Chapter 7

Summary and Future Work

In the central regions of active galaxies the neutral gas and dust are thought to be responsible for both obscuring and fuelling activity, whereas in the outer parts of galaxies the neutral ISM often extends beyond the optical extent. To further understand the physical mechanisms that are involved in the numerous processes that occur in galaxies, such as galaxy evolution, star-formation, galactic dynamics and activity, it is essential that the distribution and kinematics of neutral gas is understood in more detail.

This thesis has reported high angular resolution HI absorption observations of eight active galaxies using MERLIN. These results considerably increase the number of active galaxies that have had their neutral gas component investigated with angular resolutions of less than an arcsecond. To complement these results lower resolution HI observations made with GMRT and sub-arcsecond resolution optical images from the *HST* have also been presented. The GMRT results presented in this thesis represent some of the first scientific observations to be made with this newly operational telescope.

The 21 cm line of neutral hydrogen provides an invaluable tool to probe the neutral ISM of galaxies, producing unique information about the distribution, kinematics and the total mass of HI. Via emission this line can be used to study the neutral gas out to the furthest reaches of galaxies and via absorption it can be used to investigate gas at the very highest angular resolutions, which correspond to linear scales as small as just a few parsecs in the nearest galaxies. The work presented in this thesis has concentrated upon observations of HI in absorption against the centres of active galaxies with the purpose of investigating the distribution and dynamics of the gas within this region. These observations constitute the highest angular resolution, HI absorption, observations of these sources made to date.

Of the eight galaxies that are presented in this thesis, one is a narrow line radio galaxy (3C 293), two are Seyfert galaxies (NGC 7674, type-2 and NGC 7469, type-1) and five are luminous infrared galaxies, LIRGs, (NGC 6240, III Zw 35, UGC 2369, IR 0335+1523 and Zw 49.0). Although all of these source have differing characteristics, they all display HI absorption[1]. Additionally all of the sources show some evidence of being involved in galaxy-galaxy interaction and, with the exception of 3C 293 which has a $L_{\rm fir} = 10^{10.44}$ $L_{\odot}$ (Hes, Barthel & Hoekstra 1995), all have far infrared fluxes in excess of 10^{11} $L_{\odot}$, and hence can be classified as LIRGs. By observing neutral hydrogen in the centres of several different classes of active galaxies the role of neutral gas in the obscuration of the central energy source and its relation to unifying schemes, as well as the mechanisms which gas, as a fuel, is transported into the centres of galaxies, can be more fully understood.

[1] HI absorption was not detected in the observation of UGC 2369 presented in this thesis, although it was previously detected in this source by Mirabel & Sanders (1988)

7.1 Conclusions of Work Presented in this Thesis

7.2 HI Absorption against Radio Galaxies

At present relatively few high resolution observations of HI absorption against radio-loud active galaxies have been made (e.g. Cole 1999; Taylor 1996 Conway 1999; van Langevelde et al. 2000; Pihlström et al. 2000; Peck & Taylor 2002). These have almost exclusively used VLBI techniques to observe HI absorption against milliarcsecond radio jets close to the cores of these sources. The majority of these results have concluded that the observed HI absorption is evidence for neutral gas distributed within circumnuclear rings or discs. There have been even fewer observations of molecular gas in these sources due mainly to their greater distance, than radio-quiet AGN. None of these sources have been observed to display maser emission.

7.2.1 3C 293

In chapter 3, an in depth study of the neutral hydrogen distribution and kinematics in the central few kiloparsecs of the radio galaxy 3C 293 is presented. 3C 293 is a quite exceptional source to be studied using HI absorption techniques with MERLIN because 3C 293 is not only relatively nearby (z=0.045) with extensive sub-arcsecond radio continuum structure but also contains large amounts of gas and dust.

This extensive study of the neutral hydrogen in 3C 293 is only the second detailed study of HI absorption against a radio galaxy to be made with MERLIN.

Summary of the Main Conclusions

- Extended sub-arcsecond resolution radio continuum emission from the central few kiloparsecs of the radio galaxy 3C 293 has been imaged. This radio continuum structure resolves into four luminous components with diffuse lobe-like extensions aligned in an approximately east-west direction.

- Extensive HI absorption has been imaged across the entire radio continuum structure of 3C 293. The HI absorption consists of two distinct components; one with narrow ($<$40 km s^{-1}) line width and one broad ($>$65 km s^{-1}) line width. The broad HI component is predominantly distributed infront of the AGN whereas the narrow component is observed across the whole of the background radio continuum.

- Two velocity gradients are observed across the central region. The lowest of these velocity gradients (46 km s^{-1} arcsec^{-1}) matches velocity gradients observed in optical ionised gas which extends out to $\sim$10 kpc from the centre of 3C 293. This lower velocity gradient appears to be primarily associated with the narrow HI absorption component. Centred upon the AGN a velocity gradient of 178 km s^{-1} arcsec^{-1} is detected in the neutral hydrogen absorption. This velocity gradient is consistent with neutral gas distributed in a circumnuclear ring that extends to radius of $\sim$600 pc. This implies an enclosed mass of $\mathrm{M_{dyn}}(< 600\,\mathrm{pc}) \leq 3.9 \times 10^9 (\sin^{-2} i)\,\mathrm{M_\odot}$, where i represents the inclination of the disc.

- Several individual absorption features with velocities highly shifted from the systemic velocity of the galaxy are detected against the AGN. These high velocity clouds, both blue and red-shifted relative to the systemic velocity, are consistent with previous observations and it is concluded that these features are produced by infalling and outflowing clouds of neutral gas.

- The distribution of the optical depth of HI infront of the radio continuum shows significant enhancements (a factor of ∼4 compared to adjacent regions) which are cospacial with dust lanes observed in *HST* images. Using standard gas-to-dust ratios, the HI absorption columns imply an increased optical extinction of ∼1.5 magnitudes for the dust lanes. This estimate is consistent with the extinction values observed in archival *HST* images of this galaxy.

- It is concluded that the narrow HI absorption is physically associated with both these dust lanes and the ionised gas that extends to a radius of ∼10 kpc. From this conclusion it is reasonable to assert that these components form part of the quiescent ISM at distance of up to 10 kpc from the central region.

7.3 HI Absorption against Seyfert Galaxies

Narrow, localised HI absorption has been observed against two Seyfert nuclei with MERLIN. Although there have been several other MERLIN investigations of HI absorption in Seyfert galaxies, the majority have only detected absorption against radio jets of these sources. Against both the Seyfert-1 nucleus of NGC 7469 and the Seyfert-2 nucleus of NGC 7674 narrow, localised HI absorption has been detected.

7.3.1 NGC 7674

Summary of the Main Conclusions

- Highly localised, deep HI absorption is detected within ∼100 pc of the Seyfert-2 nucleus of NGC 7674. No HI absorption ($\tau > 0.07$) is observed against extended radio continuum.

- The narrow absorption is attributed to gas within a circumnuclear disc which is viewed almost edge-on and illuminated by a compact background radio component, most probably the Seyfert nuclei itself. This is consistent with the detected HI absorption arising from a circumnuclear torus.

- Assuming the HI gas has an extent of $\sim$100 pc and is evenly distributed, the HI gas mass observed infront of the nucleus of NGC 7674 is $\lesssim 4 \times 10^5$ $M_\odot$.

7.3.2 NGC 7469

Summary of the Main Conclusions

- The radio continuum detected in the Seyfert-1 galaxy NGC 7469 is consistent with a compact nuclear component surrounded by a diffuse radio emission from a circumnuclear starburst at a distance of between 300 and 700 pc from the AGN.

- Highly localised, narrow HI absorption (τ =0.25) has been detected against the Seyfert-1 nuclei. No HI absorption is detected against the radio continuum components of the starburst ring within the sensitivity limits of this experiment. The distribution of the HI absorption against the nuclear component is unresolved by these observations, implying a linear size of less than 50 pc. It is concluded that this HI absorption is most proably caused by quiescent absorbing gas along the line of sight of the nucleus and located outside of the nuclear region, although the resolution of these observations is not sufficient to exclude the possibility that the absorbing gas is situated close to the nucleus. These observations are not inconsistent the HI absorption resulting from gas within an obscuring circumnuclear torus.

7.4 HI Absorption against Luminous Infrared Galaxies

MERLIN HI absorption observations of five luminous infrared galaxies have been presented. HI absorption has been detected in four out of five of these sources, with a modest upper limit placed upon the single exception.

Of the five observations presented in this thesis, only NGC 6240 was observed to have extended radio continuum against which HI absorption could be extensively imaged.

7.4.1 NGC 6240

Summary of the Main Conclusions

- Extremely broad HI absorption is detected against the spatially extended 1.4 GHz radio continuum of the prototypical LIRG merger NGC 6240.
- At 1.4 and 5 GHz the radio continuum structure of NGC 6240 has been imaged at the highest angular resolution to date. The continuum structure is dominated, at both frequencies, by two compact components separated by 1.52 arcsec (715 pc). It is concluded that these two components are the remnant nuclei of the two merging galaxies.
- The broad ($300 \rightarrow 400\,\mathrm{km\,s^{-1}}$) HI absorption is detected against each of the double nuclei of NGC 6240 with column densities of up to 20.8×10^{21} atoms $\mathrm{cm^{-1}}$. There is velocity difference of $150\,\mathrm{km\,s^{-1}}$ observed between these two components. This velocity difference is consistent with the neutral gas existing in an inclined rotating disc formed as these two nuclei merge.
- Weak, narrow HI absorption ($<50\,\mathrm{km\,s^{-1}}$) is seen across the entire extended

1.4 GHz radio continuum. This absorbing component is consistent with less dynamically disturbed gas outside of the central few kiloparsecs of the merger.

7.4.2 Other LIRGs

- Against the unresolved radio continuum of III Zw 35, broad (310 km s^{-1}) HI absorption is detected with an optical depth of 0.096. This absorption is consistent in redshifted velocity and velocity width with similar resolution observations of OH megamaser emission from this source.
- No HI absorption is detected against UGC 2369. This observation was badly affected by radio frequency interference and adverse weather conditions. Any gas present must have an optical depth of less than 0.6.
- HI absorption is detected with a column density of 3.5×10^{21} atoms cm^{-2} against IR 0335+015. The radio continuum of IR 0335+015 is unresolved by these observations.
- Strong HI absorption has been detected against a single radio component in the merger galaxy Zw 49.0 with a column density of 2.57×10^{21} atoms cm^{-2}. The absorption is narrow (>100 km s^{-1}) and spatially unresolved implying a physical size of less than 100 pc^{2}.

7.5 Conclusions

In this thesis, HI absorption has been used to investigate the kinematics and distributions of neutral gas in several galaxies with MERLIN. The neutral gas distribution is, in general, consistent with structures that range in size from a few 10s of parsecs up to a kiloparsec with evidence of circumnuclear gas in the majority of the sources studied. However, the morphologies of the galaxies investigated are extremely complex, with each of the sources showing signs of galactic interaction, be that dust lanes, nearby companions or double nuclei; thus these sources are all predisposed to be dynamically disturbed in some way. Apart from in the most extreme case, NGC 6240, the effect of these tidal distributions on the observed HI kinematics and distribution are unclear. However, these disruptions may be responsible for the broad HI velocity structures and, the fact, that the observed velocity gradients show no predisposition to be aligned with either the galactic rotation or perpendicular to the radio jet axes

Without doubt some of the most disturbed and gas-rich extra-galactic objects so far studied are the luminous infrared galaxies. Unsurprisingly, a large proportion of these sources display HI absorption with the majority showing very broad absorption indicative of large gas motions. The primary energy sources for the LIRGs is either starburst or AGN dominated, although an increasing number of sources show evidence of both. High resolution observations of neutral gas in these sources have found evidence for nuclear disc-like structures and highly disturbed gas kinematics. These disturbed dynamics provide the mechanisms for the gas and dust to be driven into the central regions and fuel the starburst or AGN activity.

High resolution HI absorption studies against the centres of active galaxies, such as Seyfert and radio galaxies, have provided some of the most convincing evidence for circumnuclear gas structures. In general, observations of Seyfert galaxies (e.g. Gallimore et al. 1999; Mundell et al. 1995) have so far detected circumnuclear gas at radii greater than several tens of parsecs from their nuclei. VLBI observations of radio galaxies, such as by van Langevelde et al. (2000), Conway (1999) and Peck & Taylor (2001, 2002), have also shown that similar neutral gas structures surround the AGN in these sources. However the circumnuclear gas structures observed via HI absorption against both Seyfert and radio galaxy nuclei, in general, exist at distances from the nucleus that are well in excess of those required if they are to be considered part of neutral gas tori. In this thesis, circumnuclear gas structures on scales of several hundreds of parsecs were observed close the AGN within the radio galaxy 3C 293. Although these observations, also cannot be considered to be direct observations of a neutral gas tori, the presence of these structures surrounding the AGN does imply their involvement in the fuel processes of the AGN. Whereas, against the both of the nearby Seyfert galaxies NGC 7469 and NGC 7674 the HI absorption observed is much more distinctly associated with the Seyfert nuclei themselves. In the latter of these two sources the evidence that this HI absorption is associated with a neutral gas torus is reasonably strong. The limits that these observation were able to place upon any HI absorption against the radio ejecta close to the nuclei of NGC 7674 constrain the physical size of the HI absorption a region less than 100 pc in extent. Although this value is still significantly larger than the expected size of the neutral torus, it is limited by the angular resolution of the observations presented here, thus making NGC 7674 a good candidate for direct observations of a neutral gas tori.

In all types of AGN it is apparent that neutral gas does exist in the nuclear region, with all of the AGN that have so far been observed showing evidence for circumnuclear gas structures. This gas, and the associated dust, undoubtly plays some role in the obscuration and fuelling of the activity, but are observed to exist on many differing scales in different objects. Whether this range of scales is a function of the level of activity in the AGN, or determined by larger scale dynamics of the galaxy is as yet uncertain and will require far more extensive studies of more sources to be determined further.

7.6 Future Prospects

Without doubt the work presented here, along with the observations by Gallimore et al. (1999), Mundell et al. (1995), Morganti et al. (2001a) and others have demonstrated the need for higher resolution observations of the neutral gas content in the nuclei of galaxies. At present there have been several HI absorption observations made using VLBI techniques, such as by Peck & Taylor (2002), van Langevelde et al. (2000), Pihlström et al. (2000) and Conway (1999). However these are currently limited to just a few sources, which mostly consist of compact radio-loud objects with limited amounts of resolved structure. These results have been very successful in imaging HI via absorption against these compact sources on milliarcsecond scales, but it is evident that a wider sample of similar observations against a variety objects is needed. With the aim of extending these detailed observations, several projects to image the neutral gas component in the nuclei of galaxies have been undertaken.

Higher Resolution Observations of 3C 293

In 1999, unaware of the results from the MERLIN HI absorption observations of 3C 293 (see chapter 3), Drs. Alison Peck (NRAO) and Greg Taylor (NRAO) observed HI absorption against 3C 293 with a global VLBI experiment which include the VLBA, Phased VLA and several telescopes from the EVN. Although this experiment was successful, the majority of the flux density observed in 3C 293 at lower resolutions was resolved away leaving only a series of compact features, making this data set hard to interpret (see Fig. 7.1).

In an effort to restore some of the flux resolved away in this experiment Alison Peck, Greg Taylor and myself have combined the global VLBI data with both the MERLIN data set, presented in chapter 3, and a newly observed VLA A-

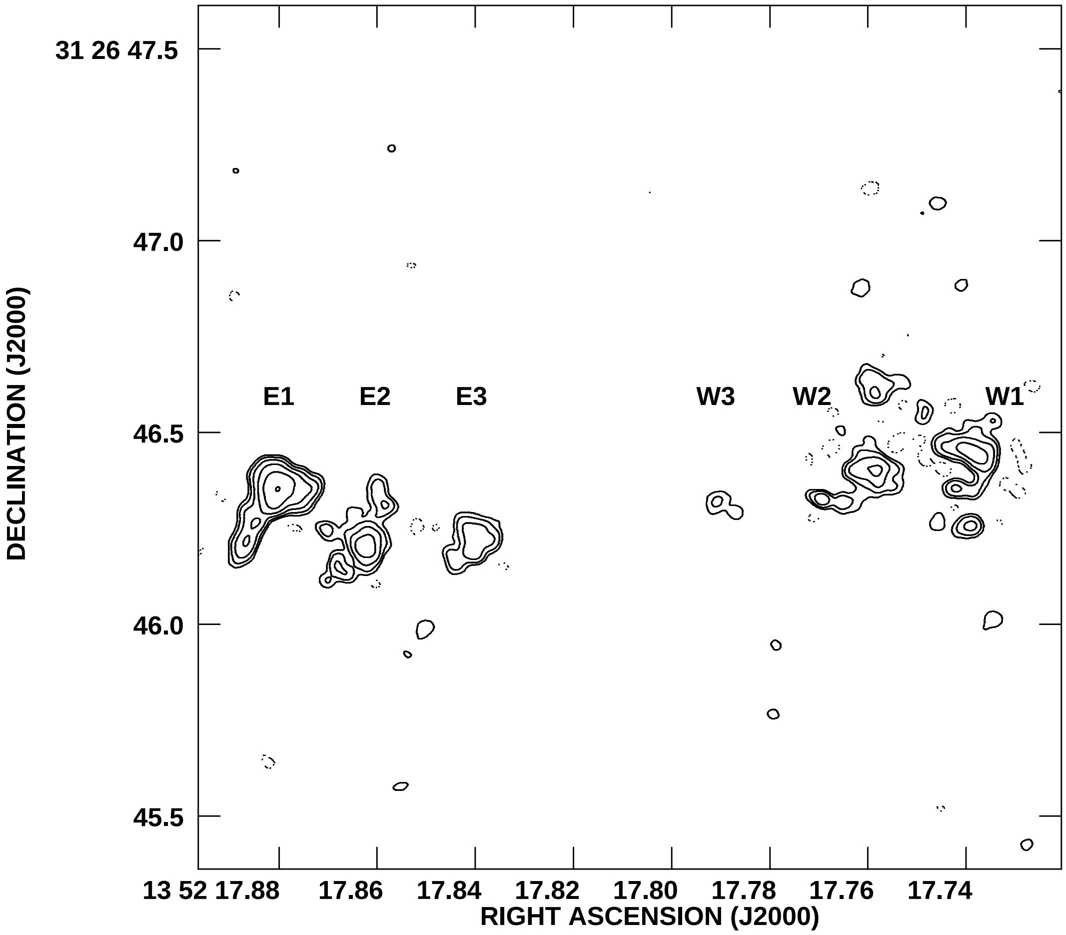

Figure 7.1: A contoured global VLBI continuum image of 3C 293 courtesy of G.B. Taylor and A. B. Peck. The contour levels are at -1, 1, 2, 4, 8, 16 and 32 mJy beam^{-1}.

array observation including the VLBA antenna at Pie Town data set. These data sets have been successfully combined enabling multi-scale imaging of the radio continuum of 3C 293 and the associated HI absorption (see Fig. 7.2). It is believed that this data set forms one of, if not the, largest combined spectral line data set to date and includes most of the regularly used radio telescopes in the northern hemisphere.

As can be seen from the comparison between Figs. 7.2 & 7.1 a considerable amount of flux density has been preserved in the combined image, although some extended

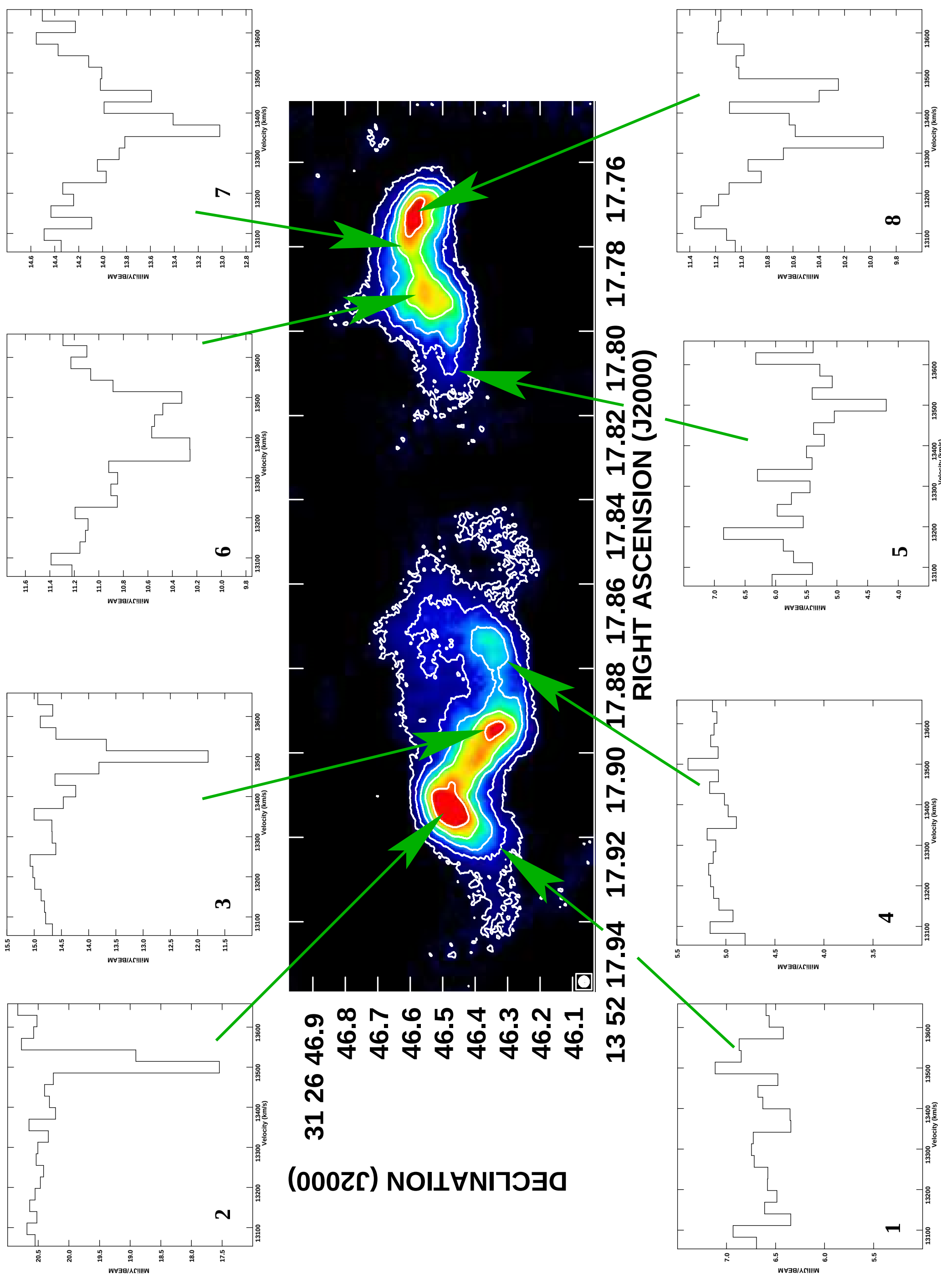

Figure 7.2: Combined global VLBI, MERLIN and VLA A–array plus Pie Town false colour continuum image of 3C 293 with selected HI absorption spectra. This image only covers the four brightest components seen in the MERLIN images, with components 2, 3, 6 and 7 equivalent to components D,C, B and A in Fig. 3.4. The continuum image has been convolved with a circular 30 mas Gaussian beam (shown in bottom left-hand corner). The contour levels are -1, 1, 2, 4, 8 and 16 $\times$ 1.2 mJy beam^{-1}. Spectra are plotted as mJy beam^{-1} against km s^{-1}.

features observed in the MERLIN data are lost. At this increased resolution it is now possible to resolve the inner parts of the jet in 3C 293. In this image the jet can be seen to deviate considerably from the linear east–west orientation that was observed in the MERLIN data set lending credence to the conclusion that radio jet is emitted perpendicular to the circumnuclear gas ring observed in the MERLIN data. However, with this factor of 10 increase in angular resolution, compared to the MERLIN data, it is unclear which 1.4 GHz radio continuum component is associated with the AGN. Within the relative astrometry the position of the core, as observed at 5 GHz with MERLIN (see Fig. 3.3) by Akujor et al. (1996), is most closely associated with the weak radio continuum at position 5 (see Fig. 7.2). The 1.4 GHz radio emission from the nucleus is heavily free-free absorbed thus not allowing the absorbing gas to be imaged infront of the nucleus.

This work is still in progress and requires a more full analysis to interpret the data.

EVN + MERLIN Studies of Starbursts/Seyfert Galaxies

High resolution follow-up HI observations of NGC 7674, NGC 7469 and Arp 220 using the EVN were recently attempted. Unfortunately, all three of these experiments failed due to high winds during the allotted observing slots. These observations have been recently re-proposed. The main purpose of the observations of NGC 7674 and NGC 7469 is to further resolve the nuclei of these two Seyfert galaxies and further constrain the size of HI absorbing region. Both NGC 7674 and NGC 7469 are extremely good candidates for direct imaging of circumnuclear gas and these observations will place further constraints upon the existence of a torus in both of these sources.

In the case of the prototypical ULIRG merger Arp 220 the purpose of these observations is to follow-up recent MERLIN HI absorption observations by Mundell et al. (2001). Both of the central components of Arp 220 show extensive H I absorption with multiple spectral components. The resolution of MERLIN is barely adequate to constrain the complex dynamics in this source. With the increased resolution of the EVN we intend to further constrain these dynamics on linear scales that are comparable with recent VLBI OH maser observations of this source.

In all three of these observations the intention is to complement the milliarcsecond angular resolution of the EVN by combining them with the existing MERLIN data sets allowing the neutral gas to be imaged on angular scales between a few 10s of mas to a few arcseconds.

Further MERLIN H I and OH Studies of ULIRGs

In addition to the MERLIN H I absorption observations that are presented in this thesis, H I and OH absorption against several other LIRGs and ULIRGs have been observed on our behalf with MERLIN. These observations are intended to further study both the H I and in some selected sources the OH components of these galaxies. The purpose of these observations is to directly image the neutral ISM and compare the distribution of OH and H I gas in these merging galaxies. The sources that are already observed are NGC 520 (H I & OH), NGC 660 (H I & OH) and NGC 2623 (H I). In addition, a re-observation of OH absorption against NGC 6240 has been proposed.

Molecular Absorption Studies

To complement the OH and H I absorption observations of active galaxies we intend to observe several sources with MERLIN in order to image H_2CO via absorption. At present our H_2CO observations of LIRGs, such as NGC 6240 and NGC 3628, have only provided upper limits, however, the Lovell Telescope upgrade will significantly increase the sensitivity of MERLIN at 5 GHz. It is hoped that this increased sensitivity will allow MERLIN to detect H_2CO absorption against several nearby active galaxies. The purpose of these studies will be to provide distributional and kinematic information about the molecular gas in these galaxies at sub-arcsecond resolutions allowing direct comparisons between the HI, OH and H_2CO components to be made.

Radio Galaxies HI Survey

It has become evident in several HI absorption observations that the neutral gas components often trace the dust obscurations observed in *HST* images. Recent *HST* imaging surveys of radio galaxies (e.g. de Koff et al. 2000; Martel et al. 1999) have shown that many radio galaxies show significant dust obscuration. If standard gas-to-dust ratios are assumed, the dust obscuration observed in these radio galaxies is equivalent to neutral gas columns $\sim 10^{21}\,\mathrm{cm}^{-2}$. Using this as a basis for selecting sources, ten nearby radio galaxies have been either observed or scheduled for observations with MERLIN. Additionally, several other more distant radio galaxies have already been observed with the GMRT.

7.6.1 Future Instrumentation

Without doubt the biggest advance in the investigations of neutral gas in active galaxies will be made with advent of the next generation of radio and millimetre telescopes.

At millimetre wavelengths it is presently possible to observe numerous molecular emission lines, however the current generation of telescopes does not provide the necessary sensitivity or resolution to investigate them fully. This deficiency will be hopefully solved in the next few years with advent of the Atacama Large Millimeter Array (ALMA[2]). ALMA is presently under development and is envisioned to consist of a multiple element interferometer, providing sub-arcsecond resolution observations of unprecedented sensitivity at millimetre wavelengths. Some of the key science drivers of ALMA are to image the molecular gas components within the central few parsecs of galaxies. At millimetre wavelengths ALMA will be able to penetrate the obscuring dust in the centres of these sources and observe the molecular gas components at sub-arcsecond scales, providing a unique means by which the molecular gas and dust can be studied in the nuclei of galaxies. ALMA will hence be able to resolve single molecular clouds, in the nearest galaxies, and study their physics and chemistry by tracing the molecular gas using the higher rotational lines of CO, HCN and the fine structure lines of [C I]. Additionally, it is envisioned that ALMA will be used as the largest element in some mm-VLBI experiments, resulting in angular resolutions of $\sim$10s of μas; the highest angular resolution of any instrument in astronomy. With this resolution and the increased sensitivity that ALMA will provide mm-VLBI experiments, it will be possible to image the centres of radio-loud AGN at millimetre and sub-millimetre wavelengths on scales similar to the neutral torus itself.

At decimetre wavelengths the next generation of telescopes and interferometers will be dominated by the proposed Square Kilometer Array (SKA[3]). One of the primary science drivers of this ambitious project is provide the sensitivity, via phenomenally large collecting areas, to observe H I emission in galaxies at resolutions comparable to MERLIN. Additionally it in envisioned that the SKA will be able to observe continuously down to frequencies of a few hundred MHz thus enabling redshifted H I to be detected from sources at high z.

Both of these projects will provide a deluge of information about neutral gas in

[2]Information available on the world wide web at http://www.alma.nrao.edu/.
[3]Information available on the world wide web at http://www.skatelescope.org.

wide range of galaxies enabling a much more complete picture of the role of gas in all galaxies to be formed in the future.