ASTRONOMY REPORTS

First observations of SNR 1987A at 12 mm

One of the principal scientific justifications for the 12-mm system on the Compact Array, part of the 1997 MNRF upgrade project, was to obtain higher resolution images of continuum sources, and of the radio remnant of SN 1987A in particular. SN 1987A, first observed on 23 February 1987, was (and remains) the brightest supernova observed for 400 years. It occurred in the Large Magellanic Cloud, close to the giant nebula 30 Doradus. Optically, the supernova was visible with large telescopes for more than a decade, but the initial burst of radio emission, the "radio supernova", faded in just a few days. Following this, no radio emission was detected for more than three years. In July 1990, radio emission was again detected with the Molonglo Synthesis Telescope and (for the first time) with the Compact Array. Since then, monitoring observations at both Molonglo and the Compact Array have shown that the emission has increased more or less steadily (Figure 11). This increasing emission signals the birth of a supernova remnant, the first time such an event has been observed.

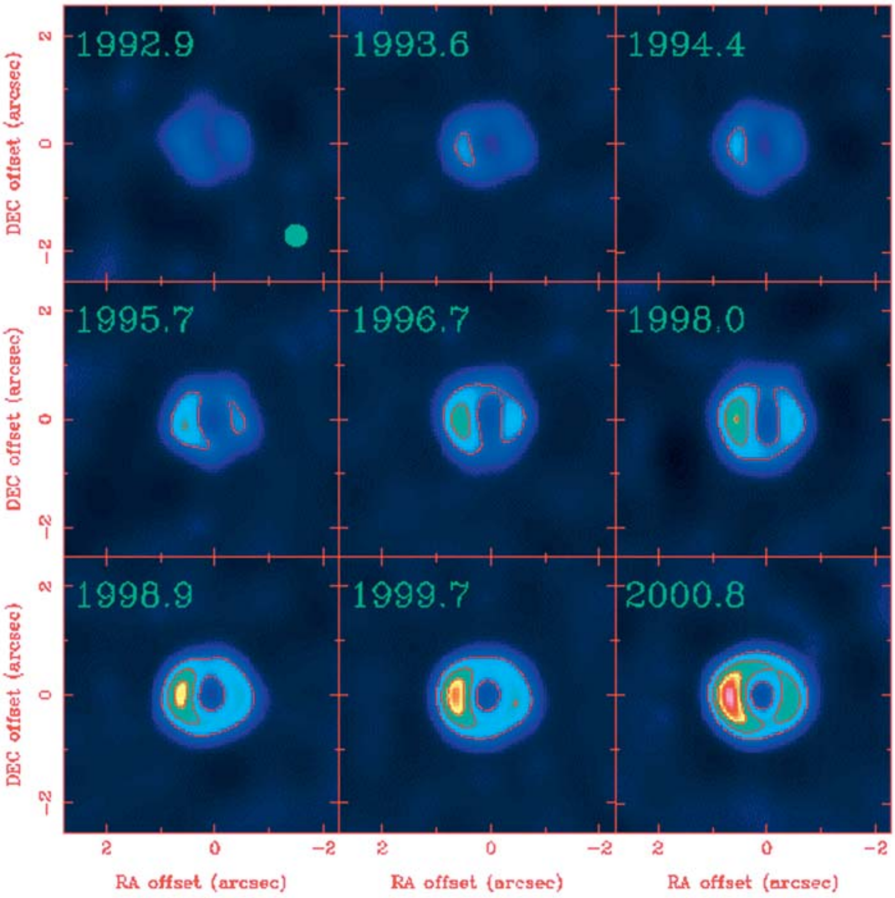


Figure 11 *This set of nine images, obtained between 1992 and 2000 with the Australia Telescope Compact Array, shows the radio emission at a wavelength of 3 cm from the expanding supernova remnant SNR 1987A.*

Observations with the 6-km Compact Array at 3 cm have a diffraction-limited beam size of slightly less than 1 arcsecond. Currently, the diameter of the remnant, SNR 1987A, is about 1.6 arcseconds, so it is barely resolved. We have been able to apply super-resolution techniques to the data to obtain apparently reliable images with a resolution of 0.5 arcsecond. These show a shell structure, with enhanced emission on the east and west sides, corresponding to the major axis of the projected central ring observed in optical recombination lines and lying within this ring.

At the completion of the MNRF upgrade, expected in the first half of 2003, all six Compact Array antennas will be equipped with 12-mm systems. It is likely that this system will provide the highest-resolution high-dynamic-range continuum images that are possible with the Compact Array. The minimum beam size will be about 0.3 arcsecond, significantly better than the super-resolved 3-cm beam size. It is possible that super-resolution can be applied to the 12-mm images as well, resulting in a resolution comparable to that of the Hubble Space Telescope and exceeding that of the X-ray satellite observatory *Chandra*. This will be of enormous benefit in improving our understanding of the astrophysics of this system.

In October 2001, three antennas (CA02, 03 and 04) were equipped with interim 12-mm receivers and phase-stable local oscillator systems. Twelve hours of data on SNR 1987A were obtained at two frequencies, 16.96 and 18.88 GHz, within the 12-mm band. The systems were dual polarization and had a bandwidth of 128 MHz at each frequency. Phase stability was excellent for all but the last 2.5 hours. The maximum baseline was 1.1 km, giving a beam size of approximately 2.8 by 1.8 arcseconds. The remnant was clearly detected at both frequencies, with an integrated flux density of 20 milliJansky at the lower frequency and 18 milliJansky at the higher frequency. These values are slightly higher than those predicted from the cm-band spectrum, but consistent with the prediction within the uncertainties. Figure 12 shows the image obtained by combining data from the two frequencies. The remnant was barely resolved by these observations, giving an image which is similar to the diffraction-limited image at 3 cm.

This is the first image of SNR 1987A at 12 mm. The results were reported in an IAU Circular, the first publication resulting from the MNRF upgrade. They make it clear that the completed 12-mm system will be able to produce superb images of the supernova remnant.

R. N. Manchester, L. Staveley-Smith, A. K. Tzioumis, M. J. Kesteven, J. E. Reynolds (ATNF); B. M. Gaensler (Centre for Space Research, Massachusetts, USA); V. C. Wheaton (ATNF/Sydney University): N. S. Bizunok (Centre for Space Research, Massachusetts, USA/Boston University, USA)

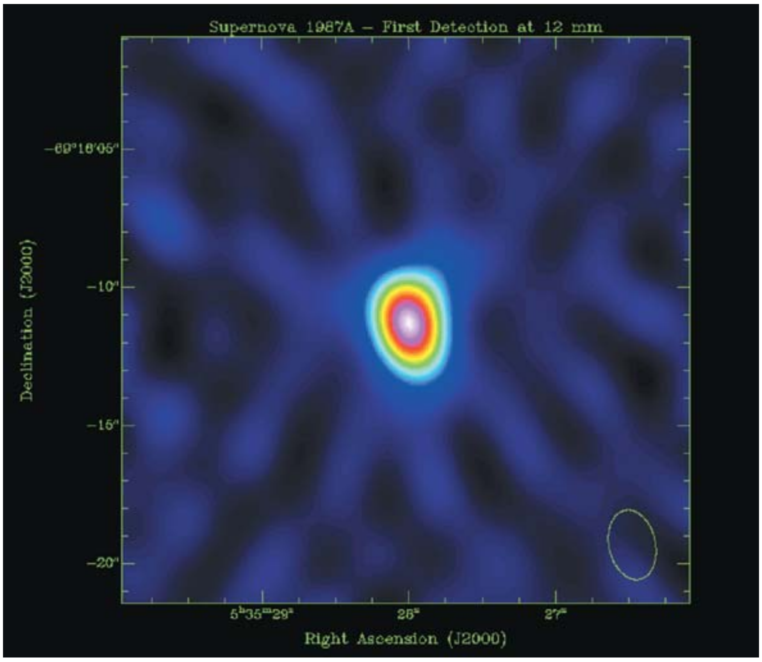


Figure 12 *Composite image of SNR 1987A obtained in October 2001, by combining Compact Array data at 17 and 19 GHz. Three Compact Array antennas were used with a maximum baseline of 1.1 km. The ellipse in the lower right corner shows the diffraction-limited beam size.*

HIPASS J0352–6602: a nearby galaxy forming its first stars?

We have recently discovered a giant intergalactic cloud of neutral hydrogen gas that challenges many of our ideas about how galaxies form and evolve.

The cloud was discovered in October 2001 from radio images of an elliptical galaxy, NGC 1490, taken with the Australia Telescope Compact Array. This galaxy was targeted because data from the recently completed HI Parkes All Sky Survey (HIPASS) implied that it contained an unusually large amount of neutral hydrogen gas for an elliptical galaxy. Unlike our own Milky Way and other spiral galaxies, giant elliptical galaxies like NGC 1490 undergo a rapid period of star formation in the early universe which uses up almost all the available gas. When neutral gas is seen in these galaxies, it is usually a sign that the elliptical galaxy has recently swallowed a smaller, gas-rich galaxy.

Surprisingly, the Compact Array radio image (Figure 13) showed that although the gas found by HIPASS lies at the same distance as NGC 1490, it is associated with another, previously unknown galaxy which is barely visible to optical telescopes. This gas cloud, now designated HIPASS J0352–6602, is at least as large as our own Milky Way Galaxy, but is apparently only just starting to form its first generation of stars. In contrast, its companion galaxy NGC 1490 turned all its gas into stars very rapidly during a short period in the early Universe. This extreme diversity in star-formation history between members of a galaxy group is quite unexpected, especially since theories of galaxy formation predict that giant neutral hydrogen clouds of this kind should be found only in very isolated environments.

One possibility is that HIPASS J0352–6602 has only just begun to condense out of an intergalactic gas reservoir surrounding the galaxy group of which NGC 1490 is a member. If so, a significant fraction of the baryons in the local Universe may be associated with intergalactic gas clouds rather than with visible galaxies. Further study of HIPASS J0352–6602 is in progress to test these ideas.

E. Sadler (University of Sydney); T. Oosterloo, R. Morganti (Netherlands Foundation for Research in Astronomy, Netherlands)

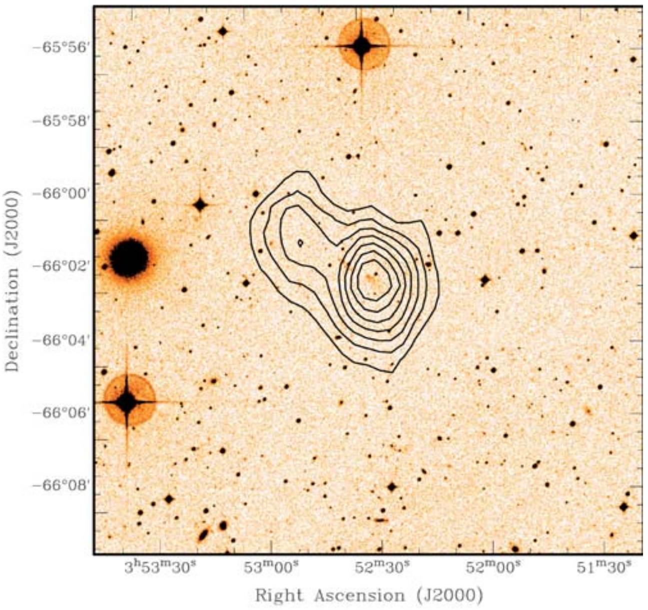


Figure 13 *Radio emission at a wavelength of 21 cm from neutral hydrogen is shown here as black contours superimposed on an optical image from the Digitized Sky Survey (UK Schmidt Photographic Atlas). The elliptical galaxy NGC 1490 is seen on the left of the image. The hydrogen cloud is associated with a barely visible and previously unknown galaxy.*

Polarization in methanol masers

The strongest class II methanol maser emission is produced by the 6.7 GHz transition, which was discovered in 1991. These methanol masers are only found in high-mass star-formation regions and are often closely associated with main-line OH masers. From the first high resolution observations of class II methanol masers many sources have been found to show a simple spatial and velocity distribution, which contrasts with the complex morphology usually observed in OH masers. Some of the methanol masers have a linear spatial distribution and monotonic velocity gradient, consistent with the maser arising in an edge-on rotating disk (Figure 14). However, to date, this hypothesis has not been conclusively demonstrated for any source. If some methanol masers do originate in disks then they would represent a unique opportunity to study accretion in high-mass star formation at unprecedented resolution.

One aspect of methanol masers that has not previously been investigated in detail is their polarization properties. Polarized emission from masers occurs when the orientation of the molecules producing the maser radiation is not random. Radio-frequency molecular lines are produced between rotational quantum levels and these only arise in molecules that have a dipole moment. Thus magnetic fields are able to align masing molecules, and the degree to which this occurs depends upon the strength of the field and the rate at which collisions and radiation interactions disrupt the alignment process. Methanol is a diamagnetic molecule and the separation of the Zeeman components produced by magnetic fields of 1 – 10 milliGauss (typical of star-formation regions) is much less than the width of the maser line. In these circumstances modest linear polarization can occur, but any circular polarization is expected to be very weak.

The exact role that magnetic fields play in the star-formation process is still a matter of heated debate, and as the polarization properties of masers depend critically upon the magnetic field they are potentially useful probes. In addition, the magnetic field associated with a circumstellar accretion disk is expected to be well ordered, and so if the methanol masers do originate in a disk then the polarization should show

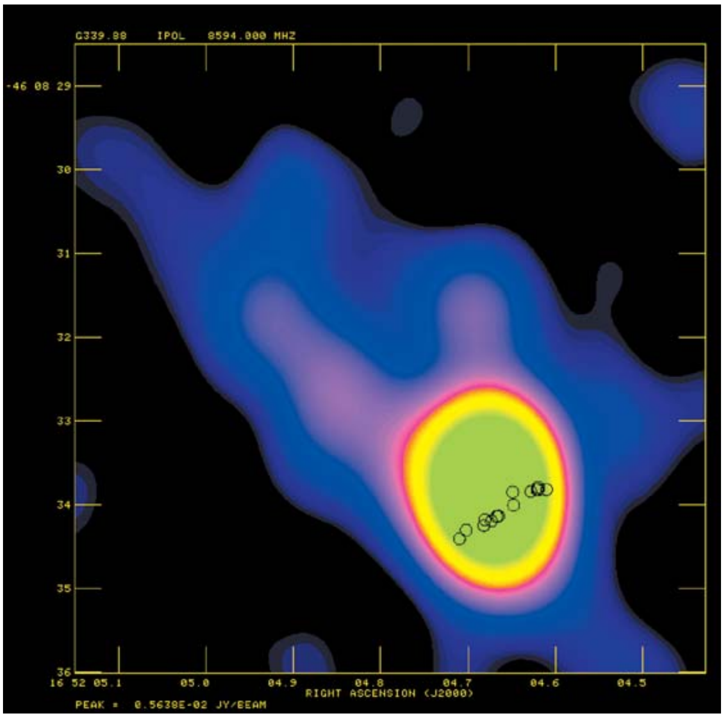


Figure 14 *This false colour image shows the radio continuum emission at 8.6 GHz from the ultra-compact HII region G339.88–1.26 (observed with the Australia Telescope Compact Array). The overlaid circles represent the positions of the associated methanol masers at 6.7 and 12.2 GHz.*

regular structure. If we naively assume that the magnetic field will be oriented perpendicular to the disk (from an edge-on perspective) then the masers are propagating perpendicular to the magnetic field (Figure 15). In this situation the position angle of the linear polarization will also be perpendicular to the magnetic field (i.e. parallel to the position angle of the disk). This ignores the effects of Faraday rotation, which will not mask the presence of regular structure, but may shift the position angle of the polarization vectors.

The Australia Telescope Compact Array has been used to make the first full polarization observations of 6.7-GHz methanol masers. Four strong sources were observed and linear polarization at levels between a few and 10% were detected towards all sources. None of the sources show circular polarization stronger than 1.5%. The majority of spectral features show linear polarization at levels of 2 – 3%, with a small number of (usually) strong features exhibiting levels of linear polarization of up to 10%.

G339.88–1.26 is one of the best methanol maser disk candidates. The maser emission is coincident with a weak ultra-compact HII region and there is some evidence for an outflow perpendicular to the line traced by the masers (Figure 14). The greatest degree of linear polarization in this source is 10%, which is exhibited by one of the weaker maser features (Figure 16). The position angle shows smooth variation across the velocity range decreasing from near 90 degrees at the lowest velocities to approximately 50 degrees at the highest velocities. For a number of features the position angle changes significantly across the line, perhaps indicating some spectral blending. Polarization VLBI observations which resolve the individual maser spots are required to determine if this is the case. This result is not consistent with a simple model of the maser emission arising in an edge-on disk, as that should produce polarization vectors with a small range of position angles, even if they are not parallel to the disk due to Faraday rotation.

S. Ellingsen (University of Tasmania)

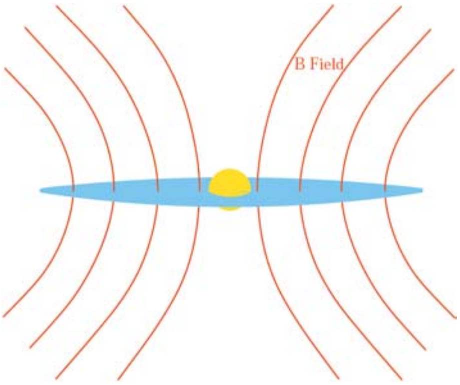


Figure 15 *A naïve model of the magnetic (B) field associated with a high-mass star still in the process of accretion. In reality the field above and below the disk is likely to be twisted by the rotation of the system, which will also affect the angle of the field as it passes through the disk.*

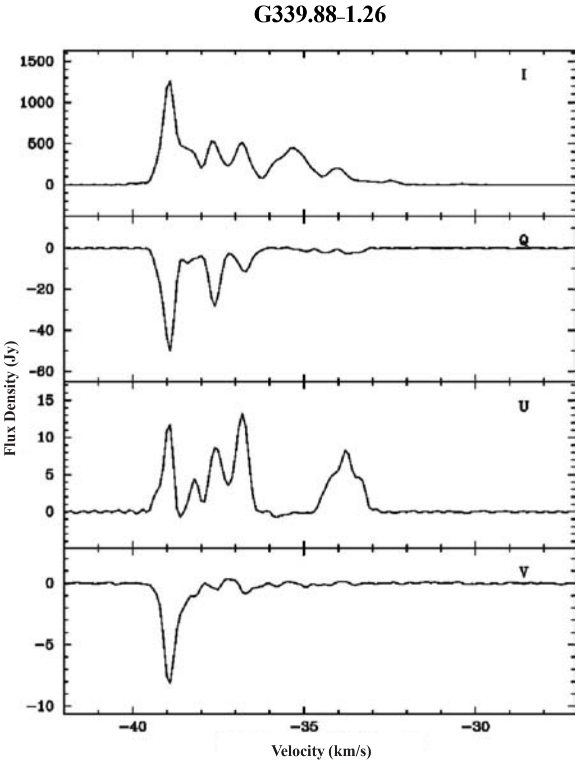


Figure 16 *Australia Telescope Compact Array full polarization observations of the 6.7 GHz methanol masers in G339.88–1.26.*

Searching for neutral hydrogen in groups of galaxies

Like people, galaxies have a tendency to gather together. Galaxies have their small towns—groups with only a few galaxies loosely spaced, and their big cities—giant clusters with hundreds or thousands of galaxies tightly bunched while spanning a large area. Roughly two thirds of all galaxies reside in a group of some sort, while the remaining third live in isolation as hermits. These groupings of galaxies are an important building block for structure in the Universe. Not only do the majority of galaxies reside in them, but most of the baryonic (normal) matter in the Universe is likely to be contained in groups as warm and hot gas. While many astronomers have studied the dense clusters and compact groups of galaxies, very few have studied the more diffuse components of structure known as loose groups.

Loose groups of galaxies are collections of a few (typically two or three) large galaxies and tens of smaller galaxies. The large galaxies in these groups are well spaced, with separations of order 100,000 parsecs, and they are spread out over a volume of roughly one cubic Megaparsec. They tend to be dominated by spiral galaxies, but some contain one or two large elliptical galaxies. Our Galaxy, the Milky Way, is part of a loose group known as the Local Group of galaxies. Although we are inside this group, there is much we still do not know about the Local Group and other similar loose groups. In particular, we do not know whether groups of galaxies, and the galaxies in them, are still forming.

Over the past few years, a 30-year old suggestion, that the high-velocity clouds (HVCs), clouds of neutral hydrogen (HI) spread around the sky at velocities inconsistent with the rotation of the Milky Way, are primordial material associated with the formation of the Local Group and its galaxies, has been revived. In 1999, Leo Blitz and collaborators as well as Robert Braun and Butler Burton proposed that at least some of the HVCs may reside at distances of up to a million parsecs from the Milky Way and contain of order 10 million solar masses of HI. For this hypothesis, the HVCs contain primordial material still falling into the Local Group and building up the galaxies in it. In this case, other groups similar to the Local Group should contain analogous HI clouds also lacking stars.

In an attempt to test these predictions we have set out to map HI in a sample of loose groups of galaxies with similar content to the Local Group using the Parkes telescope with its multibeam receiver. Using the narrowband mode, we have mapped the entire regions around four loose groups of galaxies. Two of the groups, LGG 93 and LGG 180, are at a distance of approximately 11 million parsecs, contain only spiral and irregular galaxies, and span 25 square degrees on the sky. The multibeam in its narrowband mode allows for rapid mapping of a large area of the sky down to low mass limits, below one million solar masses of HI at these distances, permitting the detection of possible analogues of HVCs in these two other groups. In addition to searching for HI clouds associated with galaxy formation, we are also making a census of the gas-rich galaxies in these groups and are examining the dynamical structure of the groups. The relative number of small galaxies and the presence of dynamically distinct components in the group (sub-groups) can be used to constrain the various models of galaxy formation and dark matter. Together these datasets will shed a great deal of light on how galaxies and groups form and evolve.

Observations of LGG 93 revealed the six previously known galaxies in the group, plus four new HI detections with HI masses of 10–100 million solar masses. Of the new detections, one is clearly identifiable as a dwarf galaxy, ESO 200-45, while for the other three the poor angular resolution of Parkes makes it impossible to identify a single optical counterpart. An example is shown in Figure 17.

For LGG 180, we detected all 10 group galaxies, plus three new HI detections, all of which have uniquely identifiable optical counterparts (ESO 434-G17, ESO 373-G6, and ESO 434-G8). These objects have slightly higher HI masses (100–1000 million solar masses). The HI detection of ESO 434-G17 is shown in Figure 18. There is still much work to be done to constrain the models of HVCs and galaxy formation.

The detections in both groups should be mapped at higher resolution with the Australia Telescope Compact Array to assure that they are single objects, and accurately identify them with optical counterparts. Optical imaging to place firm limits on the stellar content associated with the hydrogen clouds is also essential. Finally, observations of more loose groups using the Parkes telescope will assure that these groups are not anomalous in their properties.

D. J. Pisano (ATNF); B. Gibson (Swinburne University of Technology); D. Barnes (University of Melbourne); L. Staveley-Smith (ATNF); K. Freeman (Research School of Astronomy and Astrophysics, Australian National University)

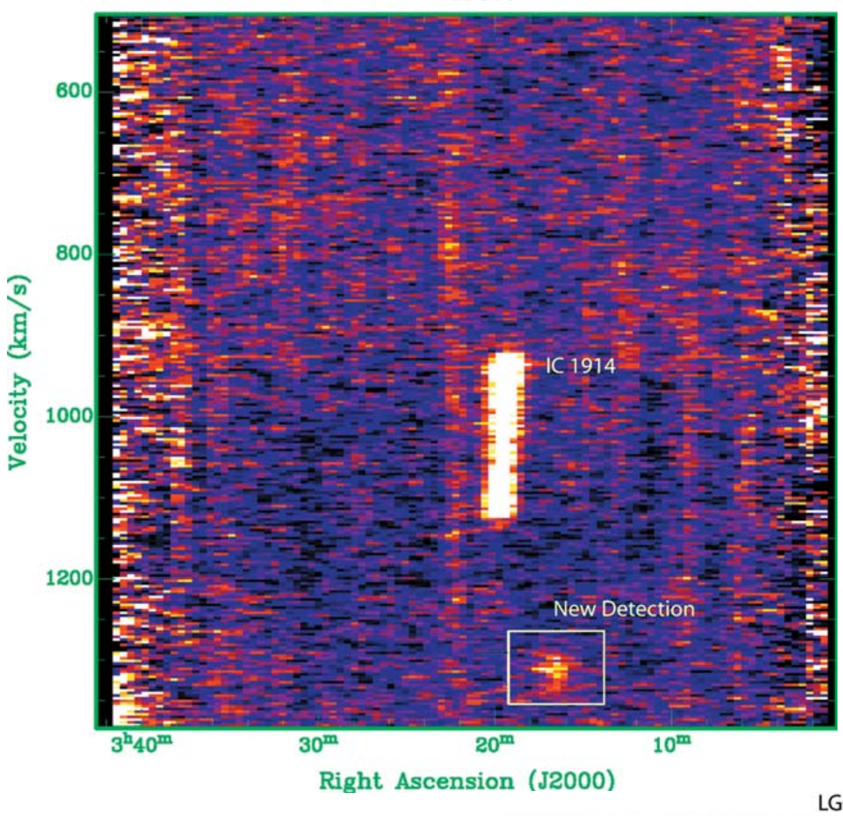


Figure 17 *This image, obtained from data taken with the Parkes radio telescope, shows a "position-velocity" diagram for part of the loose group of galaxies known as LGG 93. The previously known galaxy IC 1914 is seen as the bright strip extending over velocities from approximately 900 to 1,100 kilometres per second. The new detection of a cloud of neutral hydrogen shows a much smaller velocity range.*

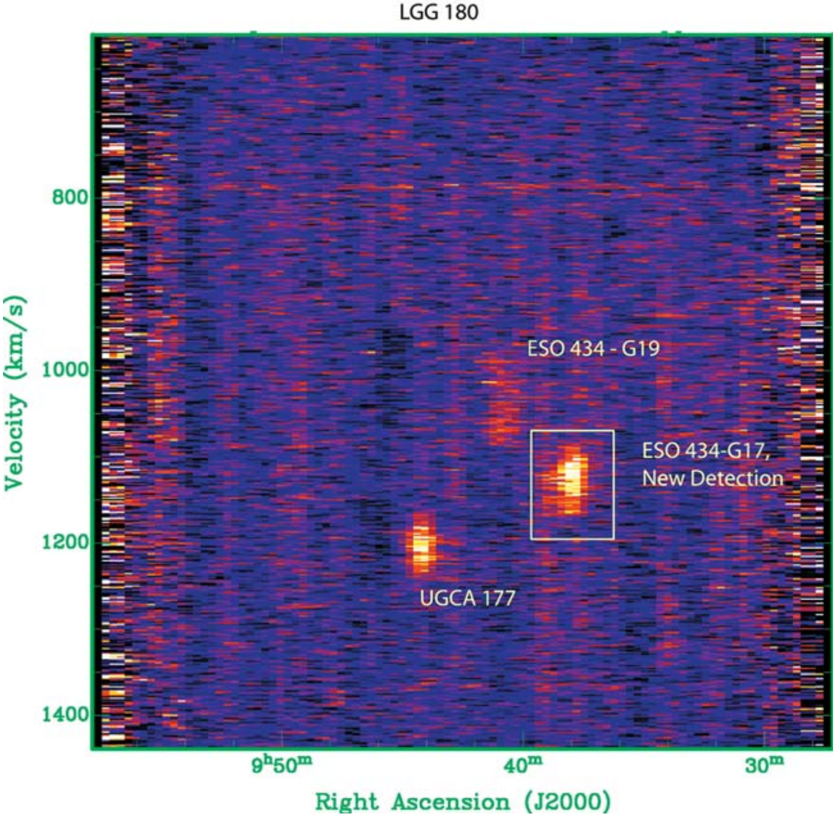


Figure 18 *A position-velocity diagram for part of the region around the loose group of galaxies, LGG 180. This shows a new detection of neutral hydrogen emission from the galaxy ESO 434-G17.*

The magnetic fields of barred spiral galaxies

We have used the Australia Telescope Compact Array and the Very Large Array (VLA) to study the magnetic fields of barred spiral galaxies. The centrally located bars in these galaxies are believed to cause streaming motions in the surrounding gas which lead to enhanced star formation. The galactic magnetic fields are expected to follow the gas flow.

Until recently there have been few detailed radio polarization observations of barred galaxies and little has been known about how the central bars affect the galactic magnetic fields. To study the magnetic fields of barred spiral galaxies, we selected a sample of 20 barred galaxies with an optical size of at least three arcminutes, from the radio surveys of Whiteoak (1970) and Condon et al. (1998). Ten galaxies were observed with the Compact Array at 6, 13 and 20 cm and 10 galaxies were observed with the VLA. For 17 of the 20 galaxies we detected polarized radio emission, indicating the presence of large-scale regular magnetic fields. The radio data will be published as an atlas of magnetic fields in barred galaxies and are available on the Web at http://www.mpifr-bonn.mpg.de (research – archive).

As examples, Figures 19 and 20 show the radio emission at a wavelength of 5.8 cm from the southern galaxies NGC 2442 and NGC 7552, overlaid onto optical images from the Digitized Sky Survey. The contours show the total intensity of the radio emission while the dashes indicate the orientation (assuming little Faraday rotation) and strength of the magnetic field.

NGC 2442 (Figure 19) is a member of the Volans Group of galaxies. The optical image has an asymmetric appearance possibly indicating a tidal interaction with another galaxy. Ionized hydrogen emission from the galaxy shows an unresolved central source and a circumnuclear ring of enhanced star formation which has a radius of approximately 600 parsecs. NGC 2442 exhibits strong radio emission from the nucleus and the ends of the bar. Strongly polarized emission is detected from the northern spiral arm, which has a massive dust lane. The magnetic field lines in this arm are aligned, possibly indicating a compression and/or shearing of the magnetic field.

NGC 7552 (Figure 20) is a member of the Grus Quartet of galaxies. This galaxy also has a starburst circumnuclear ring with a radius of approximately 800 parsecs. The galaxy does not have an active nucleus but has a nuclear bar (observed in radio continuum and near-infrared) aligned perpendicular to the main central bar. NGC 7552 shows strong, highly polarized radio emission from the centre of the galaxy, the bar and the inner parts of the spiral arms. The angular resolution of the Compact Array observations was not high enough to resolve the circumnuclear ring. The polarized radio emission from NGC 7552 is strong upstream of the dust lanes and the magnetic field lines are oriented at large angles to the major axis of the central bar.

From this study we find that the radio surface brightness and the rate of star formation in spiral galaxies are highest for galaxies with a high content of molecular gas and with a high quadrupole moment of the bar's gravitational potential. However, galaxies with strong bars do not always have bright radio emission. For barred galaxies with moderate radio brightness, the magnetic fields, traced by the polarized radio emission, are strongest between the optical spiral arms, or have a diffuse distribution. For radio-bright barred galaxies we find that the magnetic fields are often strongest upstream of the bar's shock front which is delineated by massive dust lanes, in conflict with numerical models. The magnetic fields are oriented at a large angle to the bar and curve smoothly towards the bar without an indication of a shock front. We propose that shear in the velocity field around a large bar enhances the magnetic fields in barred galaxies.

M. Ehle (XMM-Newton Science Operations Centre, ESA, Spain); R. Beck (MPIfR, Germany); V. Shoutenkov (Pushchino Radioastronomy Observatory, Russia); J. Harnett (University of Technology, Sydney); R. F. Haynes (University of Tasmania); A. Shukurov (University of Newcastle, UK); D. D. Sokoloff (Moscow University, Russia); M. Thierbach (MPIfR, Germany)

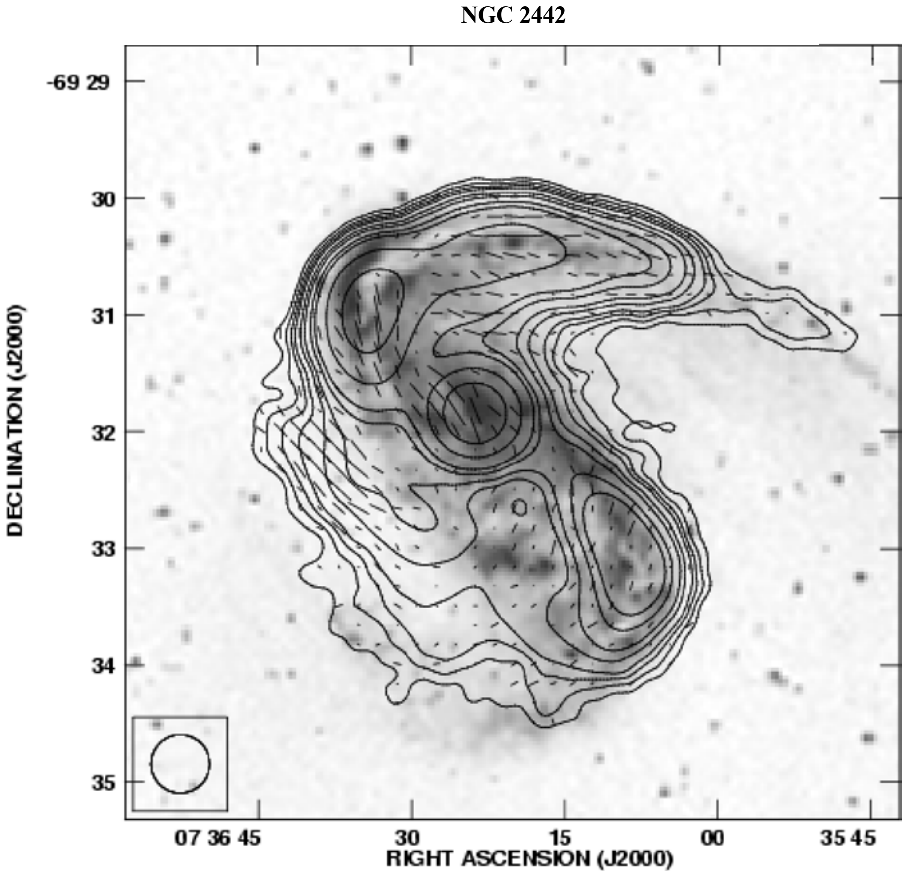
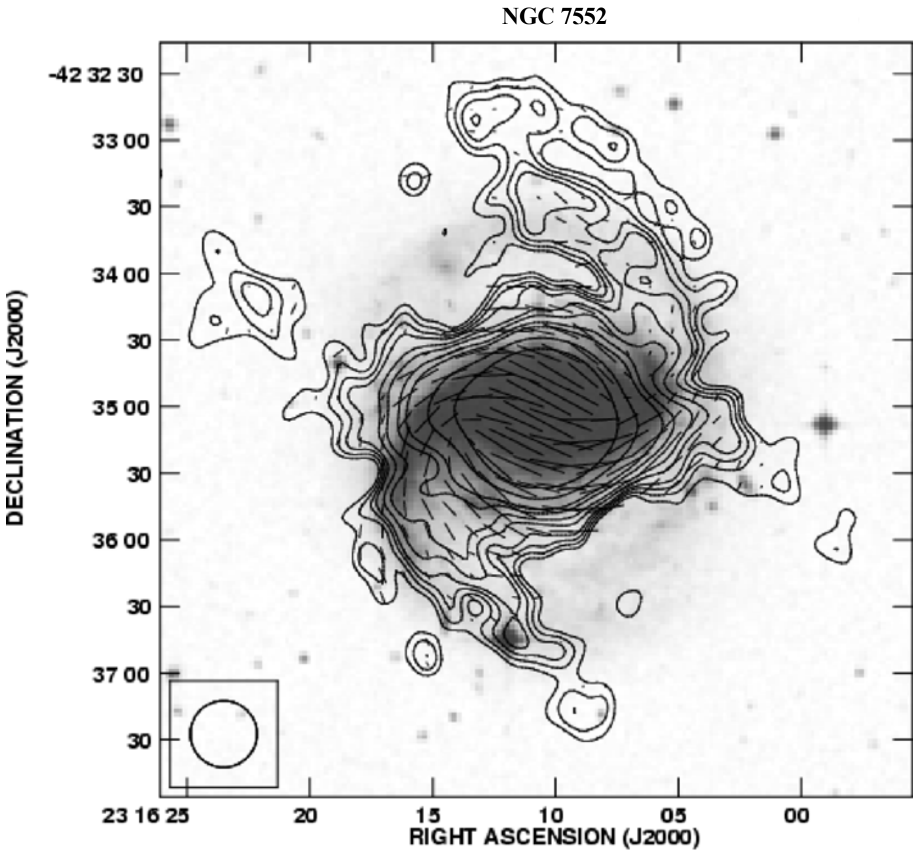


Figure 19 *Total intensity contours and magnetic field vectors showing the total and polarized radio emission at a wavelength of 5.8 cm from NGC 2442, overlaid onto an optical image from the Digitized Sky Survey (UK Schmidt Photographic Atlas). The contour levels indicate the strength of the radio continuum emission. The angular resolution of the radio observations is 30 arcseconds. The dashes indicate the strength of the polarized radio emission and the orientation of the galactic magnetic field. A vector of one arcsecond length corresponds to a polarized intensity of 10 microJansky per beam area.*

Figure 20 *Total intensity contours and magnetic field vectors showing the total and polarized radio emission at a wavelength of 5.8 cm from NGC 7552, overlaid onto an optical image from the Digitized Sky Survey (UK Schmidt Photographic Atlas). Note that the outer regions of the image show some artefacts caused by incomplete sampling of the data.*



PKS 1257-326: a scintillating quasar

Radio variability on time scales shorter than a day has been observed for the past 20 years in a number of compact, extragalactic radio sources. There has been much debate over the origin of this intraday variability (IDV). On the one hand, many radio sources vary at all observed wavelengths, from radio to gamma-ray, and this broad-band variability may thus be explained as being intrinsic to the source. The main problem with very rapid radio variability, if intrinsic, is that it implies a very high source brightness temperature, much higher than allowed by the conventional synchrotron emission mechanism for nonthermal radio emission.

On the other hand, it is known that sources with sufficiently small angular size can be observed to vary as a result of interstellar scintillation, a propagation effect produced in the turbulent, ionized interstellar medium (ISM) of our own Galaxy, which affects only radio wavelengths. An extragalactic radio source small enough to vary on time scales shorter than a day is certainly small enough to scintillate. Interpreting the variability as scintillation generally allows larger source sizes and hence lower source brightness temperatures.

How do we know for sure whether the intraday variability is scintillation, or intrinsic?

Recent Compact Array observations have now confirmed that the principal cause of this radio IDV is interstellar scintillation. Key to this has been the discovery and detailed monitoring of the variability in the recently discovered very rapid variable, PKS 1257–326. This source is one of the three most rapidly variable quasars known. Its flux density has been observed to vary by 40% in 45 minutes.

We have monitored the variability of PKS 1257–326 every six weeks with the Compact Array over the course of the last year, and found an annual cycle in the characteristic time scale of variability, as shown in Figure 21. This annual cycle occurs because the velocity of the interstellar medium, as seen by an observer on Earth, changes due to the Earth's orbital motion. The scintillation pattern is produced by focusing and defocusing the radio emission, as it passes through patches of turbulence in the interstellar medium. The time scale of variability is set by the speed at which this series of patches moves past the observer. For some periods of the year, the relative Earth/ISM velocity can be quite large, so that the scintillation pattern moves rapidly past the observer, and the observed time scale of variability is short. Six months later the ISM and the Earth are moving in much the same direction, so that the scintillation pattern is observed to pass by quite slowly, and the observed time scale of variability is long. The presence of such an annual cycle in PKS 1257–326 shows unequivocally that the IDV in this source is due to interstellar scintillation.

Importantly, this interstellar scintillation can be used as a probe of micro-arcsecond source structure, and of the scale and structure of turbulence in the local ISM. Our data tell us that the angular extent of the scintillating source is at most a few tens of micro-arcseconds. At the distance of PKS 1257–326, 10 micro-arcseconds corresponds to a linear distance of around three light months. We find that the scattering material along the line-of-sight to PKS 1257–326 is likely to be very nearby, less than 100 light years away from the solar system. Modelling the annual cycle also shows strong evidence for a highly anisotropic scintillation pattern.

Thus, with the Compact Array, which has an angular resolution of arcseconds, we can use the ISM and the Earth's orbit to achieve a resolution of tens of micro-arcseconds. That's like extending the Compact Array's railway tracks all the way to the moon!

H. E. Bignall (University of Adelaide/ATNF); D. L. Jauncey, J. E. J. Lovell, A. K. Tzioumis (ATNF); L. Kedziora-Chudczer (AAO/ATNF); J.-P. Macquart (University of Groningen); S. J. Tingay, D. P. Rayner (ATNF); R. W. Clay (University of Adelaide)

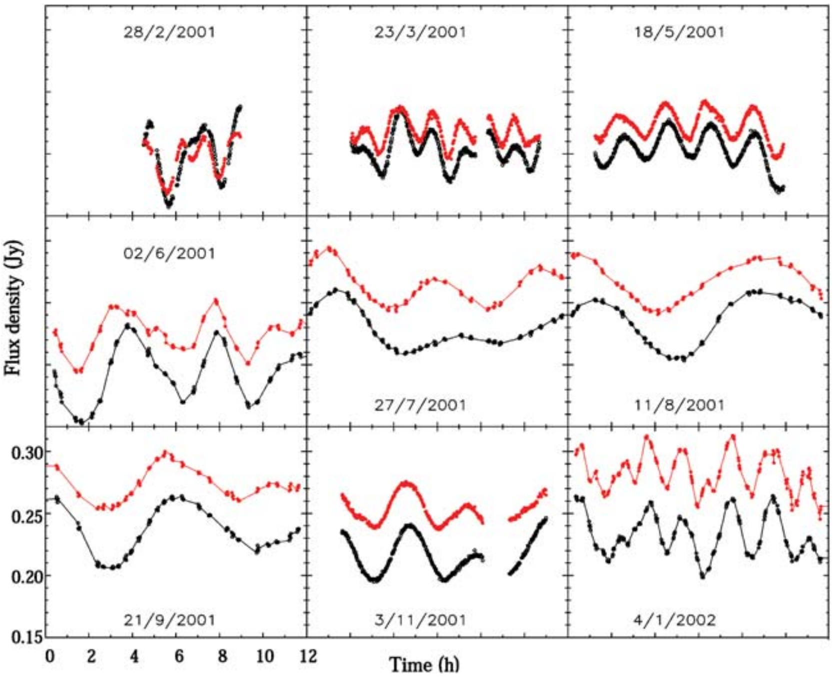
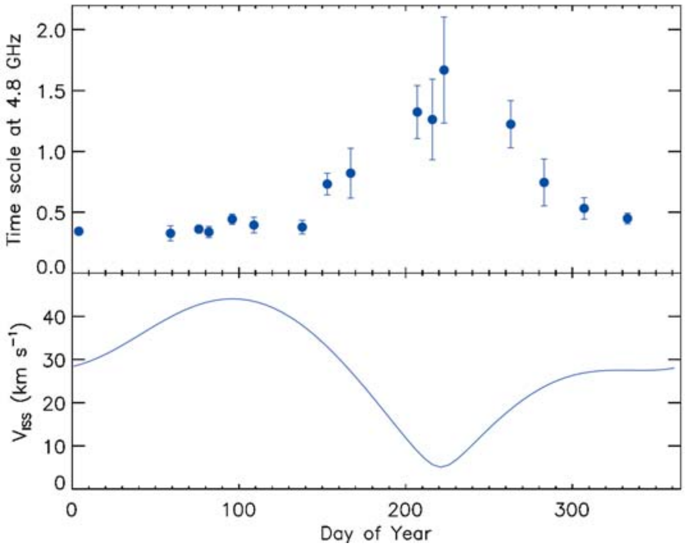


Figure 21 *Flux density measurements of PKS 1257–326 over the course of a year, showing the clear annual cycle in variability time scale. From June through September, the rapid variability slows down, then speeds up again towards the end of the year. Six-cm data are plotted in black, and 3-cm data in red. Each box shows one day's data, and represents the same range of values, shown in the bottom left-hand corner.*

Figure 22 *The characteristic time scale of variability at wavelength 6-cm, defined from autocorrelation functions, measured over 2001. Plotted underneath is the speed, observed from Earth, of a medium moving with the local standard of rest, in the direction of PKS 1257–326. The time scale of variations shows a clear signature of the Earth's orbital motion.*



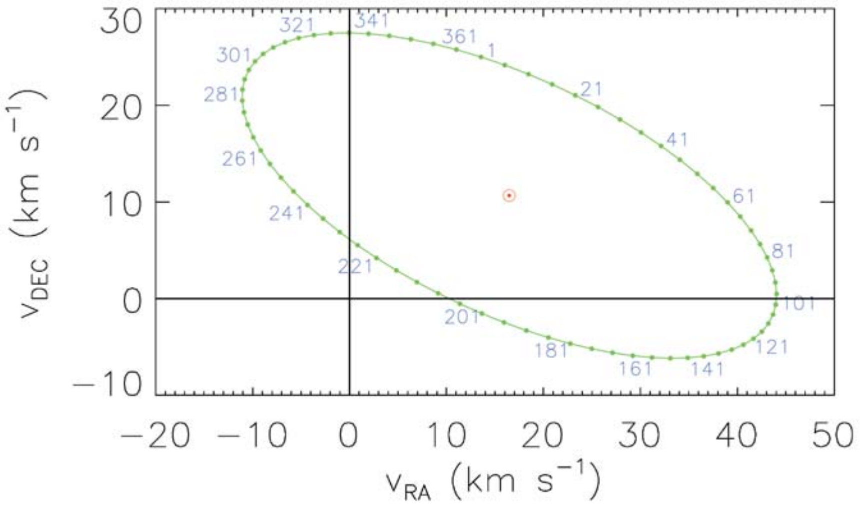


Figure 23 *The Earth's velocity with respect to the interstellar medium, for each day of the year, projected onto the plane of the sky. This shows that over the course of a year, there is a large change in the direction of the scintillation speed, which allows us to probe the two-dimensional structure of the scintillation pattern.*

On the trail of gamma-ray burst progenitors

Gamma-ray bursts may be the most luminous events in the Universe but they have not given up their secrets easily. For the past several years we have been part of an international effort to unveil these mysterious sources responsible for such explosive events. Now, thanks to observations made at the Australia Telescope Compact Array and elsewhere, we have found a direct link between gamma-ray bursts and the death throes of massive stars.

Any successful gamma-ray burst model must be capable of releasing an enormous amount of energy on a time scale of tens of seconds. One of the more promising candidates has been the collapsar model, in which a massive star, more than 20 times the mass of our own Sun, ends a lifetime of nuclear burning and undergoes core collapse, forming a black hole at its centre. The outer layers of the star are driven outward at speeds of 20,000 to 60,000 kilometres per second in a brilliant supernova explosion. Not to be outdone, the newly formed black hole, powered by infalling material, forms collimated beams of material along its rotation axis at speeds approaching that of light (Figure 24). The interaction of different shocks within the jet is responsible for the gamma-ray emission, while particle acceleration from the ultra-relativistic shock which is driven into the circumburst medium gives rise to long-lived X-ray, optical and radio “afterglow” emission, dwarfing the light from the supernova.

For some time now evidence has been slowly accumulating in favour of the collapsar model. All well-localised gamma-ray bursts occur in host galaxies which are actively undergoing star formation, sometimes at a rate of several hundred solar masses per year. Likewise, the radial distribution of gamma-ray bursts closely follows the (stellar) UV light from their host galaxies. Substantial gas and dust along the line-of-sight to gamma-ray bursts has also been inferred from the absorption of low-energy X-rays and extinction of optical afterglows. In many cases the dust extinction is large enough to produce optically

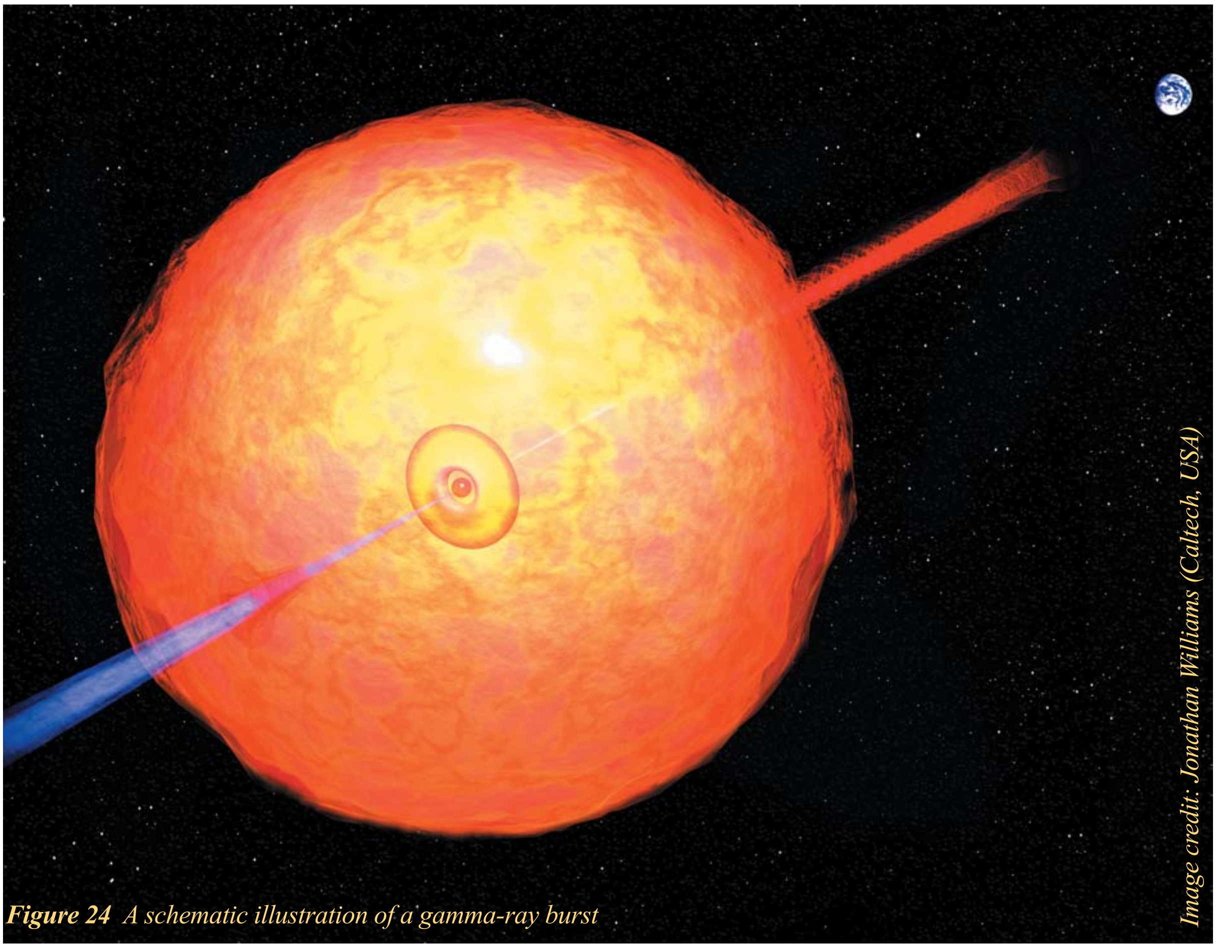


Image credit: Jonathan Williams (Caltech, USA)

Figure 24 *A schematic illustration of a gamma-ray burst* "dark" gamma-ray bursts which are visible only in the radio and X-ray bands. While these indirect indicators have been telling us that gamma-ray bursts originate in the same dusty, gas-rich environments as massive stars, the decisive evidence in favour of the collapsar model has remained elusive.

Fortunately, the collapsar model provides two powerful observational tests. The massive star progenitor undergoes prodigious mass loss prior to collapse, shedding nearly all of its hydrogen envelope. The relativistic shock driven outward must propagate through this gas and hence we expect to see the mass-loss density profile imprinted on the spectral and temporal evolution of the afterglow emission. Observations at radio wavelengths are especially important in detecting the wind signature since they probe the rise and fall of the afterglow emission as the shock propagates through this density gradient.

Another inevitable consequence of the collapsar model is that a supernova explosion will occur simultaneously with the gamma-ray burst. The light from the afterglow and the supernova can be distinguished from each other since the former undergoes a pure power-law decay, while the latter exhibits a rise to maximum several weeks after the burst, followed by an exponential decay. Similarly, the optical spectrum of the afterglow is a featureless (synchrotron) continuum, whereas the supernova spectrum has characteristic red colours. Detecting the weak supernova signal in the presence of the afterglow and the host galaxy is not an easy task. Prior claims of late-time red "bumps" and stellar wind signatures have been made but not together and not with a high degree of confidence. With the gamma-ray burst of 21 November 2001 (also known as GRB 011121) we had our long-awaited opportunity to search for both.

GRB 011121 began innocuously enough. It was detected as a 30-second long burst at 18:47 UT by the Dutch/Italian satellite *BeppoSAX,* and the subsequent ground-based response by our group and others quickly identified the optical and radio afterglows. A pleasant surprise awaited us when an optical spectrum, taken at the Baade 6.5-m telescope, showed that the redshift of this burst was $z = 0.36$, making GRB 011121 the nearest cosmological gamma-ray burst known to date. By contrast, most of the two dozen bursts with distance determinations lie at redshifts between one and two. Since nearby gamma-ray bursts are ideal for carrying out tests of the collapsar model we immediately began a large observing campaign on GRB 011121.

Broadband optical observations were undertaken at the Anglo-Australian Telescope (AAT) with the newly commissioned IRIS2 instrument, and the du Pont 2.5-m and Baade 6.5-m telescopes at Las Campanas Observatory. These observations enabled us to determine the spectrum and the power-law decline of the optical afterglow at early times. When the light curves were extrapolated to a time between 15 and 75 days after the burst we found that our Hubble Space Telescope measurements taken at this time were an order of magnitude brighter than expected. Both the light curve of this flux excess and its observed spectral shape were consistent with the expectations for a supernova of type Ib or Ic.

Meanwhile at the Compact Array we had made seven epochs of observations of the afterglow at 4.8 and 8.7 GHz, spanning from one day after the burst to 70 days later. By comparing the early evolution of the optical afterglow with that of the radio afterglow, we were able to eliminate all other potential afterglow models, including an isotropic or highly collimated outflow expanding into a constant density medium. Taken together the optical and radio data are consistent with a gamma-ray burst exploding into a wind-blown circumburst medium. Moreover, careful modelling of these data tell us that the mass loss of this pre-supernova star was 10^{-7} solar masses per year, typical of evolved stars.

If all long-duration gamma-ray bursts are due to the core collapse of massive stars, as these observations certainly suggest, then we are likely witnessing the birth of a stellar black hole. Looking ahead, this raises the exciting possibility that in the future gamma-ray bursts could be used to trace star formation when the Universe was very young. The extreme luminosity of gamma-ray bursts and their accompanying afterglows means that in principle they could be detected out to redshifts of 10 or higher, at a time when the first stars were still being formed.

D. A. Frail (National Radio Astronomy Observatory, USA/Caltech University, USA); P. A. Price (Research Schoool of Astronomy and Astrophysics/Caltech University, USA); E. Berger (Caltech, USA); M. Wieringa, R. Subrahmanyan, R. Wark (ATNF)

The Australia Telescope Compact Array

Photo: David Smyth