Chapter 6

Luminous Infrared Galaxies

6.1 Introduction

In the early to mid-1980s the *Infrared Astronomical Satellite Survey* (*IRAS*) discovered that a considerable number of extra-galactic objects have luminosities dominated by their far-infrared emission (Soifer et al. 1984). The source of the extreme infrared luminosities observed in these galaxies is most likely to originate from dust grains which have been heated by UV radiation from a central energy source. This central energy source may be either an AGN and/or a region of intense starburst activity (Genzel et al. 1998), with several of these sources observed to contain both AGN and starburst activity, for example NGC 1068 (Gallimore et al. 1996), NGC 7469 & NGC 6240 (discussed in the previous two chapters). More comprehensive samples of luminous infrared galaxies, LIRGs, such as by Veilleux et al. (1995), have also noted that although the dominant energy source for LIRGs (with $L_{\rm fir} > 10^{10.5}\,L_{\odot}$) is intense bursts of star-formation, there is a trend for high $L_{\rm fir}$ (ultra luminous infrared galaxies, ULIRGs) galaxies to also contain AGN-like characteristics.

Previous single dish HI observations of samples of LIRGs, such as Mirabel & Sanders (1988) and Garwood, Helou & Dickey (1987) have found that there is a significant correlation between far infrared luminosity and the detections of HI in emission and absorption, and in particular HI absorption. In fact, Mirabel & Sanders (1988) concluded that in galaxies with $L_{\rm fir} \geq 2{\times}10^{10}\,L_{\odot}$ there was a $\sim$20% chance of detecting HI absorption whereas this probability increased to around 40% for $L_{\rm fir} \geq 10^{11}\,L_{\odot}$ and becomes close to 100% for ULIRGs ($L_{\rm fir} \geq 10^{12}\,L_{\odot}$).

In addition to the sources that have been presented in the three chapters prior to this, several luminous infrared galaxies have been observed as part of an on-going project to follow up single dish and low resolution interferometric observations of HI absorption at high angular resolutions. As part of these HI absorption observations of four further galaxies are presented within this chapter.

6.2 Details of the Observations

During November and December 2000 MERLIN was used to observe HI absorption against several luminous infrared galaxies (see Table 2.4). The galaxies were selected on the basis of known single dish HI absorption spectra within the observable frequency range of MERLIN (i.e. redshifted HI frequency above 1330 MHz) from the sample presented by Mirabel & Sanders (1988).

All of the four sources presented here were observed with the full MERLIN array, including the 76-m Lovell telescope, for between 6 and 12 hours with a bandwidth of 8-MHz centred upon the redshifted frequency of the HI as determined from the single dish observations of Mirabel & Sanders (1988). IR 0335+1523 and UGC 2369 were observed in both left and right hands of circular polarisation and correlated into 64 frequency channels each with a width of 125-kHz (velocity resolution of $\sim$26 km s^{-1}). Zw 49 and III Zw 35 were observed in a single polarisation (left-hand circular) with a bandwidth of 8-MHz and correlated into 128 channels. The observations of Zw 49 and III Zw 35 were made with an increased spectral resolution, compared to those of IR 0335+1523 and UGC 2369, because this spectral resolution was requested by the authors of a simultaneous proposal[1] for HI absorption observations of these sources. For consistency, spectra of both of these sources have been averaged to reduce the velocity resolution to 26.3 km s^{-1}, and consequently decrease the channel based noise levels. All four observing runs were phase referenced using nearby calibrator sources which were observed regularly throughout observations (for details of individual phase calibrators used see Table 2.4). Bandpass calibration of each of the sources was achieved from observations of 0552+398 made at the appropriate frequency for each of the target sources, with the exception of the observation of UGC 2369 which is commented upon further below.

All of the observations were analysed using the MERLIN DPROGS and then transfered into AIPS where further reduction procedures were executed. These procedures followed the basic routines and methods described, in detail, in chapter 2.

6.2.1 Notes about Individual Observations

IR 0335+1523 & UGC 2369

The observations of IR 0335+1523 and UGC 2369 were both severely affected by radio frequency interference (RFI) particularly affecting the data from the Tabley telescope. This RFI (see Fig. 6.1) was centred upon 1374 MHz which coincided with the observing bands used for both IR 0335+1523 and UGC 2369. In both cases by editing all baselines which included the Tabley telescope, it was possible to produce reliable continuum images and spectra of these sources but with the

[1] The observations of Zw 49 and III Zw 35 were shared with another proposal made by A. Polatidis et al. (OSO).

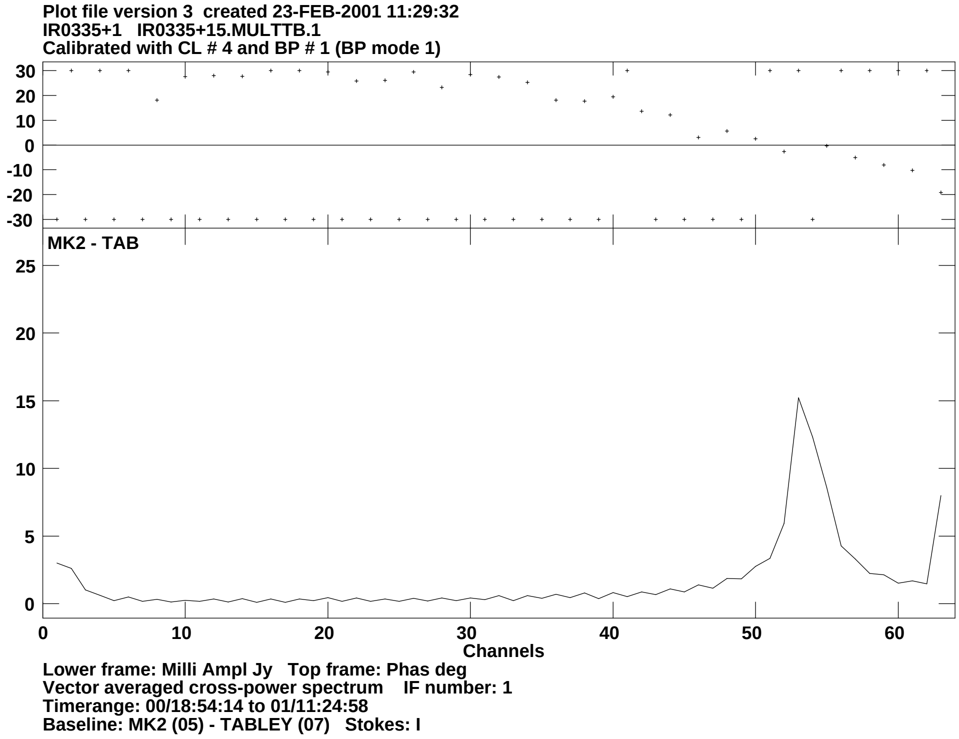

Figure 6.1: Radio frequency interference on the Tabley telescope at 1374 MHz. Taken from HI absorption observations of IR 0335+1523.

obvious sacrifices to the u, v coverage and sensitivity of the experiments.

In the case of UGC 2369 high winds across the UK also severely affected the observations of the calibration sources. Observations of both the amplitude calibrator, 3C 286 and the bandpass calibrator, 0552+398 were un-usable as only the two telescopes, Cambridge and Knockin, were able to observe. As consequence, an observation of 3C 84 was used to set the amplitude calibration for this observing run and bandpass corrections were derived from the phase calibrator 0249+171. The loss of observations from the Tabley telescope (due to man-made RFI) and of a suitable bandpass calibrator resulted in some degradation of the sensitivity of this experiment. Consequently, only modest upper limits on the detection of HI absorption against this relatively weak continuum source could be set.

Source	R.A.(B1950)	Dec (B1950)	V_c km s^{-1}	$\bar{\tau}$	$N_H \times 10^{21}$ atoms cm^{-2}
III Zw 35	$01^h\,41^m\,47^s.90$	$16°51'\,06''.0$	8175±10	0.096±0.008	5.3±0.6
UGC 2369	$02^h\,51^m\,15^s.91$	$14°46'\,04''.5$	-	<0.6	-
IR 0335+15	$03^h\,35^m\,58^s.73$	$15°23'\,03''.6$	10710±8	0.11±0.01	3.5±0.7
Zw 49.0	$15^h\,10^m\,45^s.69$	$07°24'\,42''.4$	3901±5	0.28±0.006	2.6±0.1

Table 6.1: HI absorption results for four luminous infrared galaxies.

6.3 Individual Sources

Neutral hydrogen absorption properties for all four of the sources described below are listed in Table 6.1. These include Gaussian fitted values for the radio continuum positions as well as the optical heliocentric velocities, mean optical depths and column densities of the absorbing HI gas. The column densities quoted in Table 6.1 have been derived assuming a spin temperature of 100 K and using the relationship $N_H = 1.823 \times 10^{20} \int \tau dV$.

6.3.1 III Zw 35

III Zw 35 is a well studied nearby (D=108.9 Mpc; 500 pc arcsec^{-1}) luminous infrared merger consisting of a close ($10''$~5 kpc) optical pair (Zink et al. 2000; Chapman et al. 1990). The northern member of this pair is dominant at all wavelengths and is coincident with catalogued position of III Zw 35. III Zw 35 contains a complex of strong OH megamasers emission (Pihlström et al. 2001; Diamond et al. 1999; Trotter et al. 1997) and is optically classified as Seyfert-2 or LINER (Chapman et al. 1990). However, other observed characteristics of this galaxy, such as high $L_{ir}/M(H_2){\sim}51.3$ (Sanders, Scoville & Soifer 1991) implying a high star formation efficiency, and the ratio of $60\,\mu$m to 1.4 GHz radio flux density which places it on the well-known radio to infrared correlation for starburst dominated galaxies (Helou, Soifer & Rowan-Robinson 1985), infer the existence of a starburst within this source.

III Zw 35 is a strong infrared emitter with a $L_{fir} = 10^{11.52}\,L_{\odot}$ (Mirabel & Sanders 1988) and contains a considerable gas content. Both molecular, OH megamasers (e.g. Pihlström et al. 2001) and CO emission (Sanders et al. 1991; Mirabel & Sanders 1987), and atomic hydrogen via HI emission and absorption (Mirabel & Sanders 1987, 1988) have been detected. The HI absorption detected with Arecibo (Mirabel & Sanders 1987, 1988) displays an optical heliocentric velocity of $8225\,\mathrm{km\,s^{-1}}$ and implies a total HI gas mass of $>3.2{\times}10^{9}\,M_{\odot}$.

The OH megamaser emission from III Zw 35 has been extensively studied over a wide range of angular resolutions using combined MERLIN and EVN data by Pihlström et al. (2001). They have found that the radio continuum structure, although unresolved by MERLIN, breaks up into clumpy components when it is observed at milliarcsecond resolution. The maser emission traces an inclined rotating ring of molecular gas with a radius of ${\sim}22\,\mathrm{pc}$ and a velocity gradient of ${\sim}1.5\,\mathrm{km\,s^{-1}\,pc^{-1}}$ implying a dynamical mass of $\sim 7\times10^{6}\,M_{\odot}$. These observation have provided one of the most convincing examples of circumnuclear gas close to the centre of an extra-galactic source.

Results and Discussion

The radio continuum of III Zw 35 is barely resolved with MERLIN at 1.4 GHz with some tenuous extension in north-eastern direction (see Fig. 6.2). The continuum

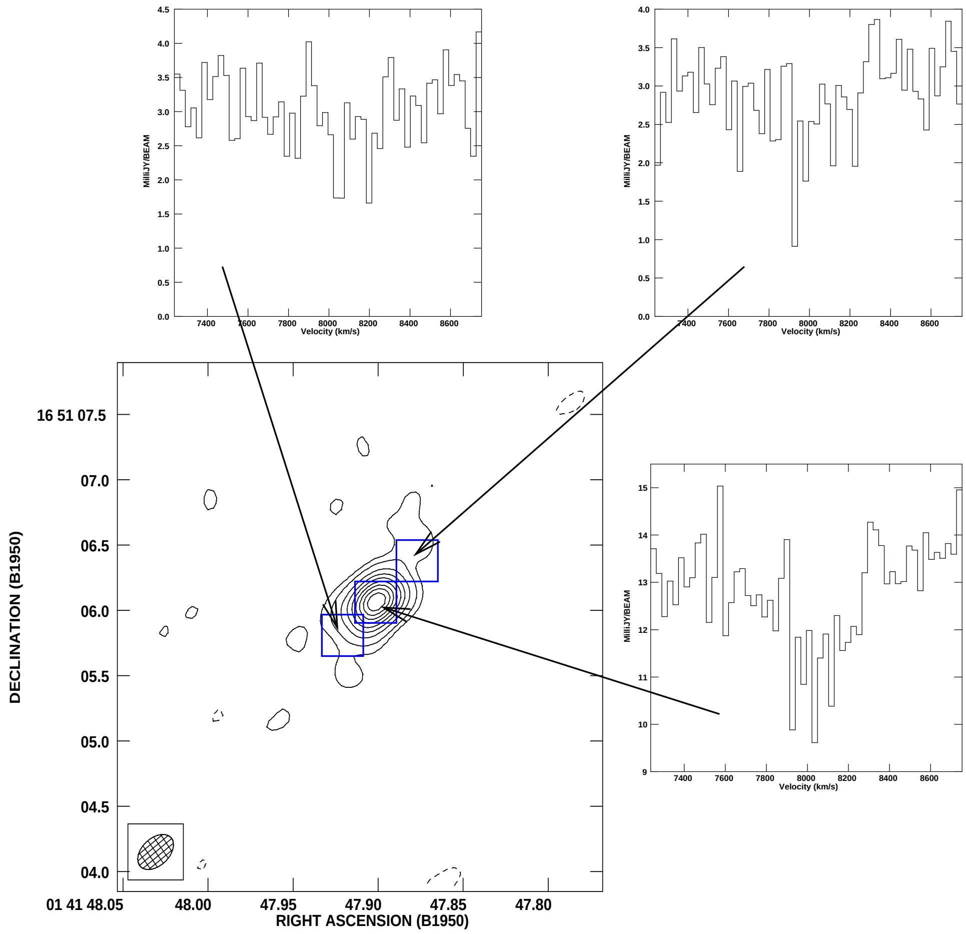

Figure 6.2: Montage of naturally weight MERLIN continuum contour map of III Zw 35 with selected H I absorption spectra. Contour levels are -1, 1, 2, 4, 6, 8, 10, 12, 14, 16 ×0.877 (3σ) mJy beam^{-1}. Angular resolution 0$''$.34×0$''$.21.

structure is consistent with observations at similar resolutions, such as MERLIN 1.6 GHz images by Pihlström et al. (2001) and VLA at 22, 15 & 5 GHz by Chapman et al. (1990) and Smith, Lonsdale & Lonsdale (1998b). The synchrotron spectrum of this galaxy shows a steep spectral index ($\alpha_5^{15} = 1$; $S_\nu \propto \nu^{-\alpha}$), but also exhibits a low-frequency turnover at ~1 GHz; similar to the turnover observed in the prototypical ULIRG merger Arp 220 by Sopp & Alexander (1989). This turnover in the radio spectrum can be attributed to free-free absorption by intervening hot ionised gas. Observed at milliarcsecond resolutions with VLBI, Pihlström et al. (2001) found the continuum structure of III Zw 35 to be broadly consistent with the radio continuum emission arising from a group of compact luminous RSNe similar to those found in Arp 220 (Smith et al. 1998a) and Mrk 273 (Carilli & Taylor 2000). Although, the existence of a heavily free-free absorbed AGN within III Zw 35 is still conceivable, the observational evidence is far more consistent with an intense starburst of Arp 220 proportions resulting in the observed emission from this galaxy.

H I absorption (τ=0.096) is detected against the radio emission of III Zw 35 with a velocity width of 310 km s^{-1}, centred upon a heliocentric velocity of $\sim$8175 km s^{-1}. The observed velocity of the H I absorption is slightly blueshifted compared to the previously published systemic molecular velocities (8225 km s^{-1}, Pihlström et al. 2001; Mirabel & Sanders 1987). This discrepancy is most likely due to the low signal to noise of the spectra recorded in this observation. The breadth of the absorption line is similar to the OH absorption observed by Pihlström et al. (2001) in areas where no maser emission is detected and is comparable to the broad H I absorption observed against other ULIRG mergers such as Arp 220 (Mundell et al. 2001) and NGC 6240 (see chapter 5). In both Arp 220 and NGC 6240, it has been concluded that the broad H I absorption arises due to disturbed neutral gas which is rotating about remnant components of the progenitor galaxies involved in the merger event. With far superior angular resolutions than these observations, Pihlström et al. (2001) have found that the distribution and velocities observed in the OH megamaser emission are convincingly explained by the existence of a rotating ring of molecular gas with a radius of 22 pc. This picture is consistent with the explanation that the H I absorption observed along a single line of sight toward the unresolved radio continuum is broadened to a width of a few hundred km s^{-1} by rotation. In this scenario the cold H I gas is likely to be associated with this molecular component, but may also extend to a considerably greater radius, thus easily providing the observed velocity widths.

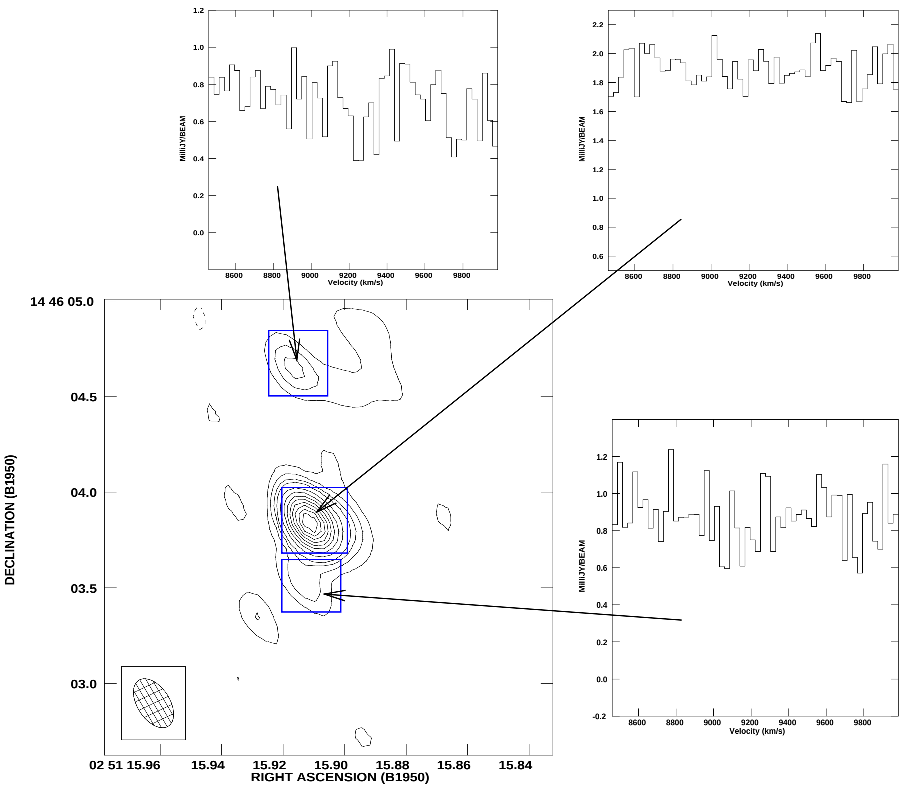

Figure 6.3: Naturally weighted continuum contour map of UGC 2369. Spectra against the continuum regions are also shown. Contour levels are -1, 1, 2, 3, 4, 6, 8, 10,12, 16, 18 $\times$0.12 (3σ) mJy beam^{-1}. Angular resolution $0\farcs30\times0\farcs16$.

6.3.2 UGC 2369

UGC 2369 (D=125 Mpc; 606 pc arcsec^{-1}) consists of a galaxy pair separated by $\sim30''$ which are connected by a faint optical bridge. The northern galaxy is considerably brighter in the optical and near infrared but the southern galaxy dominates at radio and far infrared wavelengths (Zink et al. 2000). UGC 2369 has a far infrared luminosity of $L_{\rm fir} = 10^{11.44} L_{\odot}$ (Mirabel & Sanders 1988). Although, model fitting of VLBI observations by Smith et al. (1998a) do find some evidence for resolved high brightness temperature clumpy structure, they concluded that the radio emission is too strong to be the result of compact RSNe with the emission probably originating from an AGN. HI absorption was detected using Arecibo by Mirabel & Sanders (1988) at a optical heliocentric velocity of 9406 km s^{-1} with a velocity width of 274 km s^{-1} and $\bar{\tau}$=0.018. The HI column density integrated over the line width was calculated to be 2.2$\times$10^{21} atoms cm^{-2}.

Results and Discussion

From these weather and interference affected MERLIN observations of UGC 2369 only an upper limit of $\tau_{\rm peak}$ <0.6 (see Table 6.1) can be set upon the detection of HI absorption. This upper limit is set assuming a detection rate of 3 times noise level of the spectra. The value of HI opacity of 0.018 detected by Mirabel & Sanders (1988) is well within the limits set by this observation thus it is not surprising that HI absorption is not detected. However, the HI optical depth observed with the increased resolution of MERLIN compared to this single dish observation (Arecibo) would be expected to be higher, provided the coverage of HI gas, or the illuminating radio continuum, is smaller than the size of the Arecibo beam. Of course, the non-detection of HI absorption in this experiment could also result from resolving away the radio continuum that illuminates the HI gas seen in absorption by Mirabel & Sanders (1988).

The radio continuum structure of UGC 2369 imaged with MERLIN (see Fig. 6.3) is partially resolved with some extension towards the south of the main continuum component and some additional low brightness continuum structure to the north. This continuum image is consistent with the 8.4 GHz VLA image of this source presented by Condon et al. (1991). At 8.4 GHz the VLA image shows a bright central component with some extended structure, especially towards the north of the central component.

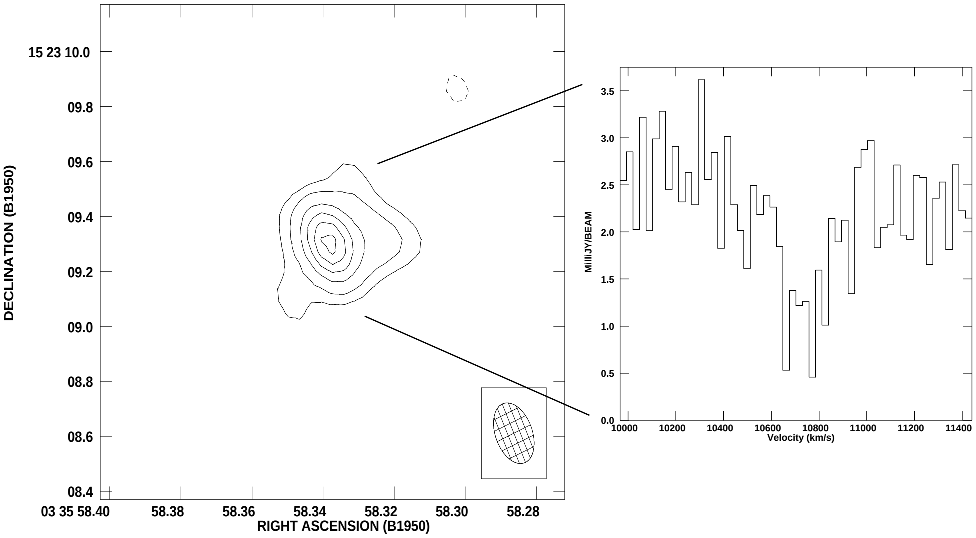

Figure 6.4: Montage of uniformly weight MERLIN continuum contour map of IR 0335+1523 with HI absorption spectra. Contour levels are -1, 1, 2, 4, 6, 8, 10 $\times$ 0.321(3σ) mJy beam^{-1}. Angular resolution $0\farcs23 \times 0\farcs15$.

6.3.3 IR 0335+1523

The bright *IRAS* source 0335+1523 is a relatively nearby, irregular galaxy which has undergone some degree of interaction. In both optical and radio images this galaxy appears to contain two core-like components with a high infrared luminosity $L_{\rm fir} = 10^{11.40}\,L_{\odot}$ (Mirabel & Sanders 1988). HI absorption was detected using Arecibo by Mirabel & Sanders (1988) at $V_{\rm hel}$=10717 km s^{-1} placing this source at a distance of 141.7 Mpc ($1''$=687 pc).

Radio observations of IR 0335+1523 at 8.4 GHz using the VLA (Condon et al. 1991) resolve two components separated by $\sim1\farcs5$. Of these two radio components only the brighter north-eastern component is detected in this experiment. This radio source is unresolved by the VLA at 8.4 GHz, and displays a flat spectral index $\alpha^{8.44}_{1.49} = 0.31$ (Condon et al. 1991). High frequency radio observations with the VLA and VLBI model fitting by Smith et al. (1998b) found that at radio wavelengths the emission is more consistent with a compact synchrotron core than a region of compact starburst emission.

Results & Discussion

The MERLIN continuum image of this source is shown in Fig. 6.4. With uniformly weighting this MERLIN continuum image shows an unresolved point source with possibly some lower surface brightness extensions towards the south-east and west of the main radio component. Gaussian fitting of this continuum source confirm that it is unresolved by the MERLIN beam implying that the source has a size of >100 pc. This is consistent with similar resolution VLA images at 8.4 GHz and 15 GHz (Condon et al. 1991; Smith et al. 1998b) and with the radio emission originating from either a compact cluster of luminous RSNe or a low luminosity AGN core.

Broad HI absorption is detected against the continuum of IR 0335+1523 with a central velocity of $10710 \pm 8\,\mathrm{km\,s^{-1}}$ and a line width of $\sim 160 \pm 15\,\mathrm{km\,s^{-1}}$. The mean HI opacity and column density along this single line of sight are 0.11 and 3.5×10^{21} atoms $\mathrm{cm^{-2}}$ respectively. Assuming a physical extent of ~ 100 pc and a uniform gas coverage this implies an upper limit upon the HI mass of $\sim 9 \times 10^{5}\,\mathrm{M_{\odot}}$.

6.3.4 Zw 49.0

Zw 049.057 is a small, irregular galaxy at a distance of 57 Mpc ($276\,\mathrm{pc\,arcsec^{-1}}$) and has a far infrared luminosity of $\mathrm{L_{fir}} = 10^{11.20}\,\mathrm{L_{\odot}}$. This galaxy is gas rich, with both OH maser and CO emission detected (Baan, Henkel & Haschick 1987; Martin et al. 1988;Planesas, Mirabel & Sanders 1991) along with strong HI absorption (Mirabel & Sanders 1988). The OH maser emission is relatively weak in comparison to bright OH megamaser galaxies, and has an almost identical line width to the observed single dish HI absorption spectra. Recent NICMOS

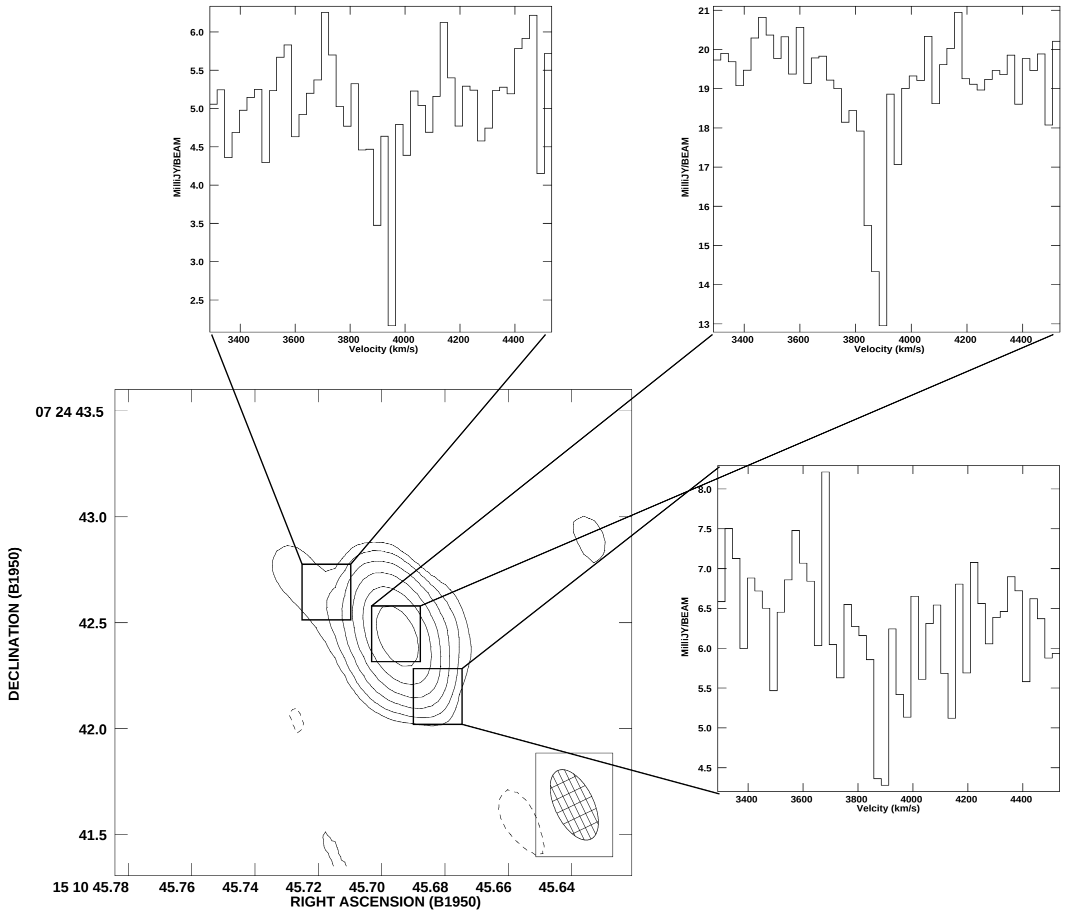

Figure 6.5: Montage of naturally weight MERLIN continuum contour map of Zw 49.0 with selected H I absorption spectra. Contour levels are -1, 1, 2, 4, 8, 16, 32 $\times$ 0.525 (3σ) mJy beam^{-1}. Angular resolution $0\farcs36\times0\farcs18$.

observations of this galaxy by Scoville et al. (2000) show that in the infrared, the nuclear region of this galaxy breaks up with a degree of clumpy structure which has been primarily attributed to varying degrees of absorption across the source. Few high resolution, radio continuum observations of this source have been previously made and no comparable resolution images have been published to date.

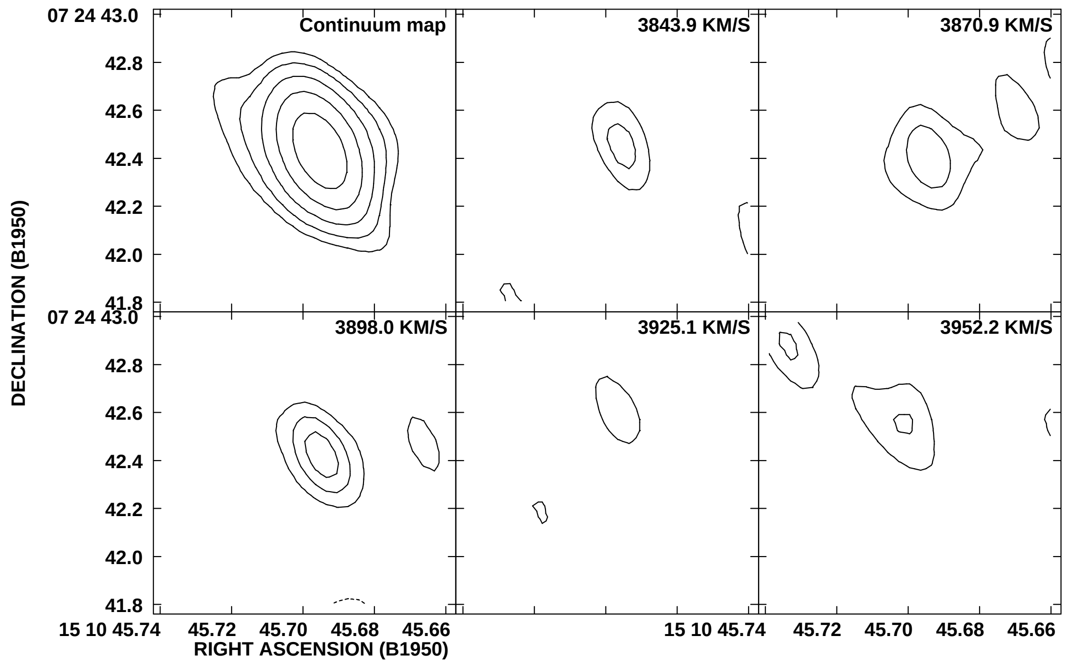

Figure 6.6: Naturally weighted channel maps of H I absorption against Zw 49.0. Contour levels are -5, -4, -3, -2, -1, 1 $\times$ 2 mJy beam^{-1}. A continuum contour map shown in the top right hand panel.

Results and Discussion

The radio continuum of Zw 049, shown in Fig. 6.5, is compact and barely resolved by the $0\farcs36\times0\farcs18$ restoring beam of these MERLIN observations. At the distance of Zw 049 ($\sim$57 Mpc) this implies that the compact radio component has a physical size of $\lesssim$50 pc. Strong H I absorption is detected (see Figs. 6.5 & 6.6) against this radio continuum component which has a broadly consistent spectra to those obtained from the previous single dish observations (Mirabel & Sanders 1988; Martin et al. 1988). The H I absorption detected has a mean optical depth of 0.28 (see Table 6.1) which is significantly higher than the optical depths recorded against the other LIRGs in this sample. Mirabel & Sanders (1988) recorded a mean H I opacity of 0.121 for Zw 049 which was the largest optical depth found for any of the 18 H I absorbing galaxies they observed. The optical depth detected in this high resolution experiment is a factor two greater than detected for the same source by Mirabel & Sanders (1988). This apparent discrepancy is easily accounted for if it is assumed that the H I absorption arises from an area that is of comparable size to the MERLIN resolution. Additionally the Arecibo observations of Mirabel & Sanders (1988) may contain some degree of contamination by H I emission from Zw 049 reducing the optical depth they observe. It is apparent from the continuum images created from this data set that the source is essentially compact, implying a physical size that is smaller than can be sampled with these observations. The H I absorption against Zw 049 is also narrower ($\sim$100 km s^{-1}) than the absorption lines observed against the other sources in this sample. The narrowness of this line is either indicative of absorption from less disturbed neutral gas (quiescent galactic gas, possible at some distance from the nuclear region) or of the compact physical size of the background radio continuum source. If it is assumed that the radio continuum component is in fact a compact synchrotron core, both the depth and narrowness of the H I absorption line is easily accounted for, since only gas along a single line of sight with an area smaller than $\sim$50 pc^2 is sampled.

6.4 General Conclusions

H I absorption is detected against three quarters of the LIRGs observed with MERLIN. The only exception to this is UGC 2369, upon which a limit of $\tau_{\rm peak}$ >0.6 is set. All of the sources presented here, have had previous low resolution detections of H I absorption, see for example Mirabel & Sanders (1988).

Of the sources presented here, all are classified as LIRGs and have far infrared luminosities between $10^{11.20}$ and $10^{11.52}$ L$_\odot$. In common with the majority of LIRGs all of these sources are either mergers or are interacting with nearby companion galaxies (Sanders & Mirabel 1996). All are relatively gas rich with either molecular CO or OH detections.

All of the sources presented in this chapter have compact radio continuum structures and are essentially unresolved with the sub-arcsecond angular resolution of MERLIN. The origin of the energy sources within all of these galaxies (either starburst, AGN or hybrid of these) is still an unanswered question, with the possible exception of III Zw 35 (Pihlström et al. 2001).

The detection of broad HI absorption against III Zw 35 is unsurprising considering the known dynamics of the system from high resolution OH megamaser observations (Pihlström et al. 2001). The breadth of the HI seen in absorption ($310\,\mathrm{km\,s^{-1}}$) is consistent with the line being rotationally broadened with the atomic gas being associated with the molecular gas ring observed by Pihlström et al. (2001). The radio continuum is unresolved by these observations with the beam size larger than the projected diameter of the circumnuclear molecular gas ring observed by Pihlström et al. (2001). Hence these HI absorption observations would be expected to see the HI absorption fully broadened by the rotation associated by this ring, provided that the HI is associated with the molecular gas components.

Against IR 0335+15 broad ($160\,\mathrm{km\,s^{-1}}$) HI absorption is detected against a single compact radio component. Although with MERLIN only one component of this merger galaxy is detected, a second weaker radio component is detected by Condon et al. (1991) approximately $1\farcs5$ ($\sim$1 kpc) from the primary component. The broad HI absorption in this source is consistent with either the cold atomic gas associated with this source being dynamically disturbed, possible by a past or ongoing interaction or with the line being broadened by rotational motions such as an unresolved ($\lesssim$100 pc) ring of neutral gas. However these observations do not have the resolution to either confirm or refute either these speculative conclusions.

Zw 49.057 has the highest 1.4 GHz flux density of the galaxies sampled here. Against this compact radio continuum component narrow HI absorption with a high optical depth ($\bar{\tau}$=0.28) is detected. The HI absorption is spatially unresolved and represents gas detected along only a single line of sight towards this compact radio component. Both radio continuum and consequently HI absorption arise from an area smaller than $\sim$50 pc^2.

All of the observations presented in this chapter, with exception of UGC 2369, have detected HI absorption with similar spectral profiles to previous single dish observations but with significantly higher angular resolution. As with all absorption line studies the primary limit of these observations is dictated by the detectable background radio continuum structure and its location. In all of the galaxies presented in this chapter the radio continuum detected with MERLIN is essentially unresolved. As a consequence only limited distribution and velocity information for the neutral hydrogen has been gained from these observation.