ASTRONOMY

Overview & Highlights

The MERLIN/VLBI National Facility has been used to study many diverse astronomical phenomena during the reporting period. Their scales range from only a few solar radii (solar wind studies) to the cosmic distances revealed by gravitational lens studies. These observations have continued to support world-class science, particularly in fields such as extragalactic astronomy and cosmology, star-formation across the Universe, stellar evolution and investigations of the extreme conditions around compact objects.

Above: The National Facility's 32m telescope at Cambridge.

The range of objects routinely studied by the National Facility include radio galaxies and quasars, Seyfert and starburst galaxies, the Galactic interstellar medium (ISM), planetary and proto-planetary nebulae, young stellar objects (YSOs), main-sequence and evolved stars and their winds, circumstellar envelopes, star-forming regions, classical novae, micro-quasars and pulsars. An equally broad range of physical conditions and processes are encompassed by such observations, from the highly-energetic synchrotron-emitting regions of active galactic nuclei (AGN) to the complex maser shells surrounding evolved stars and the beamed radio emission from rapidly-rotating neutron stars.

The key scientific achievements of the National Facility during the reporting period continue to be based primarily on the available angular resolution. However, not only the determination of the detailed structure of the radio emission, but also the probing of magnetic fields using polarisation studies and the relative accuracy with which astrometry may be performed, have undoubtedly enhanced the National Facility's recent core science. Unprecedented sensitivity has also been achieved using very long observations of Deep Fields.

In addition to conventional synthesis imaging using UK-based and continental baselines, National Facility antennas have also been used individually and in single baselines to measure interplanetary scintillation and pulsar proper motions. MERLIN has responded rapidly to reports of flares from X-ray Binaries (XRBs) and other target-of-opportunity (ToO) triggers. Other long-term monitoring projects, massive surveys and Key Programmes have also been successfully pursued.

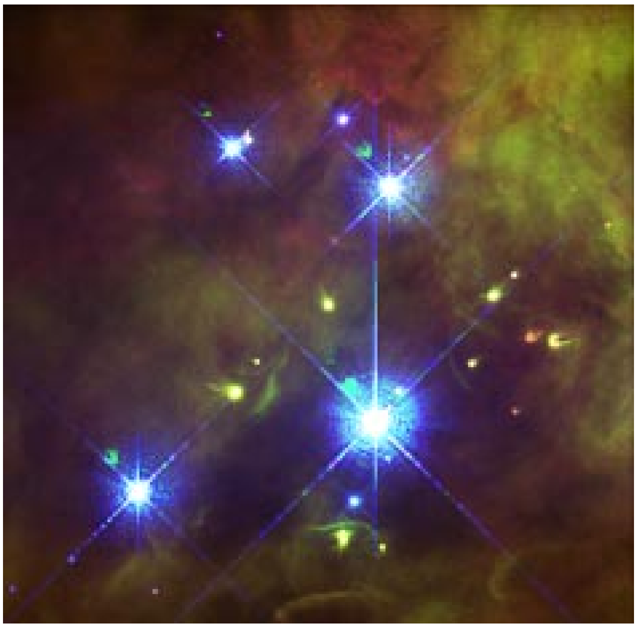
Following the successful 18-day MERLIN observations of the Hubble Deep Field, five more Key Programmes were started during 1999/2000. These were; a deep radio/sub-millimetre survey (Eales et al.), sub-mJy radio galaxies and the X-ray background (McHardy et al.), a deep MERLIN survey of the Orion Nebula (Meaburn et al.), radio imaging of star-formation in distant galaxies (Richards et al.) and a study of galaxy haloes using radio-microlensing (Koopmans et al.).

The core scientific results presented here represent a science programme that is both productive and innovative.

The Birth Process of Stars: The Orion Proplyds

Recent spectacular HST images of the Trapezium Cluster in the Orion Nebula, M42, have fuelled interest in the complex processes of star-formation and the interaction of YSOs with their environments. MERLIN observed this region at 6cm in 1998 and 1999. Over 100 hours of data have now been combined in an attempt to produce one of the deepest high-resolution radio images of the closest example of a star-forming region with both low-mass and high-mass stars. The prime targets of this observation were the proplyds; YSOs embedded in knots of gas photo-ionised by one of the bright Trapezium stars. Comparison of the accurately aligned MERLIN and optical HST images has already produced some surprising and unexpected results.

Below: HST montage of the Orion proplyds.

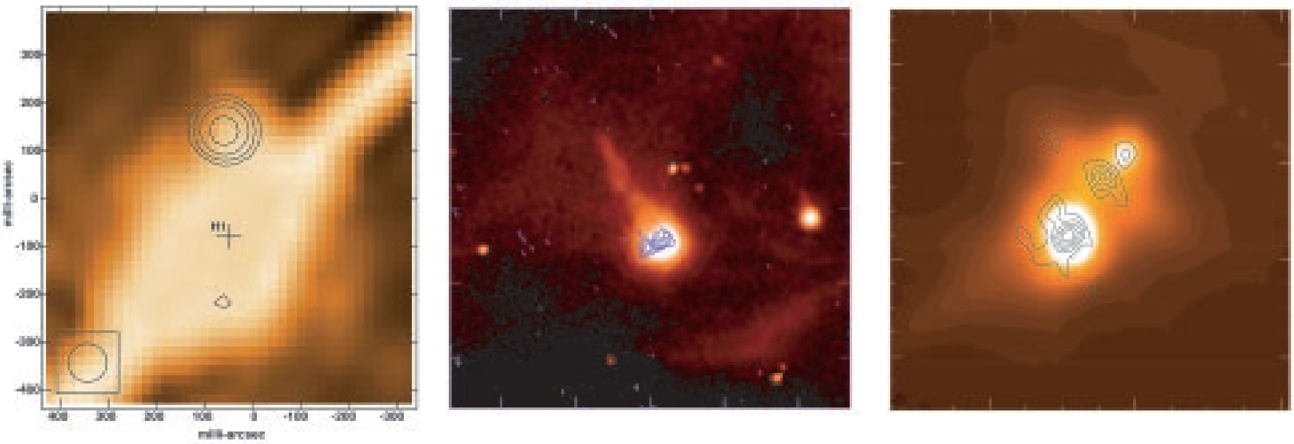


The superb MERLIN images have revealed that the bright radio star, which had always been associated with θ^1 Orionis A, is, in fact, displaced by 220 milliarcseconds from the Hipparcos optical position. Recent 2.2μ speckle images have shown that there is a $5M_\odot$ pre-main-sequence companion star at precisely the radio position. Global VLBI observations have recently been performed to investigate the nature of the nonthermal emission from this enigmatic target.

The proplyd LV2 is a superb example of a star recently formed. The MERLIN image shows the ionisation front as a narrow cusp where the evaporation flow from the circumstellar/proto-planetary disk is ionised by soft UV photons from θ^1 Orionis C. Also visible is the one-sided jet that emerges, thought to be perpendicular to this disk, at a velocity of 100-150kms^{-1}.

Another proplyd, LV1, was first resolved as two radio sources in 2cm VLA images and then by the HST as two optical objects separated by 400 milliarcseconds. The MERLIN 5GHz image clearly shows that much of the radio emission at this frequency comes from between the two optical objects, but whether this could be due to the collision of 100-200kms^{-1} jets is still being investigated.

Below: (left) MERLIN contours overlaid on an overexposed HST image of θ^1 Orionis A. The radio source is displaced 220mas from the Hipparcos position (H1). (centre) MERLIN 5GHz contours overlaid on an HST Hα frame of the proplyd LV2. (right) MERLIN contours of the proplyd LV1.

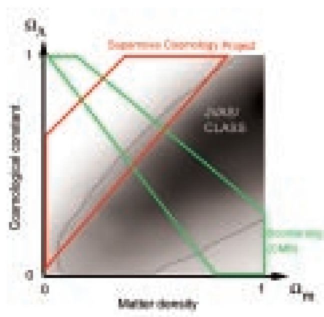


Evaluating Cosmological Parameters Using Gravitational Lenses

The pursuit of reliable values for the expansion and density of the Universe is a crucial aspect of modern astronomy. Gravitational lenses provide one method of investigating these cosmological parameters and the National Facility has continued to contribute significantly to this active field.

The JVAS/CLASS survey is the world's major gravitational lensing survey. The observations have so far covered 16,545 flat-spectrum radio sources with the VLA. Candidate complex sources were then mapped at higher resolution with MERLIN to distinguish between intrinsic structure and the multiple point-like components suggestive of gravitational lensing. MERLIN images resulted in the rejection of 80% of the VLA candidates at this stage. VLBI observations provided final confirmation for the few objects whose identification remained uncertain following the MERLIN observations. More than 20 new gravitational lenses have been identified.

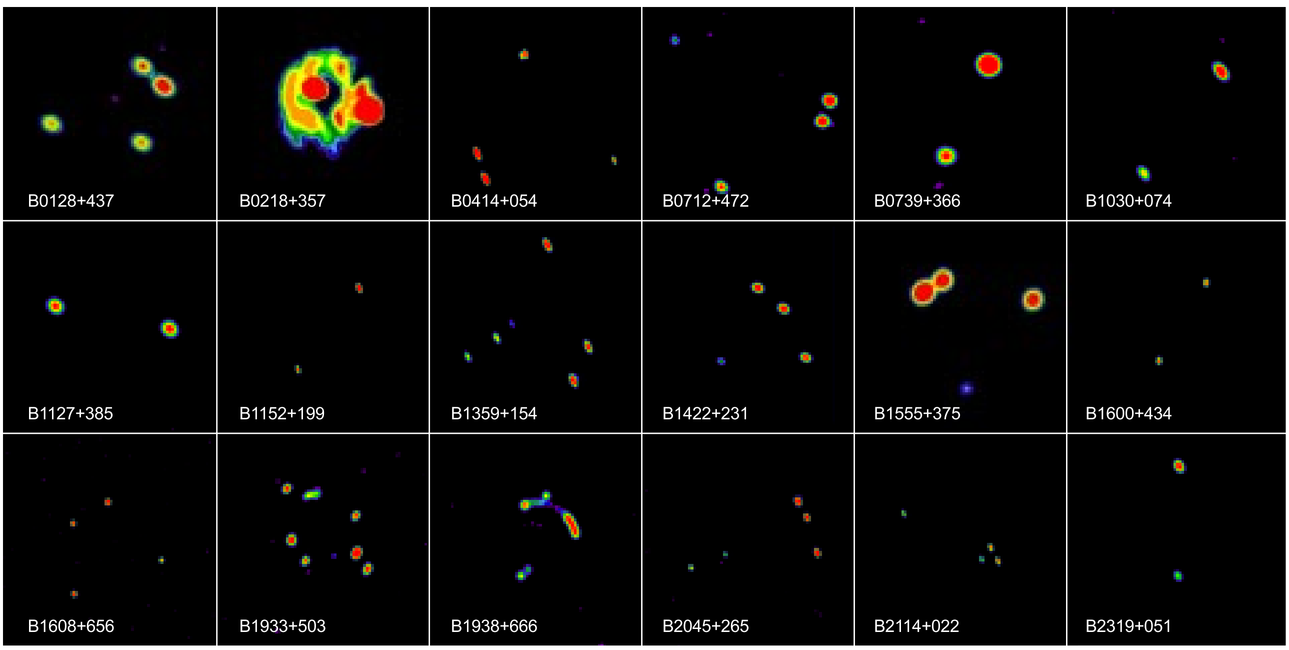
Below: Constraints at the 90% confidence level in the Ω_m-Ω_Λ plane from the JVAS/CLASS results compared to results from the Boomerang CMBR satellite and Type Ia supernova studies.



The statistics of gravitational lensing can lead to tight constraints on cosmological parameters. Individual lens systems can give a determination of H_0 if the source is variable and the brightness or polarisation variations in the multiple images show a time delay. Also, the fraction of sources that are lensed is sensitive to the universal matter density Ω_m and the cosmological constant Ω_Λ. For this method to be useful it is vital that all the lenses within well-defined limits are identified. Radio surveys are well suited to this aim due to their immunity to dust extinction and their reliably high resolution. The complete JVAS/CLASS lens search has only been possible because of the complementary characteristics of all three radio synthesis arrays (the VLA, MERLIN and VLBI) covering over two orders of magnitude in resolution.

The constraints in the Ω_m-Ω_Λ plane (at 90% confidence) from the JVAS/CLASS results put a strong upper limit of $\Omega_\Lambda<0.6$, implying a flat universe. The limits on Ω_Λ will become better determined when the final number of lenses is known in JVAS/CLASS and the redshift distribution of the parent sample is better known.

Below: MERLIN/VLA images of 18 new gravitational lenses from the JVAS/CLASS survey.



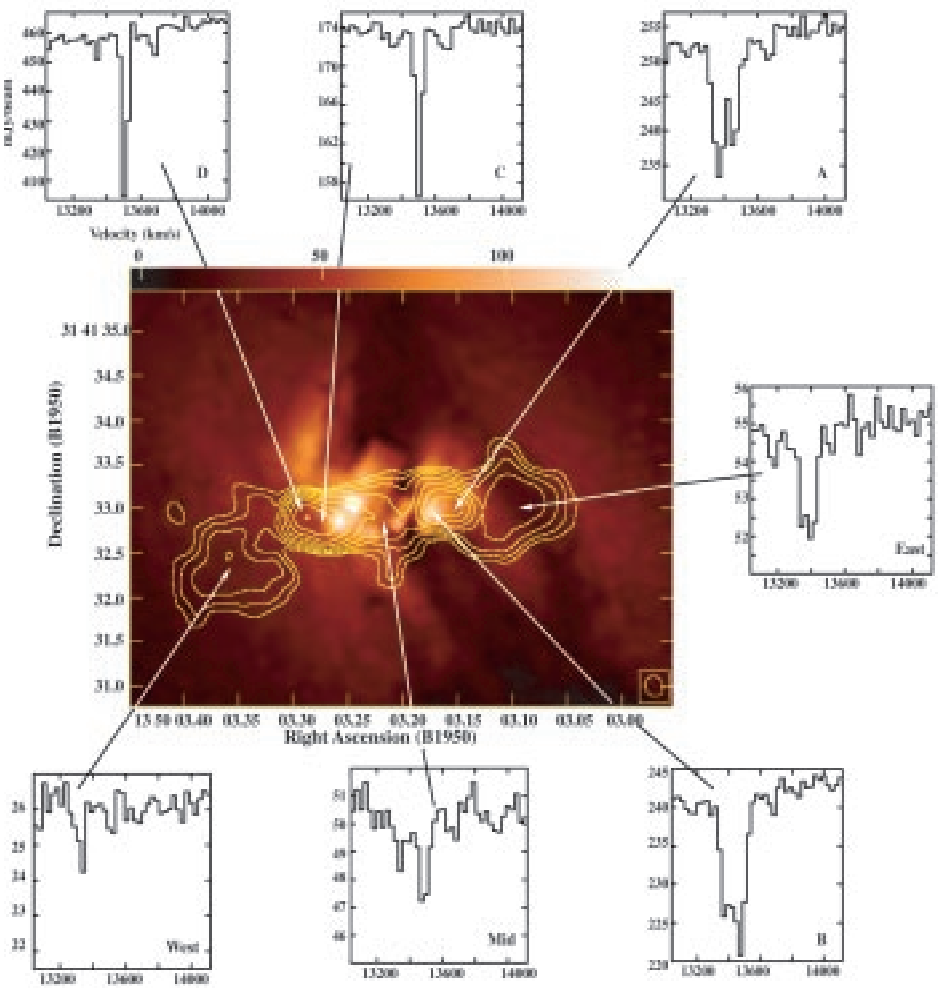
Fuelling Active Galactic Nuclei: HI in 3C293

The study of the dynamics of neutral gas in the centres of active galaxies is essential if the fuelling and triggering of active galactic nuclei (AGN) and starburst galaxies are to be understood. MERLIN is supremely suited to this kind of study since the VLA does not achieve the required resolution and VLBI observations typically over-resolve the important features.

A recent study of the HI absorption towards the central region of the radio galaxy 3C293 using MERLIN represents one of the highest resolution studies of the neutral ISM in a radio galaxy. At the distance of 3C293 (~180Mpc), the ~0.2-arcsecond 18cm MERLIN resolution corresponds to ~180pc, which means that individual clumps of gas in the centre of the galaxy can be resolved.

3C293 is a peculiar radio galaxy which shows signs of interaction with another galaxy only 28 arcseconds away. The HST WFPC2 image shows clear signs of disruption, as does a MERLIN 18cm continuum image, which shows emission elongated in an E-W direction, in marked contrast to the NW-SE aligned arcsecond-scale radio jets detected in VLA observations. The presence of large quantities of neutral gas, already known from previous low-resolution observations, also suggests the 'cannibalisation' of gas from the nearby companion.

Below: HST WFPC2 image of 3C293 overlaid with MERLIN image contours. Also shown are seven of the HI absorption spectra.



In the most recent MERLIN observations, HI is seen in absorption across the entire radio continuum source detected at 0.2-arcsecond resolution. So high is the spectral signal-to-noise that it has been possible to map the optical depth of foreground HI in 3C293, revealing structure that is independent of the background radio continuum. There is a factor of four difference in optical depth in three bands running approximately N-S across the centre of 3C293 and which appear to be co-spatial with the dust lanes seen in the HST WFPC2 image at a similar resolution. The gradient of the HI velocity across the source implies a mass of $4.5 \times 10^9 M_\odot$ within 600pc of the galaxy's core. Such observations represent a crucial tool in the study of gas dynamics in the cores of galaxies.

Faint Sources in the Hubble Deep Field

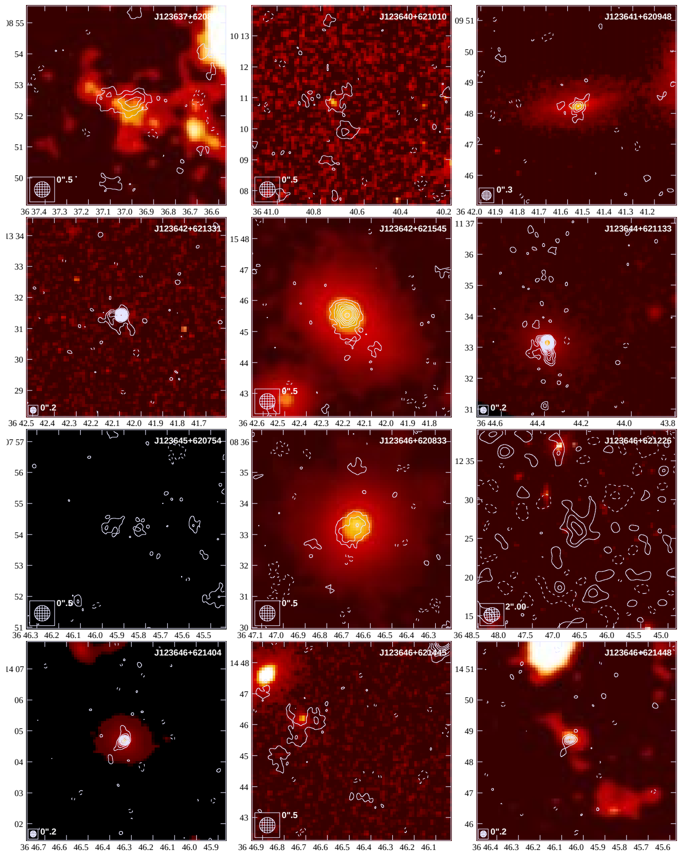
The spectacular Hubble Deep Field (HDF) is awash with faint galaxies of many morphological types at differing distances and stages of evolution. Analysis of this region and the surrounding Hubble Flanking Fields (HFF) continue to provide important clues to crucial problems in cosmology and galactic evolution. Both MERLIN, the VLA and the EVN have observed these regions; MERLIN integrating down to levels ten times fainter than ever before and the EVN producing the most sensitive high-resolution observations of radio galaxies ever achieved.

In all, 90 radio sources were detected above 27μJy/beam (7σ) by the combined MERLIN and VLA observations. Most objects are unresolved by the VLA alone but MERLIN has revealed the nature of these galaxies for the first time. The majority are identified with relatively bright galaxies, of which 30% are low luminosity AGN and 70% are powerful starbursts. Approximately 15% of sources are unidentified optically and probably represent a new population of very distant dust-enshrouded starbursts, some with embedded AGN.

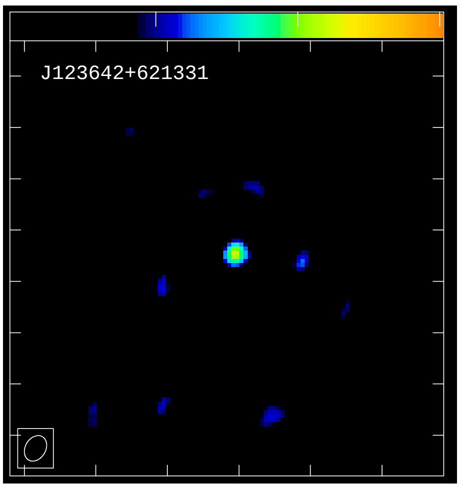
A more detailed analysis of this unique dataset has shown that the detection of radio sources weaker than ~10μJy is statistically significant at the position of optical galaxies with I magnitude <26. These objects are the tail end of the distribution of radio sources larger than 0.5 arcseconds in size, or less energetic or very distant starbursts.

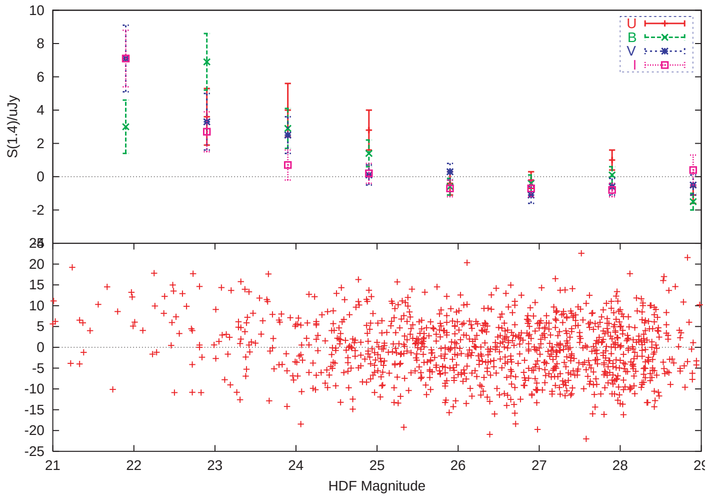
The positions of 12 of the MERLIN sources in the HDF were searched using the EVN. Three were detected, including J123642+621331, thought to be a dusty starburst at z=4.4. The other two detections are of an elliptical and a spiral galaxy. Intriguingly, the detection of compact bright radio cores suggests that all three galaxies conceal an AGN.

Below: MERLIN+VLA radio contours superimposed on the HDF/HFF for 12 of the 90 detections.



Bottom : (right) Radio flux densities at the position of optically detected galaxies in the HDF plotted against binned galaxy magnitudes in each of the four optical bands. (left) EVN map of J123642+621331.





Maser Emission in the Red Supergiant VX Sgr

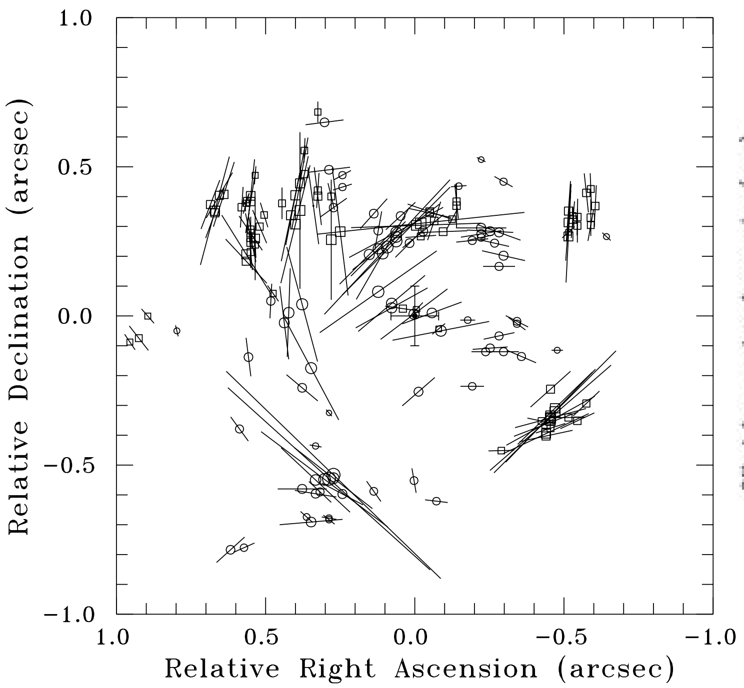
MERLIN's capability for routinely recording full polarisation information during observations is now proving crucial to the study of magnetic fields in many types of objects. In addition, MERLIN's unique resolution range perfectly matches the sizes of features found in many stellar environments. Consequently, observations of the red supergiant (RSG) star VX Sgr, have recently revealed some fascinating details of the complex environments around evolved stars.

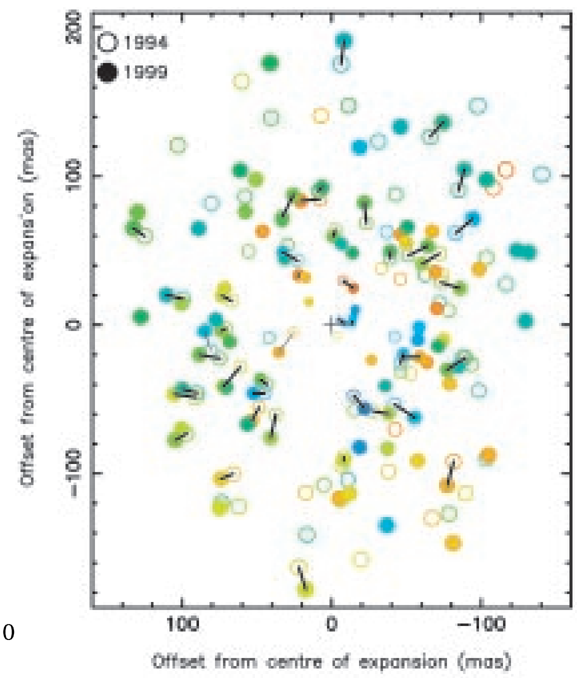
MERLIN results show that the linear polarisation vectors for the OH 1612MHz maser emission in the wind from VX Sgr are aligned tangentially. This, together with the segregation of circularly polarised components, suggests that VX Sgr produces a dipole magnetic field at a position angle of ~210° tilted at 20-30° to the line-of-sight. This is consistent with slight asymmetries in the velocity field in the H_2O and OH maser region. The magnetic field strength measured from the OH 1612MHz data is 0.3mG at 100 stellar radii, aligned toward the observer, compared with 2mG at a few tens of stellar radii deduced from MERLIN, EVN and global VLBI OH mainline observations, again aligned toward the observer. This field is strong enough to influence the direction of the stellar wind.

Below left: Linear polarisation vectors for OH 1612MHz emission in the wind from VX Sgr.

Below right: The positions of water maser clouds around VX Sgr observed in 1994 and 1999 (open and closed circles, respectively) and the corresponding proper motion vectors.

MERLIN observations are sensitive enough to reveal faint maser emission at all position angles, suggesting the wind is accelerated radially away from the star in all directions. However, H_2O maser emission (associated with dense, dusty clumps) is brightest in an equatorial belt (using the magnetic field axis to define the poles). Proper motion measurements confirm the general expansion and rule out significant rotation. This is consistent with less dense, possibly slightly ionised, parts of the wind being directed towards the poles. MERLIN is uniquely able to measure proper motions of a few milliarcseconds but not resolve out significant emission, and as more stars are studied this will reveal whether more pronounced asymmetries are related to stronger magnetic fields.

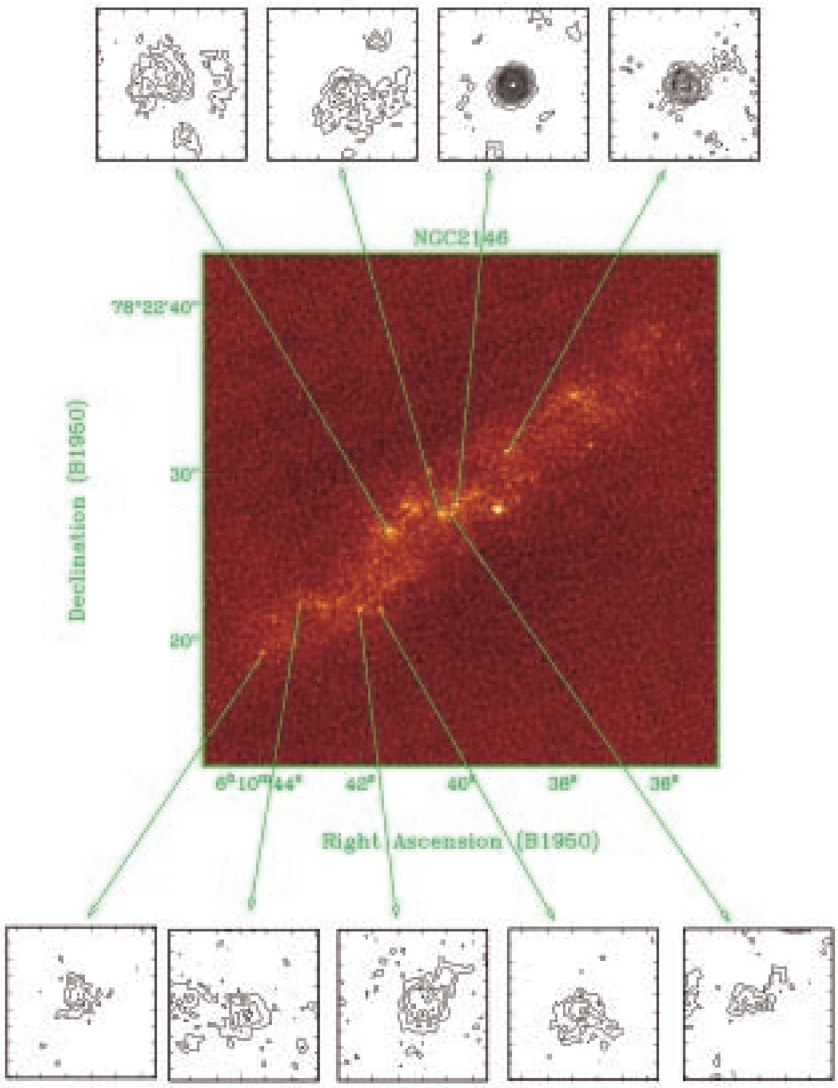




Starburst Galaxies: NGC 2146

MERLIN has an impressive legacy in studies of starburst galaxies. Such investigations not only provide information on extragalactic supernova remnants (SNRs) themselves but also provide a direct measure of the supernova rate, and hence, via the initial mass function, the star-formation rate.

Below: MERLIN and VLA 5GHz images of NGC 2146.



One such starburst galaxy, NGC 2146, at a distance of 14.5Mpc, has a nuclear region highly obscured at optical wavelengths. Early VLA radio observations revealed a population of ~20 unresolved sources, which have been interpreted as supernova remnants or radio supernovae.

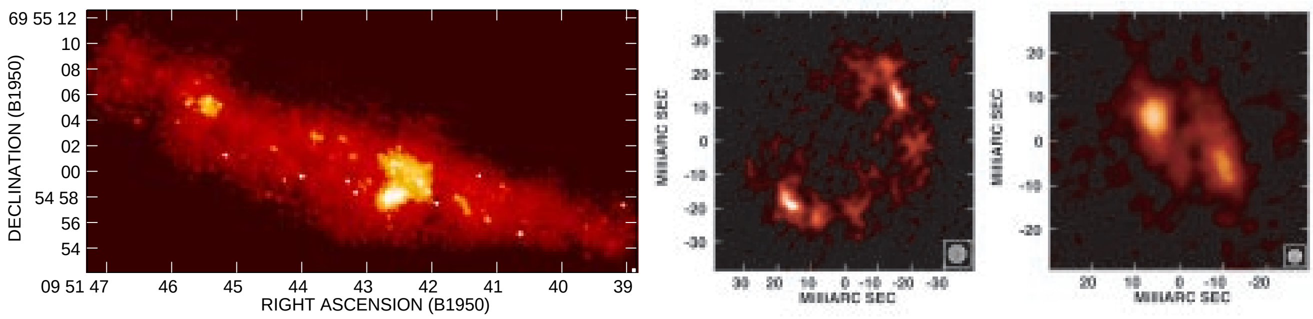
Recent MERLIN+VLA observations at 5GHz and MERLIN (only) observations at 1.4/1.6GHz with a resolution of ~150 milli-arcseconds (corresponding to ~10pc at the distance of NGC 2146) have shown that seven of the sources have a shell-like structure. Three of these sources, though still unresolved, have spectral indices that are also typical of supernova remnants. Six sources, mostly unresolved or having extended diffuse emission, have thermal spectral indices indicating that they are possibly ultra-compact HII regions associated with super star clusters. However, such spectra could also be explained by strong, free-free absorption by high emission measure, foreground, ionised gas. Observations such as these demonstrate the need for high resolution in understanding the physics of such objects.

Starburst Galaxies: M82

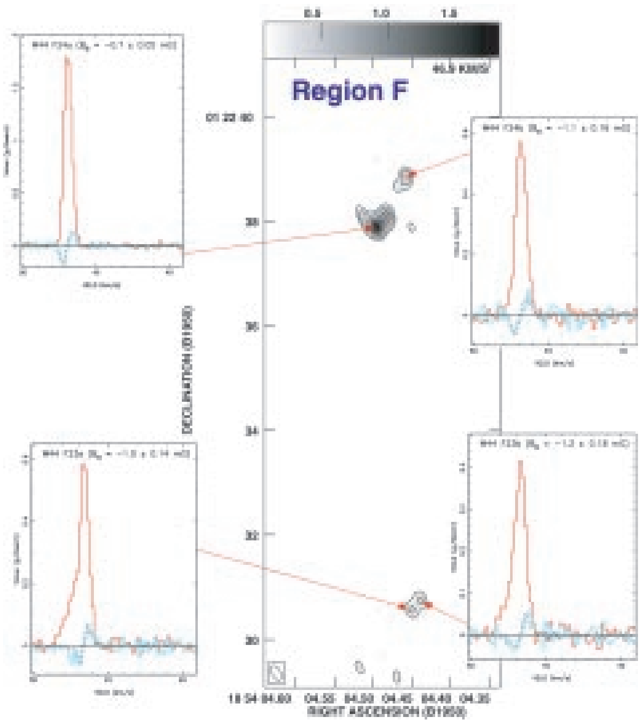
M82 is the archetypal starburst galaxy showing strong nonthermal radio emission from a central region ~1kpc across. Since the initially unresolved point sources in M82 were first resolved over a decade ago by MERLIN, most of them have now been conclusively shown to be supernova remnants. Regular monitoring of the expansion of these compact components has been continuing with MERLIN. In recent years, the first detailed images of SNRs in M82 have been made with global VLBI and MERLIN.

Most remnants, such as 43.31+592, have expansion velocities of ~10,000kms^{-1}, as expected for typical SNRs. However, 41.95+575 appears to be an enigmatic object. Firstly, the data show that the structure of this unusually bright SNR does not resemble a shell, but comprises extended diffuse emission in which are embedded two compact sources. These are separating at only 1/5 of the mean expansion velocity of the other supernova remnants in M82, which implies a zero-size birth in 1915. Secondly, unlike the other SNRs, which show no measurable flux density variations, the flux density of 41.95+575 has been decreasing at a rate of 8.5% per year. Thus, if 41.95+575 is a SNR, it is anomalous; in its youth it probably resembled the extremely luminous radio supernovae detected in Arp 220, which are thought to be of a class of which radio supernova 1986J is a prototype.

Below: (left) M82 observed with MERLIN at 5GHz. (centre) SNR 43.31+592 and (right) 41.95+575 observed in 1998 with global VLBI.



Below: MERLIN map and polarisation spectra of OH 1720MHz maser clouds in W44.



Galactic Supernova Remnants

Supernova remnants in our Galaxy provide us with some of the most spectacular images of the aftermath of the violent death of massive stars. However, the study of the physics of SNR is difficult due to the lack of useful probes of the various phenomena observed.

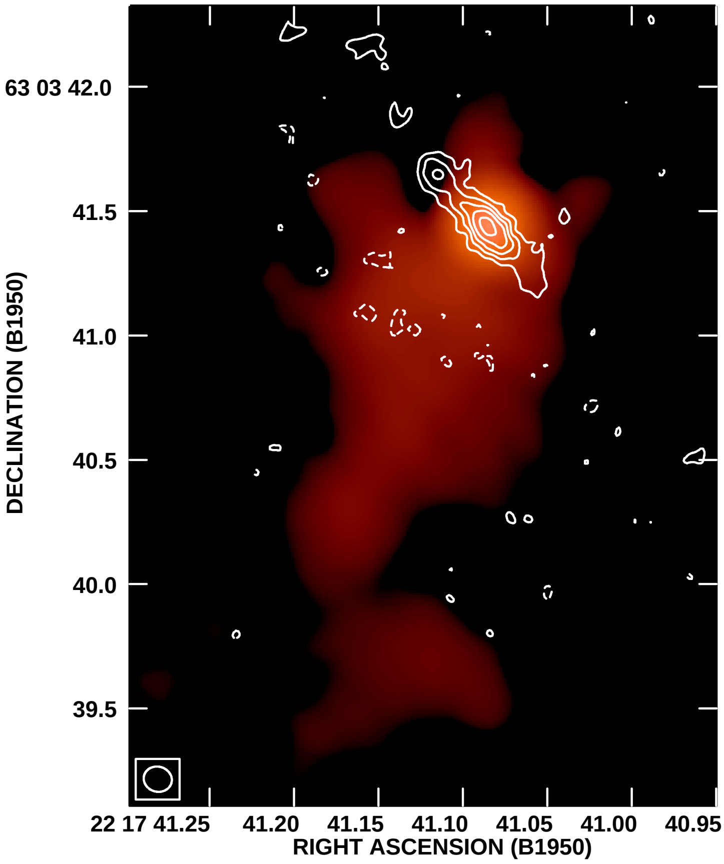
MERLIN and the VLBA have been used to measure the sizes of 1720MHz OH maser clouds that are associated with ~10% of Galactic SNR. The measured diameters, of order 5x10^{13}m, confirm the predicted column densities for these collisionally pumped masers at 100K. MERLIN full polarisation results provide details not only of the shock structure in the SNR, but also the detailed magnetic field. Thus, for the first time astronomers can study the shocks with the level of detail required to obtain some understanding of the processes involved.

In recent decades, astronomers have made significant advances in understanding the processes by which stars form. MERLIN continues to make substantial contributions to this field with its ability to observe magnetic fields and peer through dust-enshrouded regions. In particular, MERLIN has been used to investigate radio continuum and maser line emission from Galactic Young Stellar Objects (YSOs) in order to help distinguish between jets and discs.

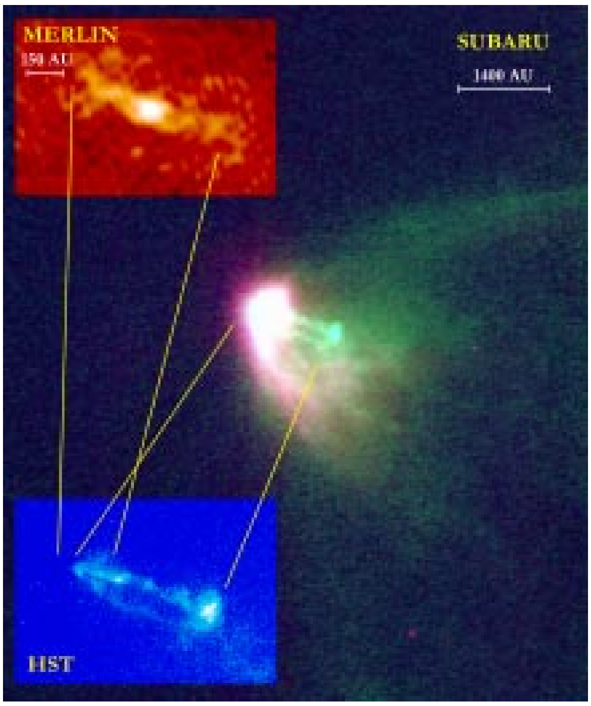
Below: An IR K-band speckle interferometry image of S140 IRS1, overlaid with MERLIN 5GHz radio contours.

Bottom: MERLIN, HST and Subaru images of the protostellar jet L1551 IRS5 in Taurus.

Spectral shifts in the H_2O 22GHz maser emission from the massive YSO, S140 IRS1, have previously been interpreted as clumpy material in Keplerian rotation around a condensation of a few solar masses. High angular resolution MERLIN mapping has shown that the spectrum is a blend of emission from regions too far apart to be all orbiting the same YSO. These individual maser features appear to be associated with a mix of rotating discs and outflowing jets. In addition, MERLIN 5GHz continuum imaging of this object has detected thermal radio emission from the ionised wind which is orientated perpendicular to the bipolar outflow seen in the near IR, and is probably an equatorial wind being driven off the surface of a disc.

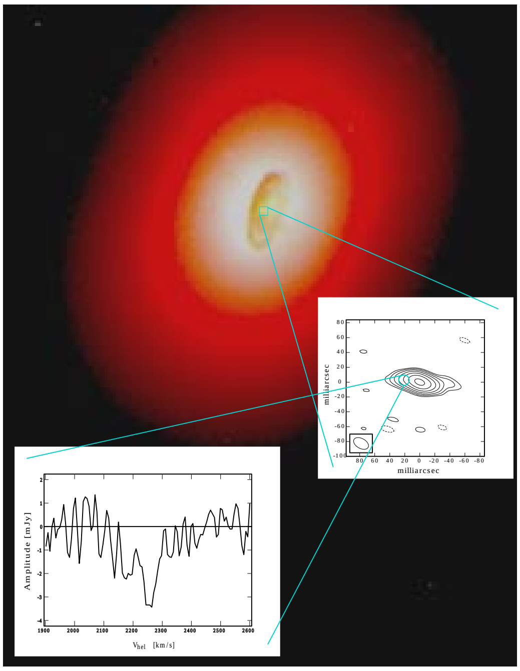


L1551 IRS5 is a proto-stellar jet enshrouded by 150 magnitudes of interstellar extinction. MERLIN observations have peered through the obscuring dust and revealed what appears to be a helical jet emanating from the core, especially on the side where no optical or infrared emission can be seen. The jet seems to originate in a binary system (seen in MERLIN 5GHz and VLA 43GHz images) and is directed perpendicularly to the projected orbital plane of the binary. High-resolution circular polarisation observations from MERLIN have also resolved the emission from the magnetised plasma for the first time. Radio observations, which peer unhindered through obscuring gas and dust, are the only way to discover the inner workings of these jets in young solar-mass stars.



Active Galactic Nuclei

Circumnuclear Neutral HI in NGC 4261



Above: The nucleus of NGC 4261 with the EVN 1420MHz map superimposed on the HST image.

The rotation curves of material orbiting galactic nuclei at radii from kpc to pc may be measured using HI absorption or OH and H_2O masers. High spatial and spectral resolution is required to separate disks from inflows or jets and thus discriminate between starburst and AGN activity. Within the EVN, the Lovell telescope's inclusion is vital in achieving the sensitivity needed to detect HI absorption on milliarcsecond scales.

During the reporting period the new EVN correlator, located at JIVE, Dwingeloo, has begun scientific operations and greatly increased the opportunities for spectral line VLBI. The first scientific results from this correlator involved a study of circumnuclear material in the galaxy NGC 4261, thought to contain a supermassive black hole.

The observations showed HI orbiting within only 7pc of the nucleus of NGC 4261. The HST, with three times lower resolution, found mainly molecular material in a disc orbiting the nucleus. The atomic hydrogen is presumably in a warmer region that is heated as material falls into the accretion disc feeding the black hole.

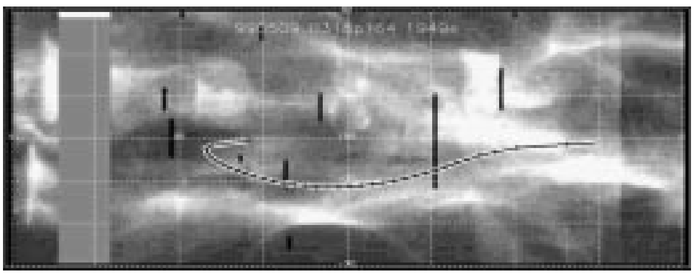
Measuring Stars & Their Winds

Interplanetary Scintillation

The mechanisms of solar coronal heating and wind acceleration are not fully understood. Two different forces may be at work; one producing the fast low-density wind above coronal holes and the other the slow, dense, highly variable wind observed above coronal streamers. With its real-time correlation and long baselines, MERLIN has the unique ability to probe the inner regions of the solar wind by measuring the interplanetary scintillation of signals from distant, compact radio sources.

Below: Ray-paths for MERLIN and EISCAT measurements of the IPS during May 1999 projected ballistically back to $2.5R_{\odot}$ overlaid on a white-light LASCO image.

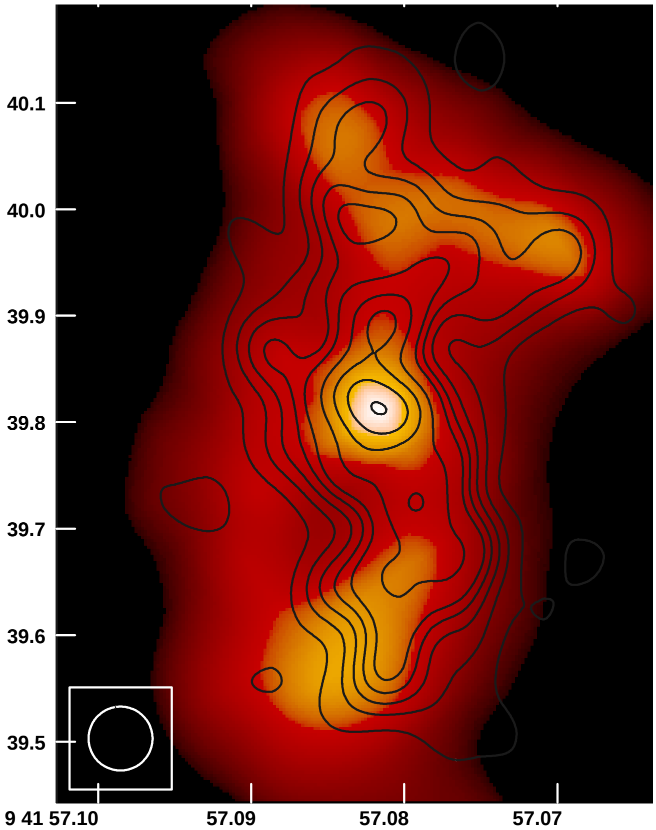
MERLIN observations of the solar wind were made at 5GHz in 1999 and 2000. These were co-ordinated with observations using EISCAT (probing the wind at a few tens of solar radii at 0.913GHz) and the white-light imager, LASCO, on the *SoHO* spacecraft. These show an intrinsically variable, slow wind outflowing at ~100kms^{-1} at 4-10$R_{\odot}$, accelerated to its cruising speed of 3-400kms^{-1} by 25-30$R_{\odot}$. The fast wind (seen above coronal holes) is at 500kms^{-1} by 6$R_{\odot}$ and reaches its top speed much more rapidly by 10-12$R_{\odot}$. This unique combination of instruments has thus allowed the fast and slow winds to be distinguished and their structures investigated. The results have given crucial clues to the location of acceleration regions within the solar wind and have shown for the first time that the wind behaves similarly at solar maximum and minimum.



MERLIN has disentangled the distinct emission mechanisms of numerous stellar winds using brightness temperature and spectral index maps. It has been possible to distinguish between thermal and nonthermal emission, and identify the processes involved, such as ionisation fronts or shocks. This has allowed an explanation of the complex shapes of the nebulae surrounding novae and other active stars.

Below: The innermost regions of the symbiotic nova HM Sge (MERLIN contours overlaid on an HST image).

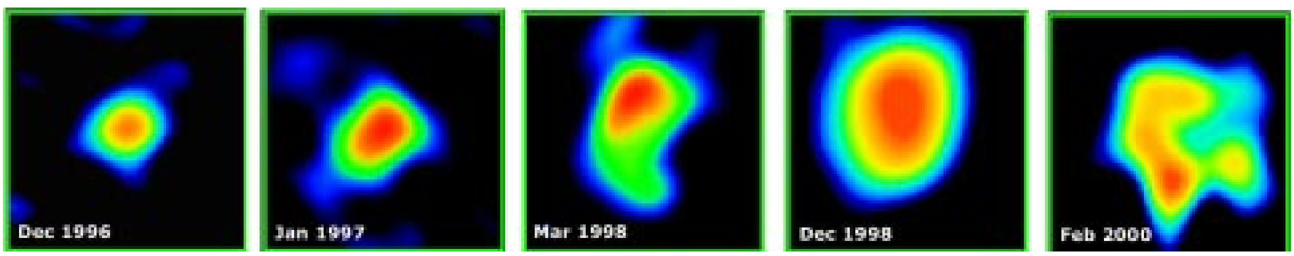
High-resolution 5GHz MERLIN images of the puzzling binary system β Lyrae reveal an extended radio nebula. It is ~40AU across with a brightness temperature <11000 K. This definitively confirms the thermal origin of the radio emission, which is consistent with emission from the wind of a B6-8II component (mass loss rate ~$10^{-7} M_{\odot}$/yr), ionised by the radiation field of the hotter companion. Present measurements indicate that almost $0.015 M_{\odot}$ have been completely lost from the system despite the onset of the Roche lobe overflow phase.



The evolution of the symbiotic nova HM Sge is complex and includes mass transfer onto a compact white-dwarf (WD) component and the effects of its intense radiation on the cool star. Optical imaging by the HST with different filters, and the precise radio astrometry at 5GHz with MERLIN, has allowed the binary star positions to be deduced. The peak emission in both datasets locates the WD in the system and has revealed the system's evolution since 1995 when there was only faint radio emission from the direction of the WD. The ridges of emission, seen either side of the WD, mark the shock fronts between the spiralling, colliding winds.

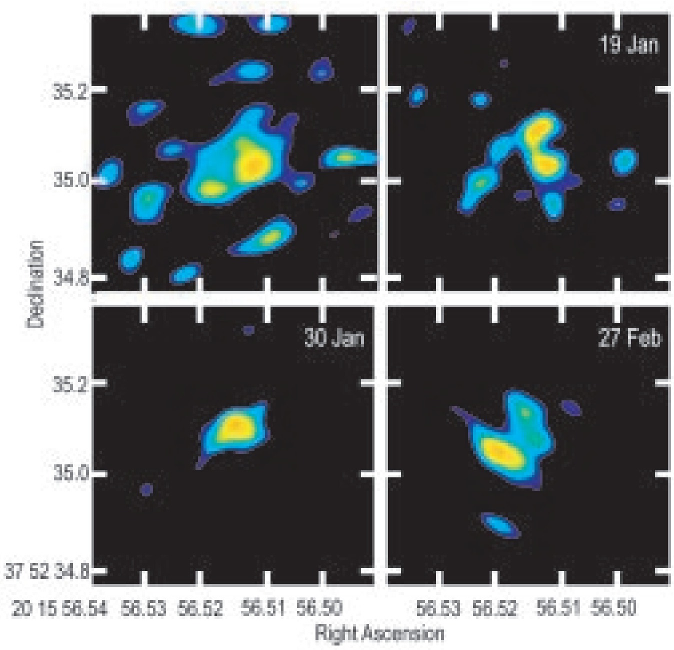
MERLIN has continued to monitor the expanding, cooling shells of several novae such as V723 Cas, which exploded in 1995. The shell is expanding at ~200kms^{-1} and has recently become optically thin. High resolution observations at different frequencies and different epochs reveal that the internal structure of the shell can be asymmetric, in contrast to the smoother outer surface of early images which gave rise to spherically symmetric models. MERLIN data, as well as optical studies, imply that multiple ejection episodes occur in a single outburst, and that interactions between the ejecta and with the binary companion, combined with shadowing by the accretion disc, are significant in shaping the outflow.

Below: MERLIN 5GHz images of the slow classical nova V723 Cas.



Understanding the later stages of stellar evolution is important for our knowledge of stellar populations and the chemical enrichment of galaxies, as well as for the life cycles of stars. MERLIN has continued studying many types of solitary evolved stars during the reporting period.

Below: MERLIN 5GHz images of P Cygni.

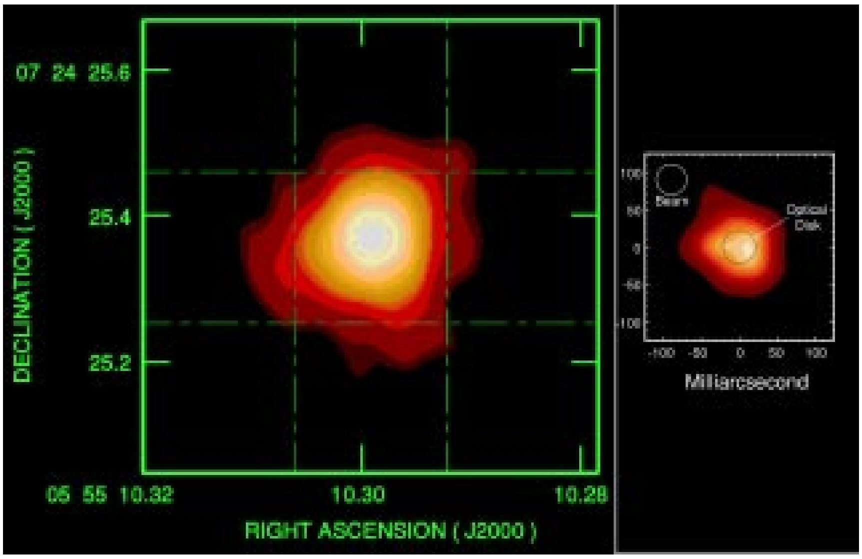


Further monitoring of the Luminous Blue Variable (LBV) star P Cygni has revealed that clumps in the wind structure vary on a timescale of a few days. These clumps are <90 AU in size and can change their flux density by ~20% in a week. This is too fast to be explained by the wind velocity of ~200kms^{-1} and may be due to recombination from small dense knots with high brightness temperatures.

MERLIN has been used to measure the size of the red giant star α Ori. At 5GHz, the radio emission is found to emanate from a region with a mean diameter three times the size of the optical photosphere. Furthermore, the emission is asymmetric. This asymmetry is also seen optically by the HST and is thought to be associated with spot activity. This may provide a key to understanding the clumpy, often axisymmetric winds from other red giants and supergiants.

Below: MERLIN 5GHz (left) and VLA 43GHz (right) images of α Orionis shown at the same scale.

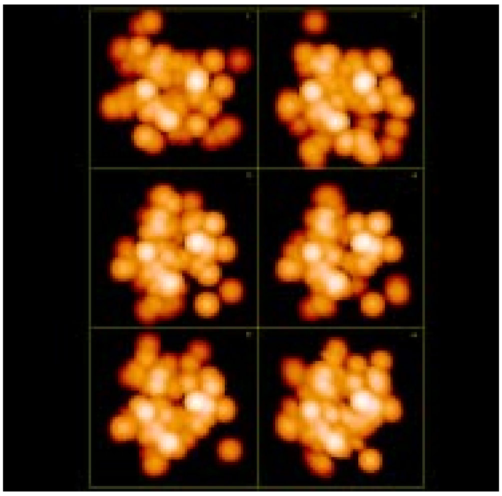
Maser emission is used to investigate the mass loss from red supergiants (RSGs), Asymptotic Giant Branch (AGB) and post-AGB stars on scales as small as an AU. MERLIN and the EVN have been used to monitor and image OH and H_2O maser emission from around a dozen objects. The combination of Doppler and proper motion measurements together with full polarisation imaging allows a complete 3-dimensional modelling of the stellar wind.

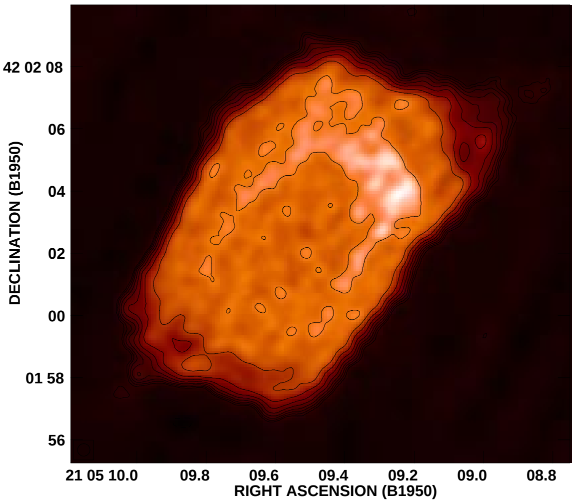


RT Vir is a solar mass Mira-like SRb star. Six epochs of monitoring H_2O 22GHz maser emission using MERLIN has shown the dramatic evolution of the wind over a ten-week period. Each clump in the wind is ~1-2AU in size. MERLIN OH mainline maser data have also shown a significant magnetic field to be present, implying that similar mechanisms may be shaping the winds in AGB stars as in red supergiant systems which are around ten times larger.

MERLIN has also been used to provide high angular resolution images of young planetary nebulae. At low resolution, the young planetary nebula NGC 7027 appears to be a smooth skewed rectangle. However, combining MERLIN and VLA data at 1.7GHz provides higher angular resolution and shows that the long edges have steeper flux gradients than the polar regions. Small-scale structure to the NW suggests that a collimated outflow has punched its way out of the shell at a slight angle to the long axis.

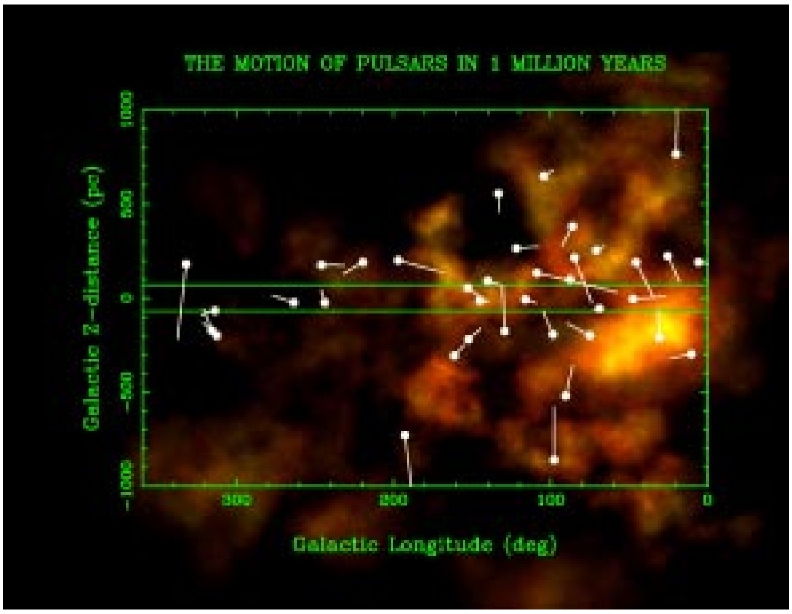
Below: (left) Six epochs of MERLIN 22GHz maser observations of RT Vir taken over ten weeks. (right) NGC 7027 MERLIN+VLA image.





Pulsar Proper Motions

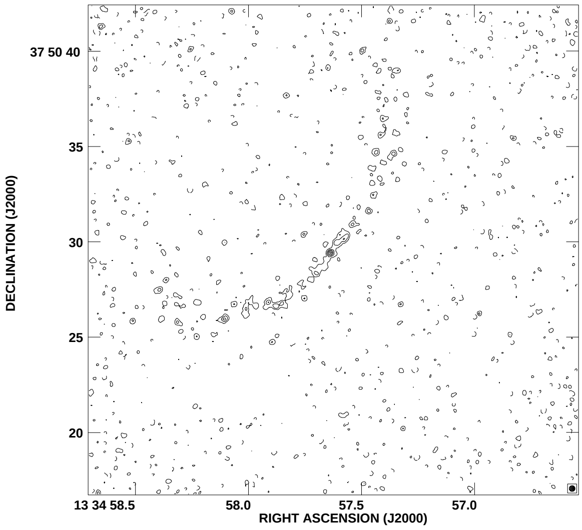
Pulsars are believed to be born with an energetic recoil resulting in high proper motions. Currently, the most accurate means to test this uses radio interferometry to measure their proper motions with respect to an extragalactic reference source. The proper motions of a sample of seven young pulsars have been measured with MERLIN over a three-year period. This involved measuring the phase difference between the pulsar and a reference source lying in the same antenna primary beam, so that the propagation and instrumental effects on the two sources were almost identical. The measured proper motions suggest more than half the sample had birth velocities ~450kms^{-1}. The results are also consistent with an RMS spatial velocity of the pulsar population of 300kms^{-1}.



Left: Pulsar proper motions measured by MERLIN. Dots show the current positions and the tails show the tracks of their motions during the last million years.

Extreme Environment Astrophysics

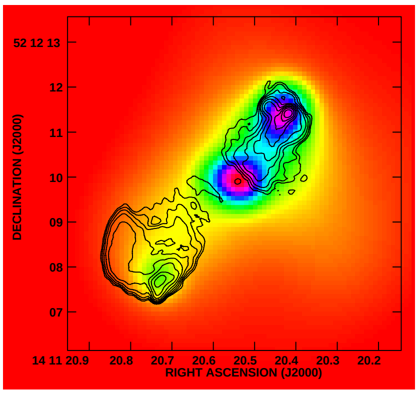
The XMM Deep Field & Other Radio-X-ray Comparisons



Above: A combined MERLIN and VLA image of a small region of the *XMM* Deep Field.

From its birth, radio astronomy has provided a window on the universe of extreme environments. The most startling discoveries have been the ubiquity of relativistic jets in contexts ranging from AGN to X-ray binaries (XRBs). During the reporting period the National Facility has continued to add to our knowledge of these spectacular objects.

A MERLIN Key Programme is investigating the relationship between mJy radio sources and the X-ray background. *XMM* observations of a 'quiet field' were made in 2000. This field, in the form of four adjacent pointing centres, has also been observed with MERLIN for 16 days. A MERLIN/VLA combination image gave an rms noise level ~7μJy/beam and showed that the weak X-ray emission is most often associated with Narrow Emission-Line Galaxies. The radio images will determine whether this originates from massive black holes or from starburst systems. One of the first radio maps shows a relatively bright 5-mJy AGN system associated with a faint optical galaxy which is the brightest member of a cluster. The compact 105-μJy AGN core component is clearly visible together with the inner parts of the curving radio jets, confirming that this is a classical head-tail radio galaxy.



Above: 1.4GHz MERLIN contours overlaid on the *Chandra* X-ray image of 3C295.

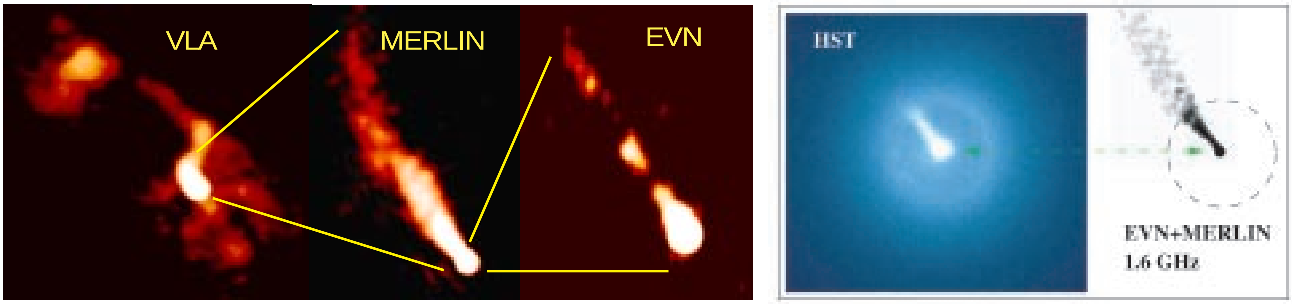
3C295 is a bright, compact DRAGN (Double Radio source associated with an AGN) at redshift 0.46 with a linear size of ~30kpc and a luminosity similar to Cyg A. The central peak in the *Chandra* image is probably X-rays from the AGN and the peaks close to the radio hot-spots are likely to be Synchrotron Self-Compton (SSC) emission. Comparing the MERLIN and X-ray maps results in an estimate of the magnetic field strength, which is very close to that predicted by the conventional minimum energy formula, only previously confirmed in a few cases, such as Cyg A.

Understanding Jets Through Multi-Frequency, Multi-Scale Imaging & Polarimetry

Radio galaxies can be mapped over two orders of magnitude in linear size at multiple frequencies and in full polarisation using the VLA, MERLIN and VLBI. Such data have been used together with HST images and, notably, new *Chandra* data, to investigate proper motions and variability in young and/or superluminal AGN ejecta, the mechanisms for decelerating relativistic jets and the applicability of equipartition.

The VLA, MERLIN and the EVN have been used to image the radio-optical jet of 3C264 on sub-kpc to pc scales. The VLBI jet is one-sided, while the large-scale morphology shows 3C264 is a classical double radio source (type FRI), with evidence for interaction with a dense intergalactic medium. The optical ring encloses a region that appears to have been cleared of dust. The HST jet is remarkably similar to the radio image at a matching angular resolution, with an almost constant optical-radio spectral index over the whole ~400pc. The position of the optical ring (the dashed line on the EVN+MERLIN image) coincides with a change in the radio properties of the jet. The optical emission is most likely to be of synchrotron origin, but it is difficult to reconcile this with equipartition.

Below: Multi-scale radio observations of 3C264 and the HST image of NGC 3862, the host of 3C264.

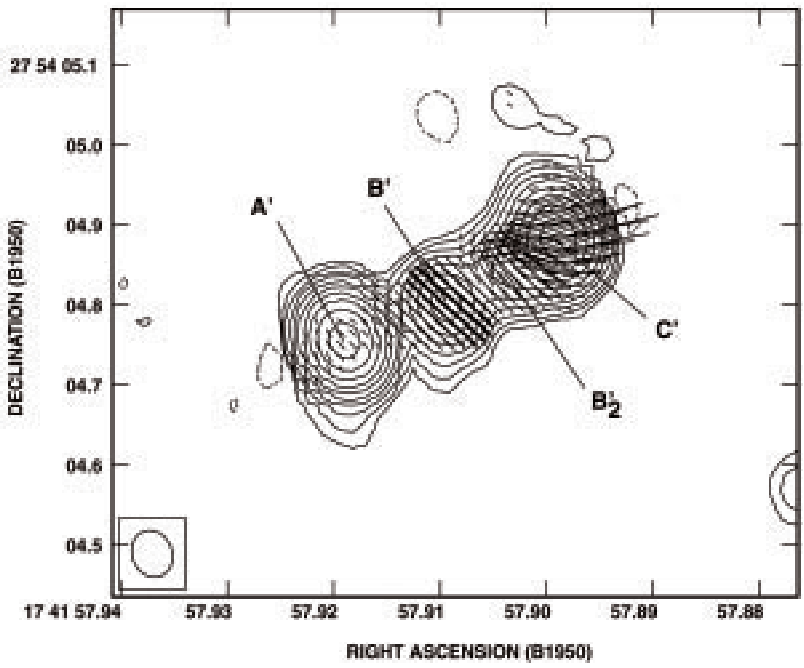


Compact Steep Spectrum Sources

The 'youth versus frustration' debate for the origin of Compact Steep Spectrum (CSS) sources continues, but observations such as those described below suggest that although the environment in which the sources are embedded has an effect which can occasionally be dramatic, such sources are in general young.

MERLIN observations of 50-80kpc radio sources have given some surprises. In 1741+279 and 1422+202, no depolarisation was detected and the low rotation measures in all the components with detected flux suggest a low level of interaction with the ambient medium. However, earlier VLBI observations had suggested that a north-south elongation of the western component represented a sharp cusp or bend in the jet at this point. The MERLIN polarisation images provide a beautiful confirmation of this suggestion with the electric vectors following the bend of the jet from an E-W direction to a Northerly direction. The most probable explanation is that the jet is running into dense material in the surrounding environment, which is somewhat at odds with the rotation measure data.

Below: MERLIN multi-frequency synthesis 5GHz image of 1741+279.

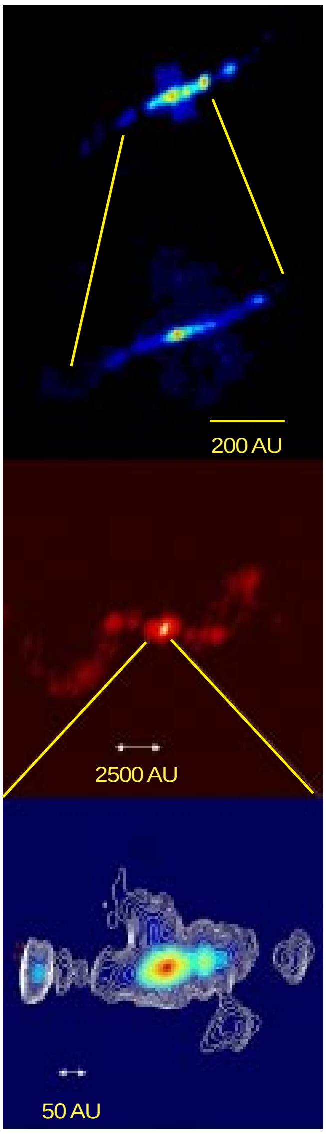


X-ray binaries (XRBs) produce some of the highest energy photons within our own Galaxy. MERLIN has previously produced some excellent results by their study and observations of several systems have been continuing.

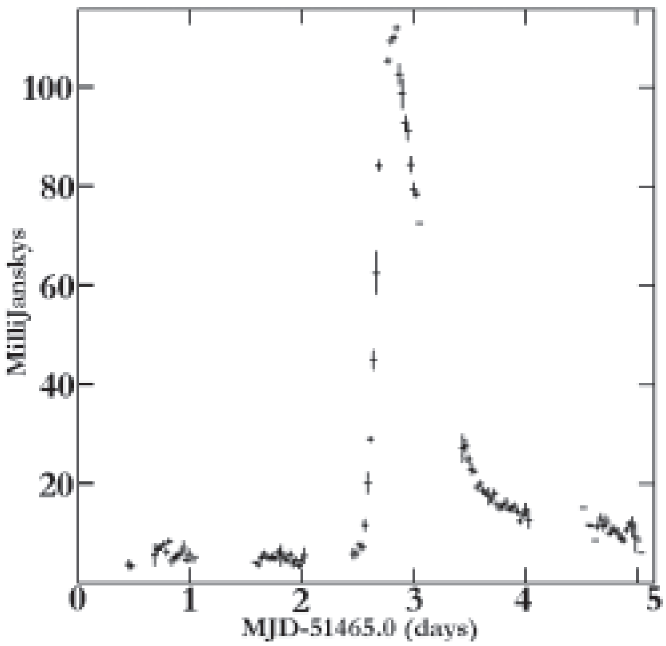
SS433 is the best-known XRB with approximately E-W jets expanding at 0.26c. Two independent groups have detected its unexpected N-S aligned extended region of equatorial emission. This was first suggested by VLBA observations in 1995, which revealed the existence of radio components perpendicular to the well-studied radio beams. MERLIN/global VLBI observations of SS433 confirmed the existence of this structure, sometimes referred to as the 'Elizabethan Ruff', which may be produced by a distinct mechanism separate from the ejection of plasmons along the precessing jet axes. This region might be related to an outflow in the orbital plane of the central binary system. The existence of such an outflow was indicated by observations in the optical and X-ray regimes also.

EVN monitoring of GRS 1915 during a minor flare also produced a surprise, in that no proper motions were detected, although assuming intrinsic symmetry the jet/counterjet brightness ratio suggests relativistic beaming in the velocity range 0.2-0.6c. During major outbursts it has apparently superluminal ejecta, but it seems that at other times moderately increased radio flux is due to continuous injection into a stable jet.

On October 11, 1999, the Rossi XTE satellite discovered a bright new transient X-ray source, XTE J1859+226. Subsequent X-ray observations revealed variability characteristic of an accreting black hole, and an optical counterpart was rapidly identified. Two days after the initial discovery, radio observations at 15GHz with the Ryle Telescope (RT) in Cambridge detected a radio counterpart subsequently confirmed with the VLA. A MERLIN ToO proposal was activated rapidly enough to capture the rise, peak and decay of a 100-mJy flare event in a few hours. Radio flares such as this almost certainly correspond to the ejection of large masses of high-energy electrons, probably at relativistic bulk velocities.



Above: 5GHz MERLIN+VLBA (top), 1.6GHz MERLIN (middle) and 1.6GHz global VLBI (bottom) observations of SS433.



Right: MERLIN monitoring of XTE J1859+226 at 1.7GHz capturing the rise, peak and decay of a 100-mJy flare event over a few hours.