accuracy of just 0.1 degrees. General Relativity predicts that as light travels past a massive body, it is delayed due to space-time distortion. The exact shape of this distortion is well-defined, and shown to be present in our data at a high level of significance. This represents a new and important test of General Relativity in pulsar binaries.

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The HI environment of superbubbles in the Large Magellanic Cloud

One of the most important processes that drives the evolution of galaxies is energy injection into the interstellar medium (ISM) from the supersonic stellar winds and supernovae of the most massive stars. These stars are given the spectral designation O and B, and have masses greater than eight solar masses. They are extremely luminous and short-lived, with life expectancies that are, at most, a few tens of millions of years, after which they explode as supernovae. The most massive of these stars are hot enough to ionize hydrogen, thereby producing the beautiful nebulae that are signatures of young star-forming regions.

Most stars, including OB stars, are formed in groups. Thus, the combined energy of multiple stellar winds and supernovae is delivered to the ISM from locations centered on these stellar groups or OB associations. The result is the creation of a large shell of gas, or superbubble, around these stars. Depending on the size and age of the OB association, and the conditions in the ambient ISM, the superbubble can be small, only a few parsecs in radius, or in the case of a starburst, it can potentially blow a gigantic superwind entirely out of the galaxy.

This superbubble action has fundamental consequences for galaxy evolution. In the first instance, there is clearly a great deal of mechanical energy that is transferred to the ISM. However, about half of the available supernova mechanical energy is thought to shock-heat gas in the superbubbles to temperatures of 1–10 million degrees Kelvin. This low-density, hot gas fills the volume of the superbubbles, and its pressure drives their shell growth. Eventually, the hot gas is thought to somehow escape the shells and form a hot component of the ISM. Thus, the more active the star formation and superbubble activity, the more important the hot gas fraction of the ISM. If the hot gas overflows the galaxy and its gravity, it could emerge into the intergalactic medium. The fate of the hot gas is especially critical because it bears the heavy elements created during the supernova explosions, which are a vital record of galaxy evolution.

We are therefore keenly interested in understanding how superbubbles evolve. For the last 30 years, the conventional model has been that of a simple, energy-conserving bubble with constant energy input. However, some discrepancies between the predictions and observations have been reported. Since there are many factors affecting the observed parameters, it is unclear how to interpret the discrepancies and evaluate their importance. One of the critical factors is the density and clumpiness of the ambient ISM which is swept up by the expanding superbubbles. A high-density environment will slow down the growth while a clumpy

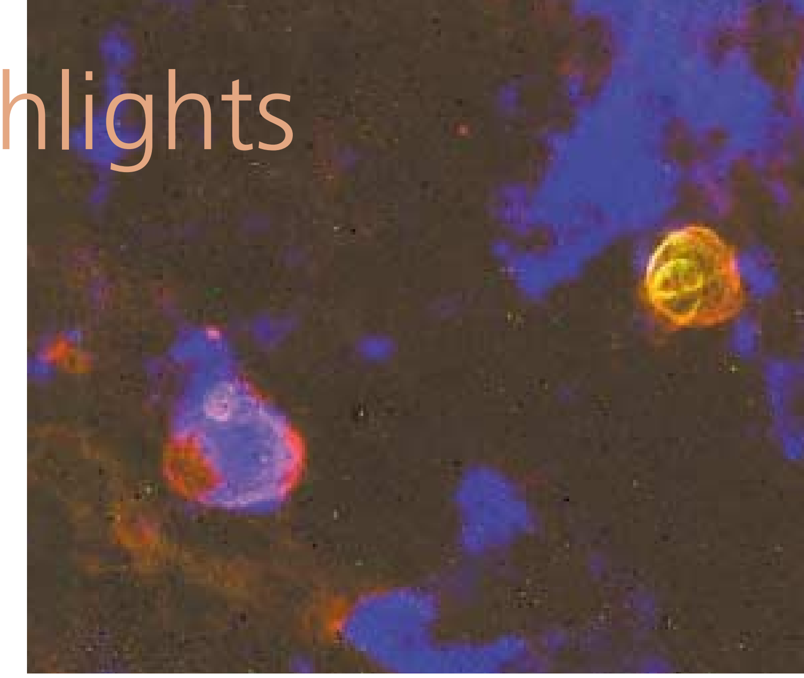

Figure 16 (a) A composite image of the region around DEM L25 (right) and DEM L50 (left). Red and green show optically-emitting ionized hydrogen and doubly-ionized oxygen, respectively; blue shows neutral hydrogen. The superbubbles are each about 100 parsecs in diameter. North is up, east is to the left.

one could cause knots to be engulfed; their evaporation by the shocks and hot gas takes energy away from the rest of the superbubble. If too much material is evaporated into the hot gas, it will cool, also causing the shell to stop growing, and eliminating the superbubble as a source of hot gas for the ISM.

The ambient environment of most superbubbles is cool, neutral hydrogen (HI), which emits light at a wavelength of 21 cm, observable with the Australia Telescope Compact Array. In order to better understand their environment, we mapped the HI distribution around three young superbubbles in the Large Magellanic Cloud. This neighbouring galaxy offers a clear, yet close-up, view of superbubbles, in contrast to our own Galaxy, where we need to peer through confusing material in the plane of the disk. Our three targets have well-constrained parameters, in particular, detailed information on the parent OB stars, and velocity information on the optically-emitting nebular gas.

Figure 16 (above right) shows a composite image of the optical nebular gas (red and green) that is ionized by the OB stars, and the HI gas (blue), for DEM L25 and L50. We also mapped the HI environment for a third object, DEM L301 (below). We find that, although the optical shells are all extremely similar, the neutral environments could not be more different! DEM L25 appears nestled between clouds of HI, and its expansion can be seen to be colliding with an HI cloud on the west. On the other hand, DEM L50 is in a large region devoid of HI, but itself shows a massive neutral component blanketing part of the shell. In contrast to both of these, DEM L301 shows no correspondence whatsoever between the optical and HI distributions. While we have gained some insight on the evolution of these individual objects, this work vividly demonstrates that the ambient environments of superbubbles vary dramatically, and that this is not readily apparent from the optical data alone. It is therefore difficult to infer anything about the neutral gas distribution without obtaining direct observations.

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Figure 16 (b) A similar composite image of the region around DEM 301.

The HIPASS Bright Galaxy Survey

The HI Parkes All-Sky Survey (HIPASS) has provided the first ever survey of extragalactic neutral hydrogen (HI) over the southern sky. This survey was completed in March 2000 and the data were released in May 2000 (http://www.atnf.csiro.au/multibeam/release). An extension into the northern hemisphere to the northern limit of the Parkes telescope is ongoing. Extensive efforts are now underway to mine the rich HIPASS data set. The most important effort is in finding and cataloguing the galaxies, both previously known galaxies and newly discovered galaxies. Considerable effort is being contributed by several teams including the University of Melbourne, the Swinburne Centre for Astrophysics and Supercomputing, and the ATNF. One of the first products is the HIPASS Bright Galaxy Catalogue, which is a catalogue of the 1000 apparently brightest HI galaxies in the southern hemisphere.

The HIPASS Bright Galaxy Catalogue represents the first unobscured view of the nearby galaxy distribution in the southern sky. Neutral hydrogen gas in nearby galaxies can be detected easily from radio observations whereas optical and infrared surveys are limited by the obscuration of light from dust and stars of our own Galaxy. HIPASS has provided many new detections of galaxies previously hidden behind the plane of the Milky Way in the so-called Zone of Avoidance (ZOA).

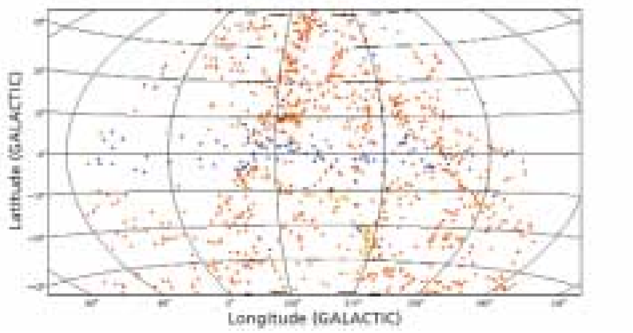


Figure 17 *Aitoff projection showing the spatial distribution of the 1000 brightest HIPASS sources in Galactic coordinates. The new galaxies are marked in blue, HI clouds in green, High Velocity Clouds in orange and all other galaxies in red.*

Figure 17 shows the spatial distribution of the 1000 brightest HIPASS galaxies. Of these, 84 have no counterparts catalogued in the NASA/IPAC Extragalactic Database. Most of the newly discovered galaxies lie in

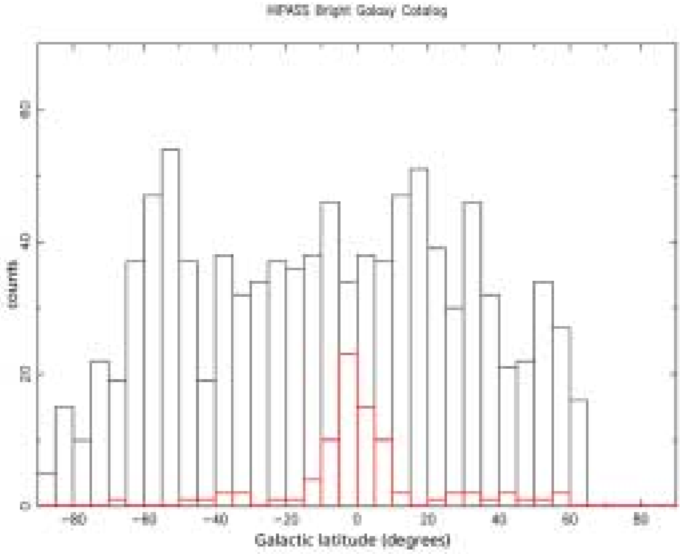


Figure 18 *A histogram showing the Galactic latitude distribution for the 1000 brightest HIPASS galaxies. The distribution for galaxies discovered by HIPASS is shown in red.*

or close to the Zone of Avoidance (Figure 18). 58 of the new galaxies have Galactic latitudes below 10 degrees while 21 have latitudes above 15 degrees. For 17 of the new discoveries, the HIPASS and optical velocities disagree. Compact Array and optical follow-up observations of these and many other galaxies are under way to confirm their identifications.

The new galaxies found outside the Zone of Avoidance can be divided into two groups, those with optical counterparts and those without, the latter being very rare. Figure 19 shows optical images from the Digital Sky Survey for ten of the galaxies with optical counterparts. These are mostly compact, late-type galaxies. We also detected several unusual sources including HI 1225+01 (the Virgo cloud) and a large hydrogen cloud, HIPASS J0731-69, which is well-separated from its apparent host galaxy NGC 2442 and shows no evidence of optical emission or star-formation (page 32). Also remarkable were the detection of HIPASS J1712-64, HIPASS J1718-59 and several other HI clouds which do not have any obvious optical counterparts. Their striking location along the Supergalactic Plane leads to speculation that such HI clouds may be the dregs of the galaxy formation process. An alternative theory is that these clouds may be high-velocity ejecta due to a tidal interaction between our Galaxy and the Magellanic Clouds.

Figure 20 shows the velocity distribution for the 1000 brightest HIPASS galaxies. The distribution is dominated by galaxies with velocities between 800 and 2000 km s $^{-1}$. For these velocities the most striking structures, shown by the spatial distribution of galaxies, are the Supergalactic Plane and the Local Void. Several new galaxies with velocities above 1000 km s $^{-1}$ have been found which better define the boundaries of the Local Void. Although we know from optical surveys that the galaxy large-scale structure is far from homogeneous, it is important to study the sky uninhibited by obscuration. Many known structures continue into and across the optical Zone of Avoidance and create a beautiful network of galaxies, dominated by groups, strings and bubbles.

B. Koribalski, L. Staveley-Smith (ATNF); V. Kilborn (Melbourne University); S. Ryder (AAO) and the HIPASS/ZOA teams

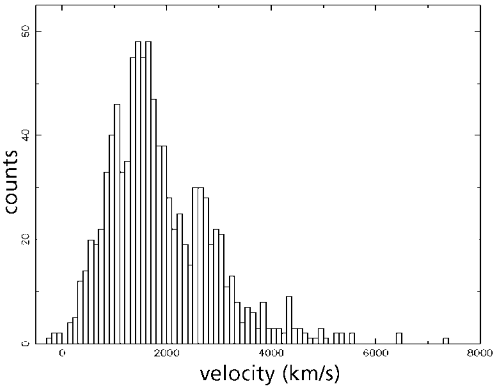


Figure 20 *Histogram of the HI systemic velocities of the 1000 brightest HIPASS galaxies.*

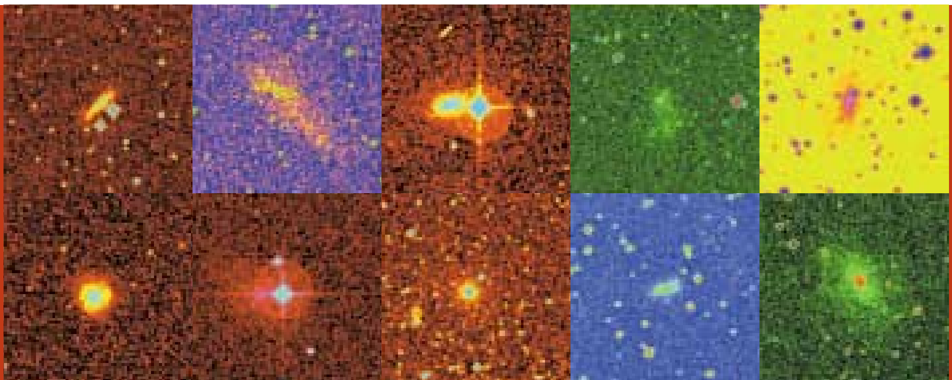


Figure 19 *Optical images from the the Digitised Sky Survey for ten new galaxies detected in the HIPASS Bright Galaxies Survey.*

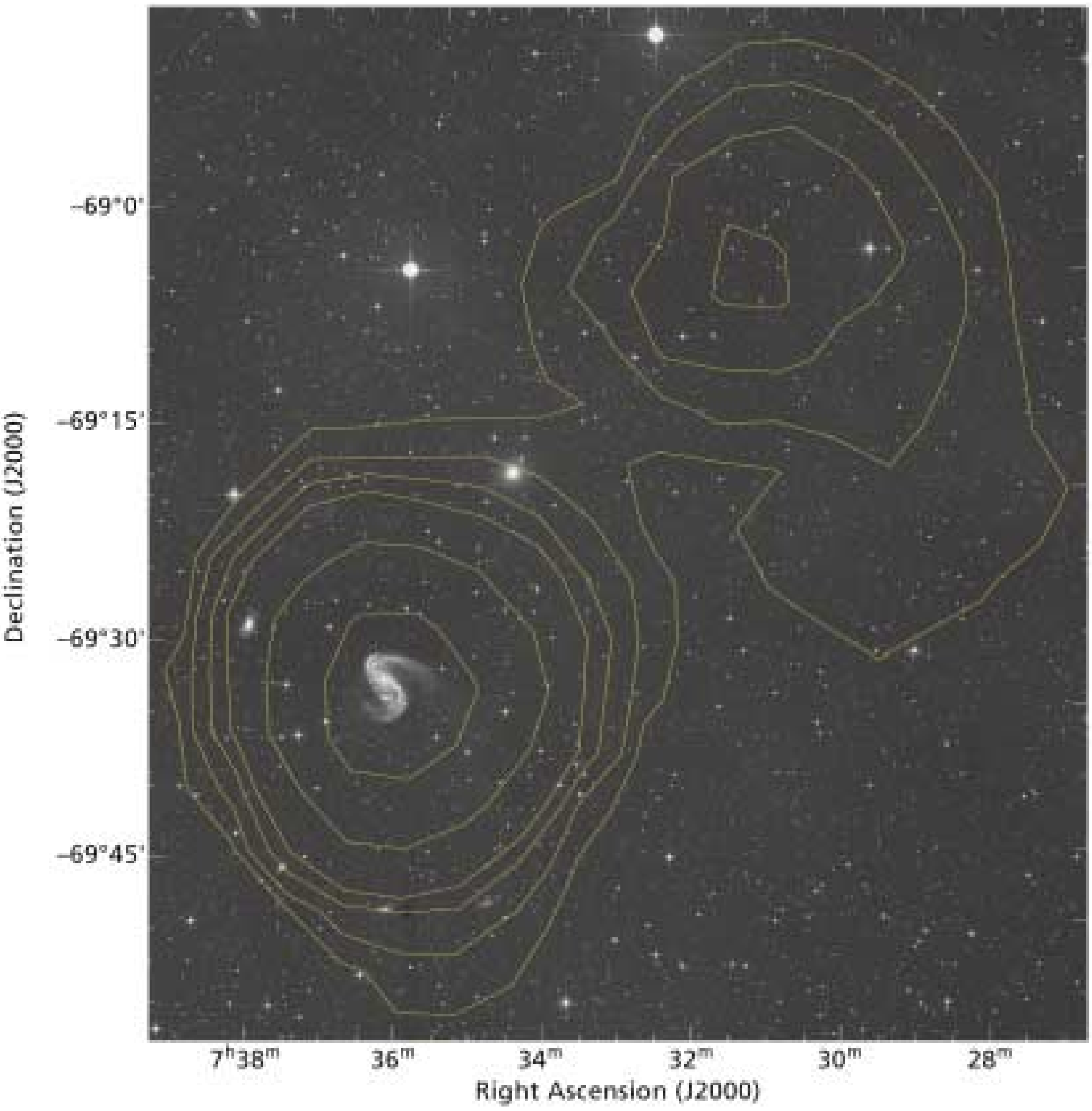
HIPASS turns up new gas in the NGC 2442 group

The HI Parkes All-Sky Survey (HIPASS), carried out between 1997 and 2000 with the Parkes multibeam receiver, continues to yield intriguing new discoveries about the local universe. While studying the properties of the 1000 brightest sources of neutral hydrogen (HI) emission in the HIPASS database, we noticed a previously unknown HI cloud adjacent to NGC 2442, a bright spiral galaxy in the constellation of Volans (Figure 21). What makes this find so unusual and so exciting is that the cloud appears to have almost one third as much gas as NGC 2442 itself, and yet not a single star, or evidence of any recent star formation, has been found to go with it.

While this is not the first such cloud found in HIPASS (see the report by Kilborn et al. in the 1999 *ATNF Annual Report*), it is one of the most massive discovered outside of our Local Group of galaxies. The cloud, designated HIPASS J0731-69, contains of order 10^9 solar masses of hydrogen, which begs the question: where did all this gas come from? NGC 2442 has long fascinated astronomers, because of its somewhat distorted appearance. The two main spiral arms are quite different, with the northern arm being narrow, acute, and cleft by a striking lane of dust; by contrast, the southern arm is broader, more open, and criss-crossed by numerous dust patches. In her PhD study with the Compact Array, Sally Houghton found indications that the gas disk of NGC 2442 is stretched in the direction of HIPASS J0731-69, but saw no other signs of a direct connection between the two.

If HIPASS J0731-69 was indeed torn out of NGC 2442 by a passing galaxy, then it could not be any of the nearby faint dwarf galaxies that have previously been suggested by others as a potential partner. Instead, a much larger object must be involved, such as the elliptical galaxy NGC 2434 (visible in the overlap region between NGC 2442 and HIPASS J0731-69, but apparently lacking any HI of its own), or the more remote galaxy pair NGC 2397 and NGC 2397A. One other possibility is that rather than tidal forces being involved, HIPASS J0731-69 was stripped as the result of NGC 2442 ploughing its way through a dense inter-galactic medium of hot gas. Such a hot medium ought to be visible in X-rays, but none has yet been detected in this region.

Despite the relatively coarse resolution of HIPASS, significant structure in HIPASS J0731-69 is apparent both spatially and in the velocity dimension. At velocities below 1400 km s^{-1}, the cloud appears as two clumps which then appear to merge together (as well as with NGC 2442 itself) at higher velocities. This structure is reminiscent of the Magellanic Stream arcing around our own Galaxy, and is most unlike the kind of motions expected of gas within a typical dwarf or spiral galaxy. Perhaps it is no surprise then that we have



yet to locate any galaxy-like optical counterpart to this gas.

Follow-up observations of HIPASS J0731-69 are underway with the 375-m configuration of the Compact Array, to tell us more about the small-scale structure and internal kinematics of the gas. In addition, a deep optical survey of the region is planned with the Wide Field Imager CCD mosaic on the Anglo-Australian Telescope, to confirm the lack (or otherwise) of stars and ionized gas within this cloud. The very existence of HIPASS J0731-69 has forced us to rethink the origin of the lopsidedness in NGC 2442, as well as revise upwards our predictions for the total amount of mass contained in loose groups such as this.

S. D. Ryder (Anglo-Australian Observatory); B. Koribalski (ATNF) and the HIPASS/ZOA teams

Figure 21 *HIPASS map of HI intensity (contours), overlaid on an optical image from the Digitised Sky Survey. Note the asymmetry of the spiral arms in NGC 2442 at the centre of the source at lower left, and the lack of any galaxy near the peak of HIPASS J0731-69 to the upper right.*

Recurrent activity in giant radio galaxies

Giant radio galaxies constitute a class of radio sources with linear sizes of over a million parsecs.

When a black hole at the centre of an elliptical galaxy is fuelled by matter spiralling in from a surrounding accretion disk, twin beams of matter often emerge from this central engine in opposite directions at relativistic speeds. Radio galaxies are created when the beams form lobes of ionized gas, known as plasma, on opposite sides of the parent galaxy. In powerful radio galaxies, the radio beams appear to end in hotspots with the brightest emission at the extremities of the double-lobed radio sources. The lobes are believed to be formed from plasma which has flowed backwards from the hotspots towards the central galaxy. Usually, the double radio sources are found to have sizes of up to a few hundred kilo-parsecs; however, in the rare giant radio galaxies, the radio sources are at least a million parsecs, about a hundred times bigger than the extent of the optical host elliptical galaxy.

A key problem is to understand why giant radio galaxies are so large. A few years ago, some of us studied the radio morphologies in giant radio galaxies by imaging several southern sources with the Australia Telescope Compact Array. We found a variety of morphological features which indicated that the beams from the central engine, which powered these radio galaxies, might have been interrupted in the past. We concluded that giant radio galaxies may have attained their large sizes as a result of a restarting of their central engines in multiple phases of activity along roughly similar directions.

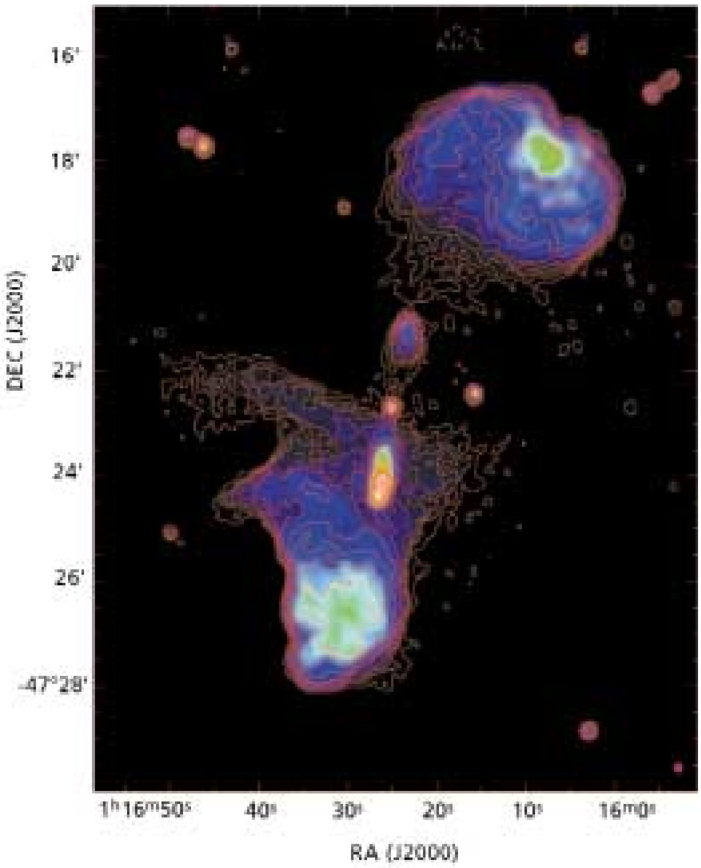


Figure 22 *A Compact Array image of the 20-cm radio continuum emission from the giant radio galaxy B0114-476.*

Recently, we imaged the detailed structure in the giant radio galaxy B0114-476 with the Australia Telescope Compact Array (Figure 22). Surprisingly, this powerful radio galaxy does not have strong hotspots at the ends of the two large lobes — while intense features are seen as bright peaks symmetrically placed on either side of the central galaxy. We seem to have caught this powerful giant radio galaxy in an act of rejuvenation. The likely scenario for this galaxy is that the outer diffuse lobes, which lack hotspots, represent relics of past activity. The beams from the central engine stopped, then restarted, and we are now seeing a new pair of beams emerging through the relict cocoon of relativistic plasma. The inner double itself has a linear size of 700,000 parsecs: its size is much larger than for typical double radio galaxies. The overall morphologies of the two inner lobes mimic the respective outer lobes: the northern inner and outer lobes are broad in contrast to the southern inner and outer lobes which are more cylindrical in shape. This indicates that the external medium on a given side may be affecting the inner and outer lobe morphologies similarly and the differences between the two sides may be attributed to differences in the ambient medium.

The ATCA image tells us that giant radio galaxies can be born again and possibly live multiple lives: could this be the cause for their large sizes?

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Photograph © CSIRO

The gaseous halos of three spiral galaxies

We have observed three southern edge-on spiral galaxies with the Australia Telescope Compact Array: NGC 1511, NGC 7090 and NGC 7462. The aim of these observations was to investigate whether galaxies with unusually warm dust, heated by massive stars, have gaseous halos — in particular radio halos tracing the presence of relativistic electrons expelled from the galaxy disks by multiple supernova remnants. Such halos are seen most easily in edge-on galaxies; for this viewing geometry it is possible to determine directly whether the radio emission arises from the galactic disks or from more extended regions.

Several Compact Array configurations were used to obtain radio continuum data at wavelengths of 13 and 20 cm, with good angular resolution and sensitivity. The success rate of the observations was 100% — all three galaxies show extended radio halo emission. The most spectacular of these, NGC 7090, is shown in Figure 23. The 20-cm radio emission is shown as a set of contours, overlaid on the optical image of the galaxy from the Digital Sky Survey. The radio emission is seen as a gaseous halo which is considerably extended on both sides of the optically-visible disk of the galaxy. The synchroton radio emission is weaker and less extended at 13 cm than at 20 cm. The radio halo of NGC 7090 is one of the most extended halos around a radio galaxy known to date.

The radio properties of the three newly detected halos provide new insights on the star-formation history of the observed galaxies. The radio halo emission occurs from relativistic electrons which are released during multiple supernova explosions over a short period of time. During a supernova explosion, most of the mass of a star is violently ejected into the interstellar medium. Both X-ray emitting gas, heated to temperatures of millions of degrees, and electrons producing synchroton radiation, escape from the explosion site. The transfer of matter away from the sites of supernovae is a cosmologically important process in which heavy elements, the building blocks of all life forms created in stellar nuclear fusion processes, are distributed in galaxies. The propagation of metals through the Universe determines its chemical evolution over cosmological time scales.

In recent years, gaseous halos have been reported from radio, optical or X-ray data for at least 20 galaxies. The gaseous halos are detected in the radio and X-ray regions of the spectrum, because the relativistic electrons and hot gas are produced simultaneously by supernova explosions and escape from the galaxy disks. While some stars have already exploded as supernovae, others, with a longer lifetime or born later, still survive. The surviving stars emit ultraviolet radiation, causing the surrounding gas to glow as diffuse optical light, including gas located in the halo. This is seen most prominently as hydrogen-alpha line emission from hydrogen atoms. The massive stars also heat the surrounding dust. Galaxies with warm dust are therefore good candidates for searching for galaxy halos. The gaseous halos are intrinsically faint and difficult to detect and the number of detections is still rising. The most recent generation of telescopes and instruments, such as the Compact Array, allow us to pick up their faint signals.

Such halos are now known to be an integral part of galaxies with high star-formation rates. Despite its relatively low star-formation rate, our own Galaxy, the Milky Way, also has a gaseous halo, identified in the 1970s from radio observations taken with the Parkes radio telescope and elsewhere. For our own Galaxy, it is difficult to study large-scale evolutionary processes because of the strong obscuration of light within the Galactic plane. Radio observations such as those of NGC 7090 provide a grand overview of large-scale processes occurring in other spiral galaxies and, by comparing the properties of these external systems with those of the Milky Way, new insights into our own Galaxy.

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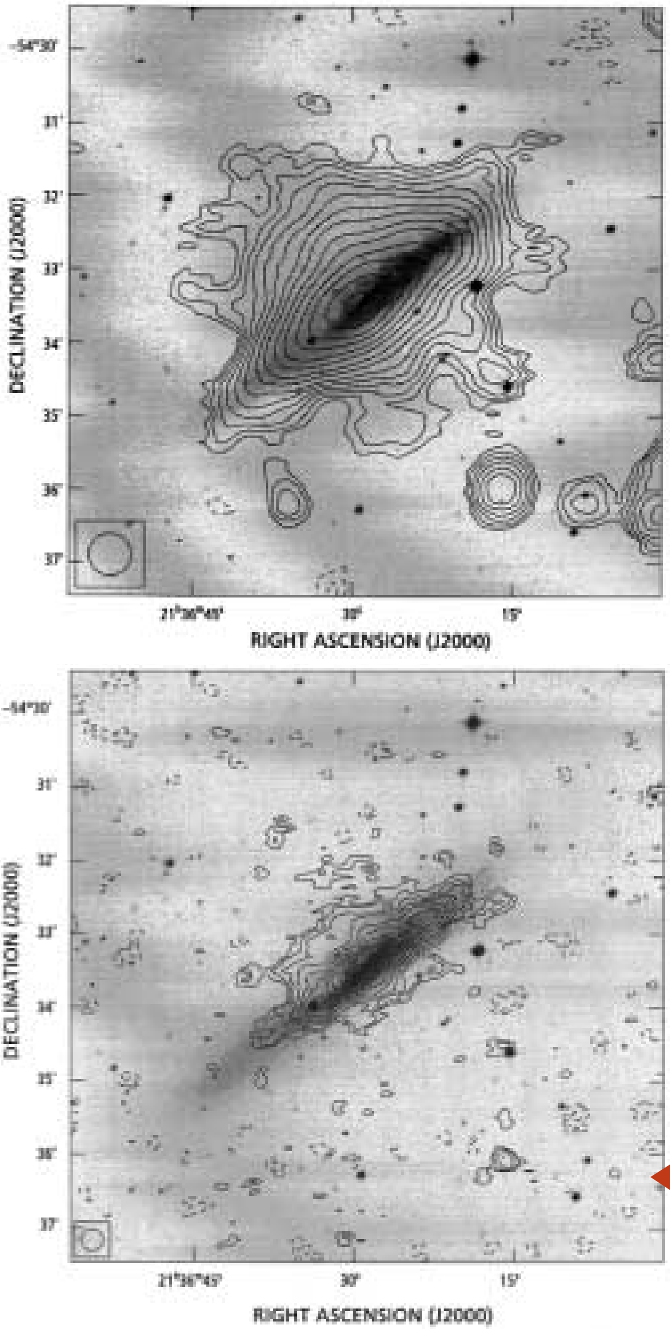

***Figure 23** Australia Telescope Compact Array image of the 20-cm (top) and 13-cm (bottom) radio continuum emission from the edge-on spiral galaxy NGC 7090 (contours), overlaid on an optical image of the galaxy from the Digital Sky Survey.*