1 OVERVIEW

1.1 The international context

1.1.1 Complementarity of radio facilities

Radio aperture synthesis now allows diffraction-limited imaging with baselines extending, with the Japanese space VLBI mission HALCA, to $\sim$3 Earth diameters. At mm–wavelengths with Earth–diameter baselines the angular resolutions are better than 100 microarcseconds. However, a practical array can effectively cover a range of no more than about 100 in baseline length (usually less), so that emission on scales more than $\sim$100 times larger than the resolution element is not recorded. It is therefore crucially important to obtain the appropriate resolution for each target, and so a range of arrays with different sizes are required. This has driven the international radio astronomy community to develop complementary facilities, in contrast to the optical/IR situation, where the major players tend to build competing facilities of essentially similar design.

1.1.2 MERLIN

MERLIN (see the illustration inside the front cover of the "MERLIN & VLBI National Facility" wallet) fills a unique niche in this international system. On the one hand it provides resolutions, $\leq$ 0.1 arcsec, up to ten times higher than the $\sim$10 km arrays such as the VLA, the new Giant Metre-Wave Radio Telescope in India, and the Australia Telescope Compact Array; and on the other, it can image objects $\sim$30 times larger than can the higher resolution arrays such as the European VLBI Network (EVN—see below) and the US Very Long Baseline Array (VLBA). In general, therefore, the science carried out with MERLIN is barely or not feasible with other arrays, particularly for frequency-specific programmes including spectral line observations, multi-wavelength imaging, and measurement of Faraday effects. It is also important to note that MERLIN is the only instrument which routinely provides the same $\leq$ 0.1 arcsec resolution as the Hubble Space Telescope.

1.1.3 The European VLBI Network

In addition to operating MERLIN the National Facility (NF) also plays a major role in the European VLBI Network (EVN–(see the illustration inside the front cover of the "MERLIN & VLBI National Facility" wallet), in particular by contributing data from telescopes at Jodrell Bank and Cambridge. At wavelengths of 18cm and longer the Lovell telescope is often used. The EVN is run by a consortium of institutes which operate telescopes in both Europe and Asia. Since its formation in 1980 the EVN has grown to include 12 active institutes with 16 radio telescopes in 10 different countries. The EVN telescopes operate as a Network for up to $\sim$ 12 weeks per year, a part of which involves simultaneous observations with MERLIN.

1.1.4 Combining arrays

Increasing use is now being made of combinations of MERLIN data with data from the VLA or from the EVN. In VLA+MERLIN maps the VLA data provide additional sensitivity, particularly to diffuse emission which could be missed in a MERLIN–only map. Conversely in MERLIN+EVN maps it is MERLIN which provides the short baseline information and hence the additional sensitivity to extended emission. These synergies emphasise the unique role played by MERLIN in radio aperture synthesis. As a result, MERLIN has a larger fraction of international users than other UK facilities.

The EVN often works in conjunction with the VLBA to form a "global" VLBI array which can include over 20 telescopes. The global array has higher resolution than either of its constituent networks and offers better sensitivity to diffuse features.

1.2 The importance of sub–0.1 arcsec imaging

While $\leq$ 0.1 arcsec imaging is currently the province of MERLIN and the HST, during the next decade other instruments will achieve comparable resolutions, in particular infrared adaptive optics on 8m class telescopes and large millimetre and sub–millimetre arrays. Even at X–ray wavelengths the resolution will rise to $\sim$ 0.5 arcsec with the launch of AXAF in late 1998. Finally towards the end of the next decade the Next Generation Space Telescope (NGST) will be launched. These instruments will lead to a much higher demand from the world–wide community for complementary data at sub–arcsecond resolution across the EM spectrum. MERLIN is uniquely placed to satisfy this demand in the radio giving the UK not merely a world–class but world–leading facility.

1.3 Restructuring MERLIN

In the course of the next two years the NF is engaged in a major restructuring exercise, principally aimed at allowing operations to be maintained at the current level in the face of a significant reduction in manpower and hence running costs. Although some improvements can be forseen the performance of MERLIN at each of its operating frequencies will not change greatly in this period. However users will benefit as a result of the completion of stage one of the frequency flexibility programme allowing change over between 5 and 22 GHz operation on the timescale of less than a minute. In stage two it is hoped to extend this flexibility to the 1.3–1.7 GHz band by the end of 2000. Another benefit from restructuring will be the integration of MERLIN and VLBI operations and the consequent increase in the amount of time available for joint MERLIN+EVN observations.

1.4 Transforming European VLBI

The capabilities of global VLBI will soon undergo a radical upgrade with the transformation of the EVN into a user–friendly and efficient system which surpasses the capability of the US VLBA in some respects, particularly sensitivity. At the heart of the change is the new 1 Gbit/sec MkIV data acquisition system, coming into operation in 1998, and the wide–band data processor (correlator) currently under construction at the Joint Institute for VLBI in Europe (JIVE) and due for completion in late 1998.

JIVE [1] has a mandate to support the operations of the European VLBI Network in the widest sense. While its major activity is currently to construct and operate the new wide–band correlator for the EVN, thus providing a clear focus for its activities, JIVE is also involved in providing comprehensive support to astronomers who may not be familiar with the VLBI technique (for further information on the EVN see the JIVE WWW pages at http://www.nfra.nl/jive).

1.5 MERLIN phase 3

To ensure that the NF can play its full part in the astrophysics of the next decade it is proposed to transform MERLIN's capabilities (MERLIN phase 3 – MERLIN3) by massively increasing the instantaneous bandwidth via fibre optic links and the upgrading of other aspects of the instrument including state–of–the art receivers at 2cm. The goal is vastly to improve the stand–alone sensitivity (1σ) to < 5 μJy beam^{-1} in a 12 hour integration at both 2 and 6cm wavelength—the corresponding 1σ brightness temperature sensitivity will be $\sim$ 100 K. If, as is hoped, the Lovell telescope is upgraded to provide good performance at 6cm wavelength, the sensitivity of MERLIN3 will be 20 times that of the current system. Combined with resolutions in the range 10–50 mas this will open up spectacular new possibilities in both galactic and extra-galactic astronomy. In particular it will bring within reach the thermal and ionized universe of stars, nebulae and active galaxies in a wavelength regime unobscured by dust.

A brief description of the proposed new instrument and some of the astrophysical questions it could address are given in section 3.

[1] JIVE was established as a scientific foundation in December 1993. The host organisation is the Netherlands Foundation for Radio Astronomy (NFRA) located in Dwingeloo, The Netherlands. Its operations are supported via multi–national funds from the NFRA, PPARC in the UK, the CNR in Italy, CNRS in France, Onsala Space Observatory—the Swedish National Facility for Radio Astronomy and IGN in Spain. A major part of the funding required to construct the VLBI data processor was initially obtained through a separate 5M ECU grant from the Dutch government.

Forward Look for the National Facility

DATES	EVENT	PRINCIPAL EFFECT
1997–2000	Restructuring	Reduced Running Costs Frequency flexible operation
1998–1999	Wide–band EVN upgrade and operation of JIVE Correlator	EVN user–friendly operation with sensitivity superior to VLBA
2000–2005	MERLIN3 upgrade	Order–of–magnitude increase in sensitivity; new high resolution imaging capability at 2cm

2 ASTRONOMICAL PROGRAMMES

To illustrate the range of astronomical programmes to which the National Facility is currently well–suited some of the most interesting results obtained in the last few years are now briefly described. The topics covered are largely restricted to MERLIN– and EVN–related science to emphasise the unique contribution of UK facilities. However a few examples of the vast range of topics now being studied with global VLBI are given.

2.1 Astrometry

MERLIN can achieve high astrometric accuracy by referencing the positions of target sources to the International Celestial Reference Frame (IRCF) defined by VLBI to sub–milliarcsec precision. The absolute astrometric accuracy achieved depends on the distance to the primary calibration source and the weather but is typically a few milliarcsec rms. Relative astrometry, using a larger but less precise net of radio sources, can be carried out at the milliarcsec level.

- **Hipparcos frame tie:** MERLIN positions of 21 radio stars have been used to link the Hipparcos reference frame to the IRCF (Morrison et al. 1997). The accuracy of the link at the epoch 1995.7 using these radio stars is 1.7 milliarcseconds, consistent with the VLBI determination at 1991.3. Only 5 of the 21 stars are common to the VLBI and MERLIN datasets; this gives confidence in the link which could have been distorted by offsets between the optical and radio positions in some of the binary systems.

- **Hubble Deep Field:** MERLIN positions of two weak radio galaxies (with an absolute accuracy of a few tens of milliarcsec) were used make the initial tie of the Hubble Deep Field to the ICRF to an accuracy of 0.4 arcsec (Williams et al. 1996). The a priori HDF astrometry is uncertain to ~ 1 arcsec which is too large to allow for routine identification of ultra–weak radio sources—see section 2.15

- **Pulsar proper motions:** Measurements of the proper motions of a sample of 99 pulsars, the majority of which were made with MERLIN (Lyne & Lorimer 1994, and references therein; see also Figure 1) have shown that their mean birth velocity is 450 ± 90 km s^{-1}. This exceeds the escape velocity from binary systems, globular clusters and the Galaxy, and so will affect our understanding of the retention of neutron stars in these systems. The origin of these large velocities is still something of a mystery but is probably related to asymmetries in the large neutrino flux released in the supernova collapse.

2.2 OH/IR stars and distances in The Galaxy

- **OH/IR stars:** Towards the end of their lifetimes, most stars lose a considerable fraction of their mass through strong stellar winds. This mass-loss is driven by strong radial pulsations that occur in the stellar atmospheres. As an evolved star pulsates, the gas in the outer atmosphere is lifted to a height of a few stellar radii where the temperature is low enough for solid grains to form. Radiation from the star then blows the grains and gas outwards, creating a circumstellar envelope in which material flows outwards at speeds of around 20 km/s. These highly evolved stars are often known as OH/IR stars as they emit strong infrared emission from the circumstellar grains and intense radio maser emission from OH molecules that form in the envelopes.

- **The method:** The OH/IR stars provide an unique means of determining accurate, geometric stellar distances. The distance to such a star can be obtained by combining the angular and linear diameters of the circumstellar envelope. The angular diameter of an OH/IR star is given by aperture synthesis imaging of the OH maser emission at 1612 MHz, while the linear size of the envelope is determined by measuring the time-delay or "phase-lag" between the OH light curves from the front and back of the envelope. The OH 1612 MHz masers vary in phase with the stellar pulsations but the photons that are emitted from the back of the envelope take longer to reach the earth than those from the front. This time-delay is directly proportional to the linear size of the envelope.

  Chapman (AAO/ATNF), Killeen(ATNF) and van Langevelde (JIVE) are working on a long-term programme to measure stellar distances for a sample of 95 southern OH/IR stars. The OH/IR stars have been selected to be located at well defined locations in the Galaxy and the distance estimates for the individual stars will be combined to yield a precise determination of the distance to the centre of our Galaxy. The long term goal of this project is to determine the Galactic centre distance to a precision of 5 per cent. For this programme the Parkes 64-m radio telescope was used to regularly monitor the OH maser emission of the 95 sources over a five-year period. The Parkes data have been used successfully to determine linear diameters for almost all the OH/IR stars in the sample. The front-back OH phase lags are typically around 10 days which corresponds to a linear size of 1,700 AU.

  The angular diameters of the circumstellar envelopes are obtained using MERLIN, the Long Baseline Array (LBA) in Australia and the Very Long Baseline Array (VLBA). Typically the angular diameters are around one arcsec in size. The sub-arcsec resolution of the MERLIN array is ideally suited to resolving the detailed circumstellar structure of these sources. As an example, the **COLOUR ILLUSTRATION** shows a set of 16 images for the OH 1612

MHz maser emission from the OH/IR star OH 30.1-0.7. Each image shows the distribution of the maser emission at a given velocity and corresponds to a cut through the circumstellar envelope. The colours represent the intensity of the maser emission. The strongest emission occurs from unresolved cap-like regions at the front and back of the envelope (first and last images). At intermediate velocities, weaker emission is detected from rings which are centred on the stellar position. The radii of the rings increases towards the central velocity in just the way expected for a spherical shell of constant radius. However at some velocities the well resolved images show the masers to be located within several arc-like filamentary structures. These define knotty regions of enhanced gas density where the maser emission is strongest.

2.3 Young stars and their outflows:

- **T Tauri stars:** T Tauri stars are young stellar objects (YSOs), similar in mass to the Sun, that are completing the transition between a collapsing cloud and a main–sequence star. Many of these objects are associated with circumstellar disks as well as energetic outflows that can extend several light years away from the YSO. These are thought to be collimated by magnetic fields but evidence for fields of the requisite strength is elusive. Using MERLIN at 6cm wavelength Ray et al. (1997) showed that the infrared companion (T Tau S) to T Tau recently ejected two large lobes of mildly relativistic particles in opposite directions. The radio emission from the two lobes exhibits strong circular polarization of opposite helicity, implying the existence of strong, ordered, magnetic fields at a surprisingly large distance from the source. These fields are almost certainly dynamically important and play a role in the collimation of the outflow from the young star.

- **S 140 IRS 1:** A MERLIN 6cm map of the thermal emission from the ionized wind of the massive young stellar object S 140 IRS 1 has been made by Hoare (Leeds) [2] and co–workers (**COLOUR ILLUSTRATION**–bottom right); the resolution is 0.1 arcsec and the wind is highly elongated with dimensions of 400x100 AU. The major axis of the wind is actually perpendicular to the outflow from this object as observed via a bipolar CO outflow and near–IR light reflected from the walls of the blue-shifted outflow lobe. This is the best example yet of equatorial mass loss from luminous YSOs which may be due to the presence of an accretion disk feeding the wind or flattening of the wind due to rapid rotation of the young star.

- **Magnetic fields in star-forming regions** The Galactic magnetic field permeates collapsing clouds and has a profound effect on the timescale of star formation. MERLIN maps of OH masers in star-forming regions show that

[2] see http://ast.leeds.ac.uk/staff/melvin.html

both linear and circular polarization is present. The magnetic field can be measured in 3 dimensions on sub-arcsecond scales. Spectral line observations combined with proper motion studies also allow the kinematics to be resolved in all directions. For example, in W75 N sub–mm polarimetry shows that the magnetic field is parallel to the CO outflow on the scale of 0.15 pc (Vallée & Bastien 1995). However the OH masers reveal field reversals showing that the magnetic field becomes twisted as if caught up in a disk within a few thousand AU from the centre of the outflow (Hutawarakorn 1997).

2.4 Stellar mass loss and circumstellar environments

- **Supergiants:** Despite their importance in the chemical enrichment of galaxies and stellar evolution, M supergiants are in general not very well understood. In particular the properties of their massive, low–speed, stellar winds and hence of their circumstellar environments are often difficult to determine (see the "Unauthorised biography of Betelgeuse" by Edmunds 1998). Skinner et al. (1997a), using a combination of VLA and MERLIN radio data at 6cm wavelength, have resolved the chromosphere of α Orionis (Betelgeuse) for the first time. Complementary UKIRT images resolve the dust shell. Overall the envelope has a gas density falling approximately ar r^{-2} consistent with a constant velocity wind outflow). A strongly–contrained model, consistent with the radio, infrared and SED of the star shows that the chromosphere has a typical radius about four times that of the photosphere and a maxiumum temperature of $\sim$ 9000K. This contrasts with the photospheric temperature of $\sim$ 3600K.

  S Per is a late-type red supergiant of about 20 solar masses. Richards, Cohen (Manchester) and Yates (Herts) are mapping the water masers (**COLOUR ILLUSTRATION**–top left) which are found between 50 and 190 AU from the star. They form about 100 clumps thought to correspond to individual masing clouds. The unbeamed size of these clouds, 15 - 20 AU, has never been measured before. They are distributed in a spherical shell; the ring-like appearance is caused by tangential beaming showing the stellar wind in this region is undergoing acceleration due to radiation pressure on dust grains.

  Masheder (Bristol/JIVE), van Langevelde (JIVE) Richards and Cohen (Manchester), Greenhill (CfA, Harvard-Smithsonian) and Gray (Bristol) have been mapping the mainline OH masers in S Per with EVN and "global" VLBI. In contrast to the water masers the OH masers are brightest at extreme velocities but close to the line of sight to the star (**COLOUR ILLUSTRATION**–top right; note that the faint striations are instrumental effects). A fainter surrounding ring is clearly resolved for the first time by these VLBI observations. This shows that the OH masers spatially overlap the water maser regions, further evidence for the clumpy nature of the outflow. Preliminary analysis of

Zeeman splitting of the OH lines suggests a magnetic field between -450 and 180 nT at various locations in the OH shell between 80 and 180 AU from the star.

MERLIN observations of the 22 GHz water masers in the circumstellar envelope of the supergiant NML Cyg (see Figure 2) show an irregular ring of emission 200 milliarcsec across plus a pair of outlying features nearly 600 milliarcsec apart (Richards et al. 1996 and references therein). Comparison with maps at previous epochs reveals proper motions of 1.9 ± 0.4 milliarcsec yr^{-1} corresponding to a tranverse velocity of 19 ± 4 km s^{-1} at a distance of 2kpc. This is the first time that proper motions have been measured for individual masers in a circumstellar envelope. The derived velocity is consistent with the radial velocity range of the 22 GHz emission. The masers which form the irregular ring can be modelled as an expanding, accelerating, shell which has acquired the escape velocity at the outer radius. The NW–SE symmetry of the H_2O masers is the same as that seen in OH masers on a larger scale and coupled with the measured expansion is strong evidence for a bipolar outflow originating close to the star. This could be a precursor to the formation of a bipolar supernova remnant which is the end result of the evolution of such massive stars.

- **P Cygni:** Luminous blue variables, typified by P Cygni, exhibit variability on a variety of time–scales and show evidence from their emission–line dominated spectra for substanatial ongoing mass loss; in P Cygni's case this is estimated to be $\sim 2 \times 10^{-5}$ $M_{\odot}$ yr^{-1}. P Cygni was one of the first stars to be found to be a thermal radio source and simple models of the radio emission suggest that its wind should produce an optically thick radio photosphere with a diameter of ~ 0.1 arcsec at 6cm.

  Observations of P Cygni with MERLIN (Skinner et al. 1997b) fully resolve the core of the stellar wind and show peak brightness temperatures of 14000 to 18000K. This is the first time that resolved radio images of a hot stellar wind have been obtained. A team led by Barlow (UCL) is monitoring P Cygni with MERLIN at 6cm. The images (see Figure 3) show that the circumstellar environment of P Cygni is highly inhomogeneous, clumpy and variable on timescales which can be as short as a few days. While recombination of the ionized gas within clumps can quench the free–free emission and hence lead to radio variability this short timescale is difficult to explain.

- **OH/IR Stars:** The MERLIN OH Maser images of one of the sources, IRC 10529, studied by Chapman, Killeen and van Langevelde reveal a highly unusual bipolar outflow. The OH masers occur in two lobes on opposite sides of the star and systematic velocity gradients are present across each of the lobes. IRC 10529 is of particular interest as the variability of its OH masers and its infrared characteristics are typical of OH/IR stars while the bipolar geometry is highly unusual. Bipolar geometries are however associated with planetary nebulae. While almost all OH/IR stars exhibit a strong degree of spherical symmetry, almost 50 per cent of planetary nebulae have bipolar or axi-symmetric geometries. The complex changes that occur in stellar winds as a circumstellar wind is swept up to form a planetary nebulae are still poorly understood. Stars such as IRC 10529 may provide considerable information on this transition phase of stellar evolution.

2.5 Planetary Nebulae

- **NGC7027 and BD +30 3639:** MERLIN/VLA images at 6 cm of the thermal continuum emission from two young planetary nebulae, NGC7027 and BD +30 3639 show small clumps of emission within the essentially ring–like structure of each nebula (Bryce et al. 1996). The peak brightness temperatures are $\sim$ 13000K. The resolution of the MERLIN/VLA radio images is similar to that of the HST in the visible band and a comparison of the radio and optical images (see the front cover of the "MERLIN & VLBI National Facility" wallet for NGC7027 and Figure 4 for BD +30 3639) reveals a basic similarity over this wide range of wavelength, especially in the case of BD +30 3639. In the case of NGC7027, however, there are dramatic differences between optical and radio images which can be attributed to dust obscuration of the optical photons. It is interesting to note that a very recent HST NICMOS infrared image of NGC7027 shows a similar inner ring to that revealed by the radio image. It is the younger object, NGC 7027, which has the largest dust content suggesting that in BD +30 3639 much of the dust which may have been generated during the formation of the circumstellar envelope has been dispersed or dissociated.

2.6 Colliding stellar winds in binaries

- **Wolf–Rayet Sytems:** MERLIN images of the X–ray luminous Wolf–Rayet system WR147 (see **COLOUR ILLUSTRATION**–bottom left) reveal thermal radio emission coincident with the WN8 star and associated with its stellar wind. The images also show non–thermal emission along the binary axis and close to the companion B star, $\sim$ 0.6arcsec to the north, detected by both UKIRT (Williams et al. 1997) and the the HST (Niemela et al. 1998). The shape of the thermal source around the WN8 star shows that its stellar wind is not spherically symmetric. The non–thermal source is direct evidence for a colliding–wind origin for the emission, with the B star being just luminous enough to provide a wind of sufficient strength. MERLIN observations of another Wolf–Rayet system, WR146 (Dougherty et al 1996) suggest similar behaviour to that seen in more detail in WR147.

- **Symbiotic binaries:** A small sub–class of symbiotic binaries show weak nova–like outbursts. HM Sge, whose binary components are a Mira variable and a white dwarf, underwent such an outburst in 1975. The radio emission of HM Sge has been monitored with MERLIN and the VLA from 1992 (Eyres et al. 1996; Richards et al. 1998). Thermal emission within 0.4 arcsec of the optical peak is elongated north–south and hot–spots appear to be moving around an anti–clockwise ellipse. If this is due to motion in an inclined disk the period is $\sim$ 88 yr. This can be explained by a colliding–wind model in which the emission peaks are co–rotating with the binary orbit as the ionization front and the hot wind from the white dwarf sweep through the dense Mira wind. On arcsec scales the emission is elongated east–west consistent with a bi–conical outflow arising from the nova outburst interacting with the previous cool wind. Unusually non–thermal emission is detected $\sim$ 0.7 arcsec from the stars which could be synchrotron radiation in a μT magnetic field.

2.7 Novae

- **Nova Cygni 1992:** Multi–wavelength MERLIN images of the bright optical nova Cygni 1992 provide the most detailed information on the early radio development of a classical nova outburst. The expanding gas shell is resolved only 80 days after outburst and is still detected after 682 days. The structure and evolution of the remant is not as simple as existing models assume. The emission distribution is not circularly symmetric and there is evidence that the direction of the preferred expansion axis varies through 90° with time. The radio emission is consistent with a mixture of optically thick and thin thermal free–free and the brightness temperature at 6cm wavelength exceeded 40 000 K 172 days after outburst; this is likely to be representative of the electron temperature at the time (Eyres et al. 1996).

2.8 Micro quasars

MERLIN and the EVN are ideally suited for studying active binary stars such as SS433, Cygnus X–3 and GRS1915+105. After outbursts these objects produce relativisitic jets and intense non–thermal radio emission. The most recent results on GRS1915+105 provide an excellent example of MERLIN's role in their study:

- **GRS1915+105:** In Autumn 1997, triggered by the observation of a radio outburst with the Ryle Telescope, MERLIN was able to capture the early stages in the development of twin relativistic jets in GRS1915+105. Relativistic expansion, following a three times stronger radio flare, was first discovered with the VLA in 1994 by Mirabel & Rodriguez (1994). During the 1997 outburst MERLIN was able to trace the development of the jets four times closer to the binary than did the VLA in 1994. The sequence of MERLIN maps (see **COLOUR ILLUSTRATION**) showed that the expansion rate was similar to that in the more powerful 1994 flare. The inferred velocity in the rest frame of the binary is 0.92c to 0.98c, depending on the assumed distance for the source (Fender et al. 1998). Attempts are now underway to understand the relationship between the ejection of the radio jets and the behaviour of the putative accretion disk diagnosed by the X–ray emission. Just prior to the radio flare the source ended a period of X–ray quiescence with an X–ray outburst, possibly indicative of the formation of an accretion disk. Strong X–ray fluctuations following the outburst are indicative of major disk instabilities and the radio jets were launched during this period.

2.9 Starburst galaxies

Although active galaxy research tends to be dominated by phenomena associated with a "central engine" the majority of activity in galaxies is starburst related. The starburst manifests itself most obviously via a high far–infrared (FIR) flux and an extended (on the kpc scale) radio source. The strong correlation between the FIR and radio fluxes can be intepreted in terms of star formation rates. Large amounts of dust obscuration often mean that starbursts are inaccessible optically so high resolution radio observations are particularly useful.

- **M82:** The nearest starburst, in M82, is being studied intensively with the VLA, MERLIN and VLBI. The VLA/MERLIN map at 18cm wavelength is the best overall representation of the radio source (see **COLOUR ILLUSTRATION**). As well as diffuse emission there are $\sim$ 50 compact sources many which have been resolved into shells (Muxlow et al. 1994). The shell structures confirm that the compact sources are indeed supernova remnants (SNR) and hence M82 is a convenient laboratory for studying SNR. European VLBI observations over an 11 year time baseline have measured expansion velocities of $\pm$9000 km s^{-1} in several remnants indicating that their ages range from $\sim$ 35 to $\sim$ 100 years. Assuming similar expansion velocities for the larger shells, mapped with MERLIN, implies that their ages are up to 1000 years. Future VLBI observations should enable the ages of many more remants to be estimated and hence allow the present supernova rate to be determined. Assuming a form for the stellar mass function, the overall star formation rate can then be calculated thus providing a direct check on the star formation rates derived from integrated properties.

  The ISM of starburst galaxies has been studied in molecular emission lines using mm–wave interferometry with angular resolutions of a few arcsec, corresponding to $\sim$ 100 pc in even the nearest galaxies. MERLIN has been used to study the absorption properties against the SNR in M82 thus probing the ISM on a scale of $\sim$ 0.1 arcsec ($\sim$ 2pc). Low frequency spectral turnovers indicative of free–free absorption reveal that the ionized gas has emission measures of 10^5 to 10^6 pc cm^{-6} (Wills et al. 1997). HI absorption measurements against $\sim$ 30 SNR (Wills et al. 1998, Figure 5) show clear evidence for rotation and suggest that the neutral gas is an a central bar. Future studies, including OH absorption, will lead to a 3–D picture of the starburst in M82.

It is obviously vital to study starbursts other than M82 and a recent global VLBI image of the archetypical ULIRG galaxy Arp220 suggests that some objects can be studied in detail out to at least $\sim$ 100 Mpc with global VLBI.

- **Arp 220:** Arp220 lies at a distance of 77 Mpc and has an infrared luminosity of 1.5×10^{12} $L_\odot$. The HST NICMOS image at 1.1μm (Scoville et al. 1998) resolves both nuclei, the result of a merger, and also reveals the presence of several luminous star clusters to the south and east. A MERLIN 18cm continuum map (Figure 6) shows two radio nuclei with dimensions $\sim$ 200 pc; the western nucleus has a clear IR counterpart in the HST image but the eastern one lies in a highly reddened complex. Global VLBI observations of the 18cm continuum (also shown in Figure 6; the resolution is 3×8 milliarcsec corresponding to 1×3 pc) show that only 10 mJy of the $\sim$ 300 mJy detected by MERLIN is in compact components. Smith et al. (1998) show the compact emission consists of about 12 unresolved sources which are interpreted as very luminous radio supernovae, similar in luminosity to RSN1986J. This interpretation strongly supports the starburst hypothesis for Arp220.

  Global VLBI images of the compact structure of the OH 1667 MHz megamaser in Arp220 (Lonsdale et al. 1998) show that there is no compact continuum emission associated with either maser complex to stringent limits. This implies maser amplification ratios > 800 and suggests that the 1667 MHz masers are saturated and lie in parsec scale clouds. These observations require a major revision of the standard OH megamaser model.

2.10 Extragalactic mega–masers

VLBI, particularly with a global array, plays a vital role in studying extragalactic megamasers, as in the case of Arp220 above. However MERLIN is also an ideal instrument for detecting the extended (0.1-0.2 arcsec) OH Megamaser emission in the centres of active galaxies and the underlying radio continuum emission. Its unique combination of high angular resolution, sensitivity to extended structure and accurate astrometry make it an ideal complement to VLBI for investigating the structure, physical conditions and dynamics of megamaser galaxies and the pumping mechanism of the 18-cm OH megamasers. In particular the angular resolution (130-mas) of MERLIN at 18-cm allows direct comparison of the radio continuum and spectral line data with 4-m telescope, using Adaptive Optics, or HST observations of the NIR and optical emission from these AGN.

- **MKN 273 and MKN 231:** Astronomers from Hertfordshire and Bristol have recently mapped the 18-cm radio continuum and OH maser emission towards two ultra-luminous infra-red galaxies, MKN 273 (z=0.038) and MKN 231 (z=0.041). MERLIN radio continuum maps of MKN 273 (Figure 7) show a compact double peaked source which is also seen in the NIR. MKN 231 shows a compact radio continuum structure with an extended (200-mas) N-S halo. The compact radio emission contains the active nuclear regions. The main axes of the maser distributions lie along the main axes of the radio and optical continuum emission. The bright maser emission coincides with the bright radio continuum emission. The total maser velocity extent detected is 800-1200 hundred km s^{-1}. In MKN 273 the changes in velocity gradient as a function of position, for both 1665 and 1667 MHz masers, are consistent with a rotating neutral torus, of 200-pc diameter, surrounding the active nuclear regions. The maser data show the disc kinematics to be solid body.

The MERLIN data also constrain our theories of maser pumping physics for OH megamasers. Imaging the extended, therefore low gain, maser emission and the underlying continuum constrains the maser pumping models and tests the ability of the physical models of the emitting region to reproduce the observed line to continuum brightness ratios. The result is to constrain the local gas kinetic temperature, dust temperature, HII number density, velocity field and the microturbulence in the emitting region.

2.11 Seyfert galaxies:

MERLIN/VLA and MERLIN/EVN continuum observations, together with HST line and continuum imaging at similar resolution, are ideal for studying the energetic jet–related phenomena in the inner few hundred pc in Seyfert galaxies. A complementary programme of HI absorption imaging can place constraints on the geometry of the neutral gas.

- **Radio jets and the ISM:** The presence of small ($<$ 1kpc) radio jets in Seyfert nuclei was established in the mid–1980s. Since then it has become increasingly clear that these jets are intimately linked with the ionised gas in the narrow emission line regions. One of the best examples of the association of relativistic and ionised gas in Seyfert nuclei, is seen in Markarian 3 mapped with MERLIN+EVN at a resolution of $\sim$ 25 mas by Kukula et al. (1998). The [OIII] emission, obtained from HST imaging, follows the synchrotron emission from a highly collimated radio jet (see **COLOUR ILLUSTRATION**). This phenomenon is proving to be common in Seyferts and gives information on both emission mechanisms in the radio jets and the physics of the narrow line regions. Hydrodynamical modelling suggests that the jet compresses a cocoon of gas which is then photo– (or collisionally) ionized. Markarian 3 is currently the clearest example of these phenomena but similar, if more complex, behaviour can be seen in, among others, Markarian 6 (Capetti et al. 1995); NCG5929 (Su et al. 1996) NGC4151 (Pedlar et al. 1993) and NGC 1068

(Gallimore et al. 1996; Muxlow et al. 1996). High resolution spectroscopy of NGC1068 with HST (Capetti et al. 1997; Axon et al. 1998) shows that within ± 0.5 arcsec of the radio jet mapped with MERLIN the emitting line gas is disturbed and split into two components separated in velocity by 1500 km s^{-1}. The gas surrounding the jet is also in a much higher ionization state compared with the surrounding NLR gas. The morphology, kinematics and, possibly, the ionization state of the NLR in the vicinity of the radio jet in NGC 1068 are a direct consequence of the interaction with the radio outflow.

- **HI absorption:** Large quantities of neutral gas appear to exist close to the nuclei of Seyfert galaxies. Initially this was surprising given the hostile environment due to the intense ultra-violet emission from these nuclei. However it appears, that not only is neutral gas present in these regions, but it also plays a crucial role both in collimating the ultra-violet emission (possibly via a dusty torus) and fuelling the nucleus. MERLIN observes neutral gas in absorption on 0.1 arcsec scales from these nuclei and hence uniquely constrains the dynamics and distribution of this neutral component. An example is the study of HI absorption in NGC4151 (Mundell et al. 1995) which supports a model in which the neutral gas lies in a disk around the galactic nucleus.

2.12 Radio quiet quasars

The quasar population can be divided into radio loud quasars (RLQs) and radio quiet quasars (RQQs) on the basis of the ratio of their total radio luminosity to their optical luminosity; for RLQs the ratio is 10–100 while for RQQs it is 0.1–1. This distinction is also apparent in ratios of both narrow–line luminosity to radio luminosity and far infra–red luminosity to radio luminosity. Furthermore all RQQs have luminosities at 5 GHz $< 10^{25}$ W Hz^{-1} sr^{-1}. The reason for this bimodality is not clear. While the RLQs almost certainly contain massive black holes and relativisitic jets it has been proposed by many authors that the radio emission from RQQs is due to a circumnuclear starburst. Alternatively RQQs could simply be scaled–down versions of RLQs.

Recent multiwavelength VLA, MERLIN and VLBA measurements of the RQQ E1821+463 strongly support a black hole–based jet–producing central engine (Blundell et al. 1996) in this object at least. The radio maps show steep–spectrum oppositely pointing jets associated with a flat–spectrum compact core. Not only is the morphological association with typical RLQs strong but also the peak brightness temperatures are too high to be due to a combination of radio supernova remnants.

2.13 Optical and radio jets in AGN

This is an area of study where the close correspondance between the resolutions offered by MERLIN and the HST is vital. Two of the best examples of radio/optical jets in AGN are:

- **3C273:** An archetypical jet visible across the electromagnetic spectrum is that in 3C273. Comparison of MERLIN 18cm and HST optical images (Bahcall et al. 1995) shows that the optical jet is narrower than its radio counterpart and that knots in the optical jet in the main correspond to narrow oblique features within the radio outline (see **COLOUR ILLUSTRATION**). Assuming the optical emission is incoherent synchrotron the lifetime of the optically emitting electrons (typically $\sim$ 1000 yr) is 1000 times shorter than at radio wavelengths. The optical jet therefore traces the present location of the active jet whilst the radio emission provides information on its history for the past 1 Myr.

  Given the age difference of the emitting electrons the close correspondence in angular size of the bright optical and radio features is puzzling. The most likely explanation is that the true jet, located along the line of the optical knots, is accompanied by enhanced radio emission. This is superposed on radio emission from a surrounding cocoon resulting from older material emerging from the jet. The variations in brightness along the true jet may be governed by geometrical factors and suggest that the jet is in the form of a helix.

- **3C264:** 3C264 is a low–luminosity FRI radio source associated with the brighter nucleus in a dumbbell galaxy located in a rich Abell cluster. The large scale radio structure is reminiscent of wide or narrow angle tail sources which are associated with the motion of the host galaxy through the intracluster medium. The base of one of the radio jets has a bright optical counterpart and this region has recently been imaged at $\sim$ 0.1 arcsec resolution with MERLIN, EVN and the HST (Baum et al. 1997; Lara et al. 1997 and references therein).

  The jet is well resolved in both optical and radio images and its properties (collimation, brightness and orientation) change dramatically as it crosses the outer boundary of an optical "ring" which is most likely the manifestation of absorption by a nearly face–on circumnuclear dust disk. This can be understood by means of a model in which an initially highly relativistic jet decelerates as it passes through a region of dense cold gas interior to the apparent ring and in the inner part of the galaxy. 3C264 appears to be an ideal laboratory for the study of relativistic entraining jets in BL Lac and FRI radio galaxies.

2.14 Radio galaxies

In this area of classical radioastronomy all the world's radio arrays, alone and in various combinations, have a role to play. Here some results of MERLIN/VLA, MERLIN/EVN and global VLBI imaging are briefly discussed.

- **The early evolution of radio galaxies:** The Caltech–Jodrell Bank (CJ) global VLBI surveys (Polatidis et al. 1995; Thakkar et al. 1995; Xu et al. 1995; Henstock et al. 1995; Taylor et al. 1994 Taylor et al. 1996) discovered that between 5% and 10% of compact radio sources are so–called Compact Symmetric Objects (CSOs). These are objects with extended emission symmetrically disposed about the active core and with linear sizes < 1 kpc. The CJ team argued that in contrast to the emission from more typical asymmetric core–jet sources seen on milliarcsec scale the emission from CSOs is largely unbeamed (Wilkinson et al. 1994). They also argued that the CSOs are most likely the young ($\sim 10^3$ yr) precursors of 100kpc–scale classical double sources (Large Symmetric Objects—LSOs). In order to account for the significant fraction of CSOs in flux limited samples the radio luminosities of CSOs must decrease by more than an order magnitude as they expand by up to 1000 times to become LSOs (Readhead et al. 1996a,b).

Essentially the same conclusions about the relative youth and the decay in luminosity with age were reached independently by Fanti et al. (1995 and references therein); they have been studying a sample of Compact Steep Spectrum Sources (CSS) with MERLIN, the EVN and global VLBI arrays. The CSS survey conducted by Fanti et al. is complementary to the CJ survey; not only do these CSS have steeper spectra but also typically they are ~ 10 times larger than the CJ CSOs. It is most likely that they are simply older, hence bigger, versions of the CSOs.

- **High luminosity radio galaxies (DRAGNS):** Leahy (Manchester) and co–workers have compiled an atlas of radio images of a complete sample of 85 Double Radio sources in AGNs (DRAGNS) with $z < 0.5$; they were selected from the 3CRR parent sample. The angular extent of these radio galaxies ranges from < 1 arcsec to $\sim 1°$ and they have been mapped at appropriate resolutions with the WSRT, VLA, MERLIN and VLBI. The **COLOUR ILLUSTRATION** and Figure 8 show six of the smaller sources from the DRAGNs atlas for which MERLIN+VLA data were required for high–quality imaging.

  The overall aim of the study is to provide high–quality radio data for comparison with hydrodynamic modelling. In particular one wants to study the statistical relationships between source morphology and both radio luminosity and source environment. The latter is best studied with X–rays and hence this programme will receive a powerful boost when data from XMM and AXAF become available from 1999. To distinguish between luminosity and redshift effects a comparison sample of DRAGNs with $z > 1.5$ is being studied by Law–Green (Leicester) and co–workers.

  Many of the DRAGN Atlas sources invite individual attention. For example the six objects shown in the illustrations are of interest since the have sizes of roughly galactic dimensions. The radio maps can thus be fruitfully compared with HST images. The smallest, 3C305, is ~ 10 kpc across and is interacting strongly with the ISM of the host galaxy. Another, 3C346, contains an optical jet which is being imaged in detail with MERLIN and the HST at sub–100 milliarcsec resolution.

2.15 Hubble Deep Field and Flanking Fields:

In order to study ultra–weak radio sources in the Hubble Deep Field (HDF) and Hubble Flanking Fields (HFF), National Facility staff working with NRAO staff, took 18 days of MERLIN data (in which data from the Lovell telescope were also included) at 20cm. In a complementary programme 60 hrs of VLA 20cm data were taken. The map from the MERLIN data alone has an rms noise level of $\sim 5\mu$Jy beam^{-1} while that from the VLA data has a noise level of $\sim 6\mu$Jy beam^{-1}. The combined map has a noise level of $\sim 3.5\mu$Jy beam^{-1} and potentially spans a field ~ 10 arcmin in diameter which includes both the HDF and the HFF. This is the most sensitive map ever made at 20cm wavelength. Currently only the HDF has been mapped with $\sigma \sim 3.5\mu$Jy resulting in detections of around 10 radio sources with integrated flux densities down to $\sim 25\mu$Jy ($\sim 8\sigma$). In the 10 arcmin field of view there are ~ 85 sources above 40μJy; further data reduction is planned which will allow the entire field of view to be imaged to the same sensitivity level as the HDF.

In another complementary VLA programme the HDF and part of the HFF have been observed at 3.6cm with a sensitivity comparable to the 20cm MERLIN+VLA maps but at the lower resolution of ~ 4 arcsec (Richards et al. 1998). Simple spectral information can therefore be obtained from a comparison of the 20cm and 3.6cm images. Since most of the radio sources have angular sizes of a few arcsec or less, morphological information can only be obtained from the MERLIN+VLA 20cm maps which have been made with resolutions ranging from 0.2 to 0.5 arcsec.

The main aim of this, ongoing, study is to see whether starbursts or AGN dominate the ultra–weak radio source population. The present results suggest that while the majority of the sources detected at 20cm have characteristics consistent with starbursts (steep spectra, extended on kpc–scale scales, shapes often consistent with optical shape of host galaxy) a significant minority are clearly AGN (recognisable morphologies or flat spectra – see **COLOUR ILLUSTRATION** and Figure 9). Typically the AGN are identified with elliptical galaxies at $z \sim 1$ while the putative starbursts are associated with disk systems in the redshift range 0.5 to 1. It is likely that the full results of this major radio–optical study will not be available until late 1998.

2.16 Cosmology: gravitational lenses

Gravitational lens systems are important for a number of reasons. Individual lenses can be studied to determine the mass distribution in the lensing galaxy or cluster. Then, if the lens is variable, measurement of time delays between the images provides the basis for determining H_0. The cosmological parameters q_0 and λ_0 can be determined from lens statistics. For these reasons large samples of gravitational lenses now play a vital role in observational cosmology.

- **Arcsec–scale lensing:** The VLA–based surveys JVAS (Jodrell VLA Astrometric Survey) and CLASS (Cosmic Lens All Sky Survey) have been the finding observations for the most successful, systematic, search for arcsecond–scale (galaxy mass) gravitational lenses. The JVAS/CLASS sample now contains 8000 flat spectrum radio sources and will soon (Spring 1998) be extended to $\sim$ 12000 sources. Flat spectrum sources are invariably single core–dominated hence observing multiple–component candidates at progressively higher resolution, first with MERLIN and then with VLBI, systematically sifts though the VLA candidates for the bona–fide multiply–imaged cores.

  MERLIN, with its 0.05 arcsec resolution, plays a vital role in this process since the jump in resolution from the VLA (0.2 arcsec) to VLBI (milliarcsec) is too great to be sure of classifying each candidate reliably. Observations with HST have acted as the final confirmation of each lens system discovered by purely radio means (top of Figure 10 and the back cover of the "MERLIN & VLBI National Facility" wallet). So far 6 lenses have been discovered in JVAS (King et al. 1998 and references therein) and 7 in CLASS (e.g. Browne et al. 1998 and references therein, with the addition of two further lenses). All but one of these 13 systems are new and several more very probable CLASS systems await final confirmation with HST/NICMOS imaging. The lensing rate is roughly 1 per 500 background sources.

  The MIT group have also been using MERLIN to study arcsecond–scale lens candidates picked out with the VLA from the various MG radio surveys. They have confirmed an arc—like quad system, J0751+ 2716 (Lehar et al. 1997) and imaged a source with a ring–like lobe (MG0248+0641) which may also be a lens system.

- **Lensing galaxies:** In the confirmed arcsec–scale lens systems there are five times as many "quads" than doubles compared with the expectations based on a model lens population dominated by galaxies with low ellipticity (Kochanek 1996; King & Browne 1996). This discrepancy could be explained if more spiral galaxies act as lenses—as would be the case if their disks are much more massive than has hitherto been thought or it they possess elliptical dark matter haloes. The HST images of JVAS/CLASS lenses suggest that several of the lensing galaxies are highly elliptical and in at least two cases the lens is certainly a spiral. In all cases a lensing galaxy is detected by the HST and the inferred M/L ranges from ~ 1 to ~ 20. On the angular scale around 1 arcsec there are no dark lenses (Jackson et al 1998). This contrasts with Hawkins' (1997) suggestion that a large population of lenses exist with separations 2 to 7 arsec and M/L ratios up to 22 000.

- **Cosmological contraints:** The number of lenses in the JVAS/CLASS sample will enable strong constraints to be placed on cosmological parameters. In an analysis which excludes the possibility of lensing by spirals Falco et al. (1997) have recently placed a 2σ limit on $\Omega_0 > 0.3$ (i.e. $\Omega_\Lambda < 0.7$ for a flat universe) from the statistics of the 2400–source JVAS sample. When the complete statistics of the 8000 source JVAS/CLASS sample are available (and depending on the contribution of spirals) this limit should be tightened significantly to $\Omega_0 > 0.5$ corresponding to $\Omega_\Lambda < 0.5$ in the case that Ω_Λ is small.

- **Lensing by compact galaxies?:** Augusto et al. (1998) have searched the JVAS and CLASS data base for objects whose interferometer visibility data are consistent with multiply compact components with separations from 0.09 to 0.3 arcsec. If the multiple components are due to gravitational lensing then the lenses would have masses appropriate to those of dwarf or compact galaxies or the bulges of spirals. The candidates were systematically sifted through with higher resolution MERLIN 6cm and finally VLBA observations. No strong lens candidates emerged from a parent sample of 1660 JVAS/CLASS sources which indicates that the frequency of lensing on these intermediate scales is several times less than on arcsec scales.

- **Milli–lensing:** Many authors have suggested that the universe could contain a large population of compact objects of $\sim 10^6 M_\odot$ since this is comparable with the Jeans mass at recombination. Global VLBI maps of over 300 compact radio sources made during the CJ surveys have therefore been examined for evidence of gravitational lensing on scales from ~ 2 to ~ 40 milliarcsec, corresponding to masses of $\sim 10^6$ to $\sim 10^8 M_\odot$. The follow–up observations are not yet completed but it is already clear that the total mass contributed by compact objects in this mass range can be no more than a few percent of the closure density.

The combination of the arcsec–scale, intermediate–scale and milli–lens seaches rules out any significant contribution (i.e. more than a few percent of the closure density) to the overall mass density of the Universe on the previously poorly or unexplored mass scales from 10^6 to $10^{12} M_\odot$ (Augusto et al. 1996).

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"MERLIN + VLBI National Facility" Wallet

Front Cover: Derek McKay, Nuria McKay, Tom Muxlow
Back Cover: Ian Morison, Neal Jackson
Inside Covers: Derek McKay, Nuria McKay, Alastair Gunn

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S Per (OH): Mike Masheder
S Per (H_2O): Anita Richards
S 140 IRS 1: Melvin Hoare
WR 147: Sarah Watson
M82: Alan Pedlar
Markarian 3: Marek Kukula
OH Shells: Jessica Chapman
GRS 1915: Derek McKay
DRAGNs: Patrick Leahy
3C273: Simon Garrington
HDF/HFF: Tom Muxlow

Line and grey scale pictures

Fig 1: Andrew Lyne
Fig 2: Anita Richards
Fig 3: Sarah Watson
Fig 4: Myfanwy Bryce
Fig 5: Karen Wills
Fig 6: Phil Diamond
Fig 7: Jeremy Yates
Fig 8: Patrick Leahy
Fig 9: Tom Muxlow
Fig 10: Neal Jackson

3 FUTURE POTENTIAL

3.1 New Ways of Observing

Two observing modes for MERLIN have been proven but not been fully exploited with the current system: long integrations on single fields and short snapshot observations of many fields.

3.1.1 Long integrations

A concerted effort on the Hubble Deep Field in 1996/7 involved a total of 18 days of MERLIN observations at 1.4 GHz (using the Lovell telescope in the array which improves its sensitivity by a factor $\sim$ 2.5) in combination with 60 hrs of VLA observations. The noise level in the MERLIN map is exactly that expected from the increased integration time. The HDF results will have a significant impact on our knowledge of the ultra–weak radio source populations. In the next two years it may well be astronomically worthwhile to spend comparable observing periods on a few target fields of astrophysical importance. Two illustrative examples are:

- **a statistical study of mJy radio sources in the 1.4 GHz FIRST catalogue:**

  Most of the mJy sources in FIRST are $<$ 5 arcsec in size and hence are ideally suited for studying with MERLIN (with Lovell) at 1.4 GHz to determine their structures. The surface density of FIRST sources also makes them well suited for multi–fibre optical spectroscopy. The combination of radio structures and spectra would enable the mix of radio–luminous galaxies (FRI, FRII, starburst, RQQs etc.) to be determined. In combination with the results from the HDF (at the 10s of μJy level) the results should give a much clearer picture of of how the active galaxy population evolves with cosmic epoch.

- **a high resolution continuum image of compact thermal sources in the Orion nebula:**

  Radio continuum observations of the Orion Nebula made with the VLA at arcsecond resolution have revealed a wealth of structures including filamentary ionization or shock fronts (Yusuf–Zadeh 1990) and stellar bubbles (Felli et al. 1993). At sub-arcsecond resolution a new population of weak (few mJy) sources has been identified (Felli et al. 1993). Some are non-thermal, such as the binary system θ^1Ori A with a size of only a few mas (Felli et al. 1991), while others correspond to compact Hα condensations, but the nature of many of these sources is still unclear.

  This 1.5 degree field contains over 40 such compact sources and is ideally suited for a deep MERLIN image at 5 GHz. Previous MERLIN observations have detected a handful of sources with modest signal/noise, but a much longer integration would allow this whole population to be studied in detail. Sixteen $\sim$ 11 hr runs could achieve a 5σ limit of 75 μJy corresponding to 650 K, 10 times deeper than the best VLA 2cm images.

The suggestion is that such data and images would be placed in the public domain as soon as they had been reduced by the MERLIN operations team. The National Facility management will consult with the UK community at the National Astronomy Meeting (and later by email) and with the MERLIN Steering Committee both to gauge the level of support for this mode of operation and to elicit other potential target fields.

3.1.2 Higher efficiency observing

Although MERLIN has only 6 telescopes and the MERLIN/EVN array typically offers 10 or 11 compared with the VLA's 27, it is often possible to to increase the efficiency of the observing programme by observing more than one target source in a 12–18 hour run. Potential observers are urged to consider the possibilities of two particular observing modes:

- **interleaving:**

  Images of two or three sources can be obtained in a single run with little degradation in image quality compared with that from a single source run by interleaving the observations. Technically this is because the additional non–sampled "holes" of the aperture (i.e. Fourier) plane caused by interleaving can still be smaller than the holes arising from the limited number of baselines. Obviously interleaving works best if the target sources are relatively close together in the sky ($< 20°$).

- **snapshots:**

  Reduced quality images of tens of sources can be obtained in a single day by observing each for a four or more snapshots each of $\sim$10 minutes or less. This mode is particularly useful if you already have some knowledge (e.g. from the VLA) of the source structure and want to examine compact sub–components at higher resolution. For example MERLIN follow–up observations of gravitational lens candidates found with the VLA were made at a rate of 20 per day using 4×15 minute snapshots. Even higher efficiencies can be obtained if all the targets are very close together on the sky and can use the same phase calibration source.

3.2 A major upgrade: MERLIN3

3.2.1 Main elements of the project

The principal elements of the MERLIN3 project are as follows:

- The existing MERLIN telescopes will be re-used but the gap in MERLIN's aperture coverage caused by the inability of Defford to work at >5 GHz (< 6 cm) will be remedied by building an 'in house' copy of of the existing E-systems (i.e. VLA–type) antennae.
- The microwave links will be replaced with optical fibres, increasing the bandwidth from the current 15 MHz per polarization to ~ 1 GHz.
- Broad-band receiving systems will be installed, covering the bands 4–6 GHz, 12–15 GHz, and 20–24 GHz (and possibly 30–43 GHz).
- A new correlator will be built to process the wide-band data and act as a powerful and flexible spectrometer with built-in interference rejection.

The equipment required at each telescope includes laser diodes, detectors, modulators and associated RF electronics. Short lengths (few km) of fibre may have to be laid from the nearest node to our telescope sites. The correlator and receivers will draw on technology developed at NRAL for JIVE and the VSA. An important issue in receiver development is to increase dynamic range, reducing the danger of saturation by local in-band interference.

The development of long-distance fibre-optic links will constitute an important part of the prototyping for the linking of EVN antennas, and for the Square Kilometre Array Interferometer (SKAI). Towards the end of the next decade we envisage that the fibre optic technology of MERLIN3 could be applied to the whole of the EVN thereby enabling real–time observations and eliminating the need for tape–recording with its high operational overheads. SKAI will be a global radioastronomy project for the second decade of the 21st century.

3.2.2 Capabilities

MERLIN3 will provide:

- A ten-fold or more increase in continuum sensitivity at 6cm and shorter wavelengthsq compared with the current system;
- Substantial increase in sensitivity at lower frequencies;
- Routine multi-frequency, polarization sensitive, imaging for continuum projects, enabling accurate mapping of objects up to ten times larger than the single-frequency limit;

- The ability to image multiple spectral transitions simultaneously, with many more channels, allowing both higher spectral resolution and a larger free spectral range.

- 0.1 milliarcsec astrometry

3.2.3 Expanding the Scientific Horizons

The scientific drivers for MERLIN3, as a stand–alone instrument and as a partner to the EVN, are manifold, spanning as diverse a range of astrophysical problems as any other astronomical instrument.

Stellar astronomy in particular will be revolutionised by the ability to detect many stars including thermal emission from many stars visible to the naked eye. At 2cm, extended emission can be mapped with a linear resolution equivalent to 1.5 AU at 100 pc. At the new sensitivity levels polarization studies of weak radio sources become possible and hence the magnetic fields can be probed in a much wider range of Galactic and extra-galactic non-thermal sources. Many more phase reference sources will be available for spectral and astrometric observations, as a result MERLIN3 will have an order of magnitude better astrometric capability ($<$ 0.1mas) compared with the present instrument; this will transform the possibilities for parallax and proper motion measurements.

The broader bandwidth receivers of MERLIN3 will allow more spectral lines to be accessed such as methanol at 6.5 GHz and 12.2 GHz and redshifted HI. These receivers will also enable multi–frequency synthesis to increase image fidelity. Interference is unlikely to be a major problem at the shorter wavelengths ($\leq$ 6cm) and we intend to develop intelligent interference rejection methods to facilitate wide–band work at longer wavelengths (particularly for redshifted HI below 21cm).

The MERLIN3/EVN combination will give $>$ 10 times MERLIN3 resolution for non–thermal sources and brightness sensitivities of $\sim$ 1000 K at three times MERLIN3 resolution for thermal objects.

3.3 Specific Astronomical Questions for MERLIN3

3.3.1 Star Formation and Evolution

Tackling virtually all the problems listed below is contingent on the sensitivity increase and the operation of MERLIN3 at 6 and 2cm.

- **How are jets produced in YSOs?**

  The study of non-thermal as well as thermal radio emission from T Tauri objects is in its infancy. MERLIN3 will give insights into the relationships between the jets, the disk and inflow processes. The magnetic field properties, vital for understanding the timescale of cloud collapse, can be studied using continuum polarization and OH masers.

- **What goes on in proto–planetary disks?**

  MERLIN3 will be able to detect continuum emission from the the disk. the physical properties of the disk can then be related to the kinematics of the surrounding gas established by measurements of H_2O masers from condensations at radii of a few AU.

- **How does stellar rotation effect evolution?**

  Stellar flares in the optical and radio from active stars are diagnostics of the stellar magnetic field. The relationships between rotation, convection and the dynamo are not well understood. MERLIN3 will detect flares in a wide range of objects including nearby solar-type (M, F and G) stars, pre-main sequence stars and evolved components of binaries.

- **How does the interaction of stellar winds produce high energy electrons?**

  The locations of (polarized) non-thermal and thermal emission regions will be found in relation to the stars in a wide range of objects including WR, O and B stars. The change of this emission with time will give insights into particle acceleration in the interaction zone.

- **What are the conditions in a Nova explosion?**

  MERLIN3 will be able to resolve and image a nova just days after outburst when the ejecta have only just cleared the binary system. Does the explosion have bipolarity as suggested by some MERLIN images? What are the physical conditions in the ejecta?

- **How are heavy elements added to the ISM?**

  Maser mapping of the kinematics of stellar winds from red supergiants provides model–dependent constraints on the composition of the dusty outflow. MERLIN3 astrometry will align the maser outflow and the star accurately.

- **Are X–ray binaries/transients really micro–quasars?**

  Mapping outflows and motions in jets in galactic superluminal sources sets limits on the amount of material ejected and constrains the mass of the compact object in the binary. A highly sensitive instrument is needed to map the mJy non-thermal emission.

3.3.2 Astrometry

The astrometric capability of MERLIN3 will be comparable with that of VLBI; the limitation of shorter baselines is compensated by the ability to use closer reference sources as a result of the greater sensitivity. To achieve this astrometric accuracy GPS receivers will also be required at the most distant of the MERLIN sites to monitor variations in atmospheric/ionospheric propagation. The major advantage of MERLIN3 is real–time operation enabling it, for example, to find and follow–up stars which are currently flaring. With the EVN the astrometric capability can be increased to $\sim 30\mu$arcsec.

- **How many Jupiter–mass planets are associated with nearby stars?**

  Optical Doppler reflex motions have revealed several giant planets orbiting nearby stars. Despite its success the technique is biassed toward finding planets close to the primary since these have the largest reflex velocities; finding planets less than 1 Jupiter mass more than a few AU from the primary is difficult. An alternative technique is to use accurate astrometry to measure the stars angular displacement by a distance RM_{planet}/M_{star} where R is the orbital radius. This technique is not only more sensitive to planets further out it can also map out the orbit in 2–D. MERLIN3/EVN will provide an rms astrometric accuracy < 30 μarcsec per observation on a few mJy star. A Jupiter mass planet orbiting 1 AU from a solar mass star at 10pc produces a reflex motion of $\pm$ 75μarcsec. Many such stars can be targeted.

- **What are the proper motions of galaxies in the Local Group?**

  Transverse motions of 500 km s^{-1} of a galaxy at a distance of 3Mpc corresponds to ~ 35 μarcsec yr^{-1}. For galaxies with detectable radio nuclei this could be measured by MERLIN3/EVN in a few years.

- **Parallax measurements of stars across the Galaxy**

  The ability to measure trigonometrical parallaxes of $\sim$ 0.1 mas will enable MERLIN3/EVN directly to measure the distances of many radio stars and pulsars across much of the Galaxy.

3.3.3 Extragalactic Research and Cosmology

Most of these problems depend on a combination of increased sensitivity, which produces higher dynamic range and enables more sources to be studied quickly at 50 mas resolution in snapshot mode; broad bandwidth, which enables multi–frequency synthesis greatly to enhance image fidelity at high dynamic range and the link with the EVN which provides higher resolution at similar sensitivity levels.

- **What are the values of the fundamental parameters H_0 and λ_0 ?**

  Statistics of lensing in large unbiased radio–selected samples constrain λ_0; accurate time delays and mass models for many individual systems constrain H_0 to a few percent.

- **What fraction of the mass of the universe is in clusters?**

Establishing the statistics of lensing on arcmin scales provides a direct way to confront numerical models of Universal evolution. Current search strategies involving flat spectrum radio sources provide a clean route to locating candidate cluster lenses in the new deep radio surveys (NVSS, FIRST, WENSS). MERLIN3 can filter out chance associations by their dissimilar radio structures.

- **What is the mass distribution in giant galaxies?**

  Ultra–high dynamic range mapping of individual lensed systems provides a direct measure of the core radius and the total (dark +light) mass distribution within a few kpc of the core. Image shear provides information on mass outside the Einstein radius.

- **How do AGN form and develop? Does starburst activity play a role?**

  High resolution imaging of the non–thermal emission from ultra–luminous infrared galaxies coupled with thermal imaging of circumnuclear gas (tori?) and ionized gas in narrow–line region in Seyferts will provide unique information on the balance between starburst and central–engine–driven activity. The close match between MERLIN and HST resolution is of particular importance here.

- **What is the formation rate of massive stars in local galaxies?**

  Counting the numbers of compact shell radio sources (non–thermal) and compact HII regions (thermal) in tens of nearby galaxies will provide quantitative information on the formation rate of massive stars.

- **Are the radio source counts explicable?**

  By working in selected $\sim 1^\circ$ fields near radio astrometric calibrators MERLIN3 can measure the radio structures of a large sample of $\sim$ 1mJy sources (the "knee" in the normalised counts) selected from the new deep radio surveys. Such fields are suitable for multi–fibre optical follow–up. The radio and optical (redshift) information will confront the predictions of evolving radio population syntheses involving redshift cut–offs.

- **Why are most quasars radio–quiet?**

  Studying the structures and proper motions of jets in nearby RQQs will give clues as to why their bulk luminosities are $1000\times$ lower than in radio loud QSOs.

- **Are the blue compact galaxies starbursts?**

  The modest starburst M82 (supernova rate ~ 0.05 y^{-1}) at $z = 0.5$ would have $S_{5GHz} \sim 10\mu$Jy and a size of $\sim$ 200 mas. Many HDF galaxies at $z \sim 1$ should be therefore be detected and resolved and have steep radio spectra.