Decimetre studies of neutral gas in starburst galaxies

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Abstract.
We will review observations of neutral gas in starburst galaxies, concentrating mainly on atomic hydrogen, but also including some discussion of OH molecules. In a number of starbursts, OH maser emission gives valuable insights into the properties and dynamics of localised regions of neutral gas, however thermal emission from neutral gas usually has a relatively low excitation temperature, and observations of this gas is severely limited by the sensitivity of current decimetre arrays and can only be observed at relatively low angular resolution (5-10 arcsec).

Absorption measurements, however, are only limited by the brightness of the synchrotron continuum background and hence it is possible to measure the distribution of absorbing neutral gas on scales as small as a few milliarcseconds. We will review progress in this area ranging from detailed studies of nearby objects such as M82, to distant, more luminous starbursts such as Arp220. We also will discuss the role of neutral gas in testing for the presence of an active galactic nucleus within a starburst.

INTRODUCTION

Starburst galaxies contain regions with a significantly enhanced starformation rate, and estimates of the available gas present usually show that this rate can only be sustained for a small fraction of the galactic lifetime–hence the term 'starburst'. The starburst usually has a size of order a kiloparsec, although in some cases merger events result in more extensive starbursts (eg NGC4038/4039 [1]), whereas others show intense starformation rates over regions of only a few hundred parsecs.

The best observational evidence for a starburst is probably the intense far-infrared (FIR) emission which is thought mostly to be dust heated by hot stars. The radio continuum flux density of a galaxy is also a good indicator of enhanced starformation, although there is often some contamination of this emission with radio emission produced via collimated ejection from an active galactic nucleus (AGN). In nearby galaxies it is often possible to resolve the non-thermal synchrotron emission into supernova remnants and/or radio jets, which enables the two mechanisms to be distinguished. This is, however, more difficult in high luminosity, high redshift objects which require higher sensitivity and angular resolution to separate the two mechanisms.

Given the high density of UV photons in the central few kpc of starburst galaxies, it is surprising that neutral gas exists in large quantities in this relatively hostile environment. This can be attributed to a number of factors, but probably the most important is that the neutral clouds contain interstellar dust which shields their interiors from UV radiation.

This neutral gas, mostly consisting of atomic hydrogen and simple molecules, can give a direct insight into the fueling, mass distributions and possible formation mechanisms for starbursts.

ATOMIC HYDROGEN EMISSION STUDIES

Fueling the starburst

Neutral gas is an essential ingredient required for formation of stars. The relatively low star-formation rates in normal galaxies results in this reservoir of neutral gas being used up relatively slowly, and hence star-formation can, in principle, proceed in a normal galaxy for of order the Hubble time. The global star-formation rate (SFR) of a galaxy can be estimated using a variety of observations ranging from radio to ultraviolet (UV) wavelengths [2]. Optical and UV observations, however, are affected by extinction, particularly in galaxies with high gas content, and often large corrections need to be applied. Radio emission from the synchrotron mechanism and far-infrared emission from heated dust, are not affected by extinction and both provide global SFRs which are in good agreement. Using these SFR estimators it is found that many galaxies have SFRs of 10-100 $M_{\odot}$ per year and in some cases an order of magnitude higher. Although the ISM is replenished via stellar winds from aging stars etc, a rough estimate of the lifetime of the star-formation can be made by simply dividing the neutral gas content by the star-formation rate.

One of the simplest ways to estimate the total neutral gas content of a galaxy is to observe in the 21cm neutral hydrogen line. Single dish observations are ideal for these measurements as, unlike interferometer measurements, they have no problem with missing low-order spacings and the relatively large beams will usually include the entire galaxy for distances greater than a few Mpc. The integrated line intensity gives a direct measure of the total number of atomic hydrogen atoms present and is independent of the spin temperature (although high optical depths can result in an underestimate). Estimating the molecular hydrogen (H_2) content is more difficult as the hydrogen molecules do not emit via rotational transitions, and the H_2 content is usually inferred from carbon monoxide observations with an uncertain conversion factor. Nevertheless the total atomic and molecular gas content of a galaxy can usually be measured to better than a factor of two, and typically is a few percent of the dynamical mass of the galaxy. Hence using this neutral gas content, it is clear that the high star-formation rate observed in many galaxies cannot continue for more than $\sim 10^8$ years, which implies that such high SFRs must be of a relatively short duration compared with the lifetime of the galaxy.

Tracing neutral gas dynamics

By observing the dynamics of a spiral galaxy it is usually a relatively simple step to derive a rotation curve and hence infer the galaxy mass distribution. Although the

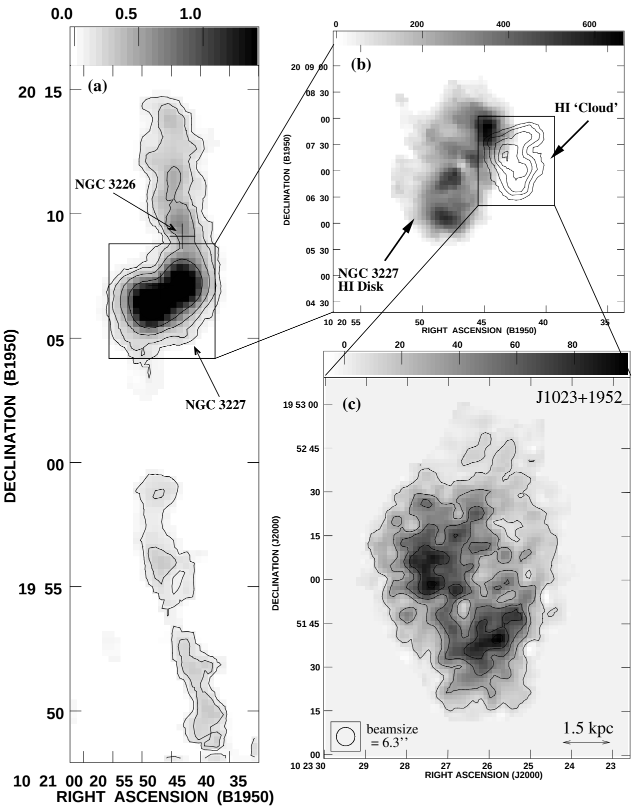

FIGURE 1. An image of neutral hydrogen associated with the interacting pair of galaxies NGC3226 and NGC3227. The plumes of HI extend to $\sim$70 kpc north and $\sim$31 kpc south of the interacting galaxies. (From Mundell et al [3]).

optical emission from ionized gas can be used to trace these dynamics, observations of neutral gas have several advantages particularly in starburst galaxies. Often the dynamics of the ionised gas have been perturbed by winds, outflows etc associated with the star-forming activity, and it is necessary to separate out these motions from rotational motion. However if neutral gas encounters such outflows it may be shock ionised and the remaining neutral gas will not participate in these type of motions. Furthermore the dust associated with the relatively high neutral gas densities found in starbursts often lead to high levels of optical extinction and hence much of the dynamics are obscured optically. Finally the neutral atomic hydrogen is usually much more extensive than its ionised counterpart, and can trace the dynamics in the outer parts of the galaxy. It is particularly sensitive to interactions with companions. The evidence for past interactions can range from fairly minor distortions such as warps in the galactic disk, to extensive plumes and tails- in many cases extending of tens or even hundreds of kpc. An example of an extensive H1 plume [4][3] associated with NGC3227 is shown in Figure 1 and many examples of this phenomenon are included in Hibbard et al [5] all of which show convincing evidence of interactions. There appears to be a well established link between such interactions and the presence of a starburst, with the obvious idea that the chaotic gas flows created by such encounters lead to shocks, density enhancements and eventually to increased starformation.

Another possible mechanism for producing enhanced star-formation in the central regions of galaxies is via non-circular gas motions associated with the bar potential [6] which lead to the gas being compressed via shocks. A number of H1 emission line studies of barred galaxies and associated starbursts have been carried out using radio synthesis instruments with angular resolutions typically of order 10". A particular good example of a barred starburst galaxy is Sersic-Pastoriza galaxy NGC1808, which, like M82, shows evidence for a strong outflows consistent with superwinds. The bar of NGC1808 was first studied in neutral hydrogen by Saikia et al[7] and later by Koribalski et al [8], who noted significant deviations from circular motion, such as an offset to the line of nodes, consistent with the bar models of Roberts et al [6]. However the $\sim$10" angular resolution for H1 emission studies attainable with existing radio synthesis instruments (see below) is often inadequate to study the dynamics of gas motions associated with bars in detail, which consequently have to be carried out optically or using molecular transitions on mm interferometers.

The effect of starbursts on the neutral ISM

In starburst galaxies, the intense starformation results in both strong stellar winds and relatively large numbers of supernovae. These both have a strong effect on the neutral ISM, and in many cases the winds etc break out of the galaxy to produce galactic bipolar outflows, the most spectacular are seen in the Hα cones associated with M82. On a smaller scale the combined kinetic and radiation pressure by stellar winds from massive stars and supernovae [9] produces holes and shells in the ISM of the host galaxy via the evacuation of the cool ISM .

These holes/shells were first discovered by single-dish atomic hydrogen measurements of the LMC [10] and later in the Milky Way [11]. Atomic hydrogen aperture synthesis observations of a number of nearby galaxies have revealed hundreds of such objects with sizes ranging from a few 10s of parsec to more than a kiloparsec. The shells can also seen to expanding at upto 40 km/s, with corresponding ages of $\sim 10^7$ years. The largest shells, sometimes called supershells or supergiant shells, require input energies over 10^{54} ergs [12] to account for their formation. Detailed atomic hydrogen studies of the dwarf irregular galaxies DDO 47 and IC 2574 [13], [14] reveal their ISM to be dominated by holes and shells, although the most extensive study of this phenomenon has been carried out using the ATCA on the LMC by Kim et al [15] in which $\sim$130 shells have been catalogued.

The limitations to H1 emission studies

The astronomical angular resolution of an instrument can be limited by a number of factors. There is, of course, a diffraction limit due to the maximum extent of the telescope and the observing wavelength, and ground-based optical studies are also limited by atmospheric 'seeing'. The resolution of telescopes studying atomic hydrogen and other decimetre transitions are limited by neither of these problems. The diffraction limited resolution is, in principle, a few milli-arcseconds and atmospheric/ ionospheric problems can be largely removed by self-calibration and use of phase calibrators. However, in the case of decimetre line studies, the attainable angular resolution is limited by the brightness temperature sensitivity of current instruments. This is largely a consequence of the Rayleigh-Jeans law in which the flux density per beam is inversely proportional to the wavelength squared, coupled with the relatively low excitation temperatures of neutral atomic hydrogen($\sim$100K) and the narrow bandwidth of the frequency channels required to give reasonable velocity resolution. This means that most atomic hydrogen studies are currently carried with angular resolutions of order 10 arcsec, although by using integration times measured in days, rather than hours, this can be reduced to 5 arcsec (eg [16]). However it is necessary to await the construction of the Square Kilometre Array (SKA) before emission studies of atomic hydrogen will have arcsecond resolution. In the meantime, valuable high angular resolution studies studies of neutral atomic hydrogen can be undertaken using absorption techniques.

Thermal OH emission has similar limitations to the H1 emission, although strong maser emission, in which the apparent excitation temperature is several million degrees, results in detectable emission on milli-arcsecond scales.

ABSORPTION LINE STUDIES

The optical depth of the atomic hydrogen absorption is determined by the column density of the neutral hydrogen and the excitation temperature. However, unlike emission line studies, the flux densities of absorption features are not limited by the excitation temperature of the gas, but by the background continuum against which the absorption is seen. At decimetre wavelengths this continuum is mostly produced by the synchrotron mechanism which typically produces brightness temperatures in excess of 10^5K - several orders of magnitude higher than typical excitation temperatures. Thus, where there is significant continuum emission, it is often possible to study the distribution and dynamics of neutral gas on scales determined by the diffraction limit of the instrument. Hence with present sensitivities, atomic hydrogen with a spin temperature of 100K and a column density of order 10^{19} atoms cm^{-2} can be detected against continuum sources of a few mJy.

A further advantage of absorption measurements is that they can constrain the line of sight geometry of source. Hence if absorption is measured against a continuum component it clearly must be between the observer and the continuum source, and hence, unlike emission spectra, easily distinguishes between outflow and inflow from the absorbed source.

The major disadvantage of absorption studies is that continuum emission is often only present over a small part of a galaxy, and, of course, absorption spectra cannot give information on gas on the far side of the continuum.

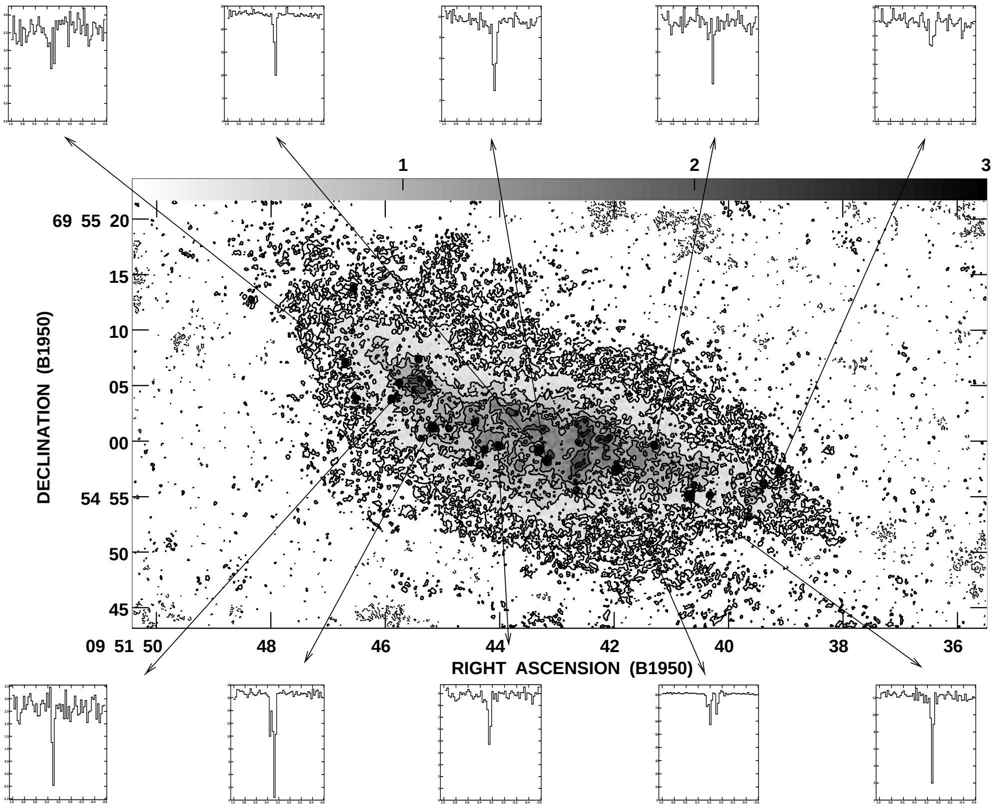

FIGURE 2. A montage of H1 absorption spectra detected against the 20cm continuum emission from M82. The data is discussed in Wills et al [19].

Absorption studies of nearby starbursts

One of the nearest, and certainly best studied, starbursts is in M82. This starburst contains ∼50 compact radio sources, the majority of which appear to be supernova remnants [17], although 16 are most likely compact HII regions [18]. The compact sources are embedded in a diffuse halo with an extent of ∼ 0.5 kpc and a flux density of several Jansky at 1.4GHz. Hence the relatively intense non-thermal continuum facilitates detailed H1 absorption studies. Wills et al [19] used MERLIN to detect H1 absorption against 33 of the supernova remnants (Figure 2). Although the angular resolution was 0.4 arcsec (∼ 6 parsecs), most of the remnants were smaller than the beam and hence the observations sampled lines of sight through the ISM of M82 on scales as small as 20mas (0.3 parsecs).

The study showed an average velocity gradient along the major axis of ~ 7 km s^{-1} $arcsec^{-1}$ in the neutral gas consistent with earlier studies. However there was also evidence for non-circular motions, such as absorption spectra with multiple components and position -velocity features with steep gradients. A later H1 absorption study, using the VLA, had lower angular resolution (1.3 arcsec=20pc) than MERLIN, but was sensitive to atomic hydrogen against much of the diffuse non-thermal background of M82. The data were in agreement with the MERLIN results, and the dynamics were initially in-

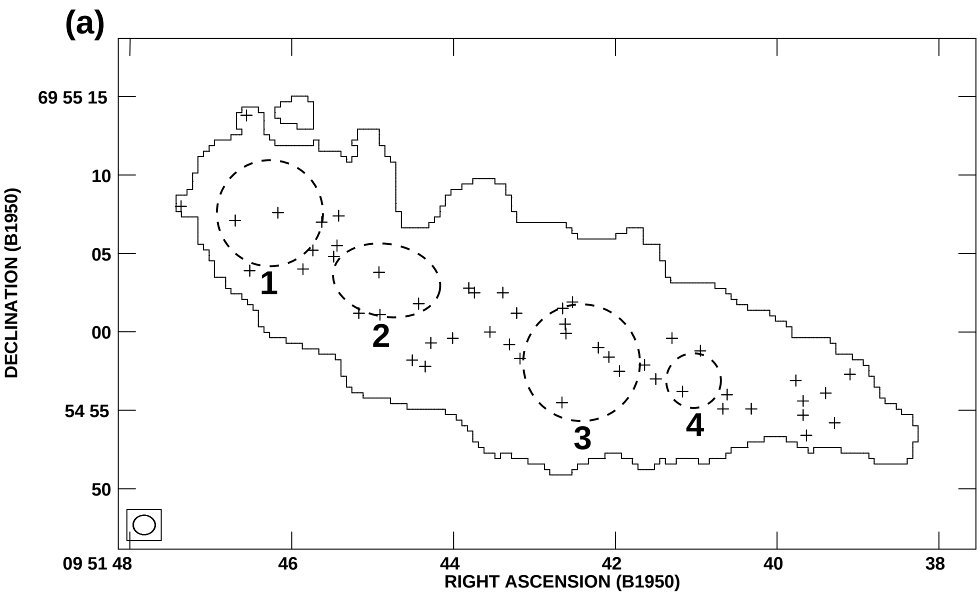

FIGURE 3. Diagram showing the position of the H1 shells seen in absorption against the continuum emission in M82. The crosses mark the position of supernova remnants. From Wills et al [23].

terpreted in terms of gas motions in a bar potential and a model for a possible bar was derived [20].

However these data also revealed a number of expanding shells of neutral hydrogen (Figure 2) similar to those seen in H1 emission discussed above. Weiss et al [21] had already noted that the dynamics of carbon monoxide molecules in M82 were consistent with a wind driven supershell, and this was confirmed by further CO measurements by Matsushita et al [22]. In fact it now appears that much of the non-circular motion in the neutral gas can be attributed to the effect of such shells and that some of the dynamics ascribed to gas flows in a bar potential may be due to this effect.

Similar detailed H1 absorption studies using MERLIN and the VLA have been carried out on a number of nearby starbursts. Cole et al [24] report on NGC3628, which like M82 is almost edge on. The main velocity structure can be attributed to a ring of neutral gas with a radius 130 pc rotating around a central starburst with a velocity gradient of 1270 km s^{-1} kpc^{-1}. A secondary absorption structure may represent outflow from the starburst region or a large-scale galactic structure.

A study of NGC520 [25] shows HI absorption velocity structure to be consistent with the velocity gradients observed in both the OH absorption and in CO emission observations. It was also noted that the velocity gradients observed for these neutral gas components appear to differ from the velocity gradients observed from optical ionized emission lines, which is attributed to the extinction of the optical emission.

A combined MERLIN/VLA study of NGC2146 [26] showed the HI gas to have a rotating disk/ring structure with column densities between 6 and 18×10^{21} atom cm^{-2}. The HI absorption shows a surprisingly uniform spatial and velocity distribution, and

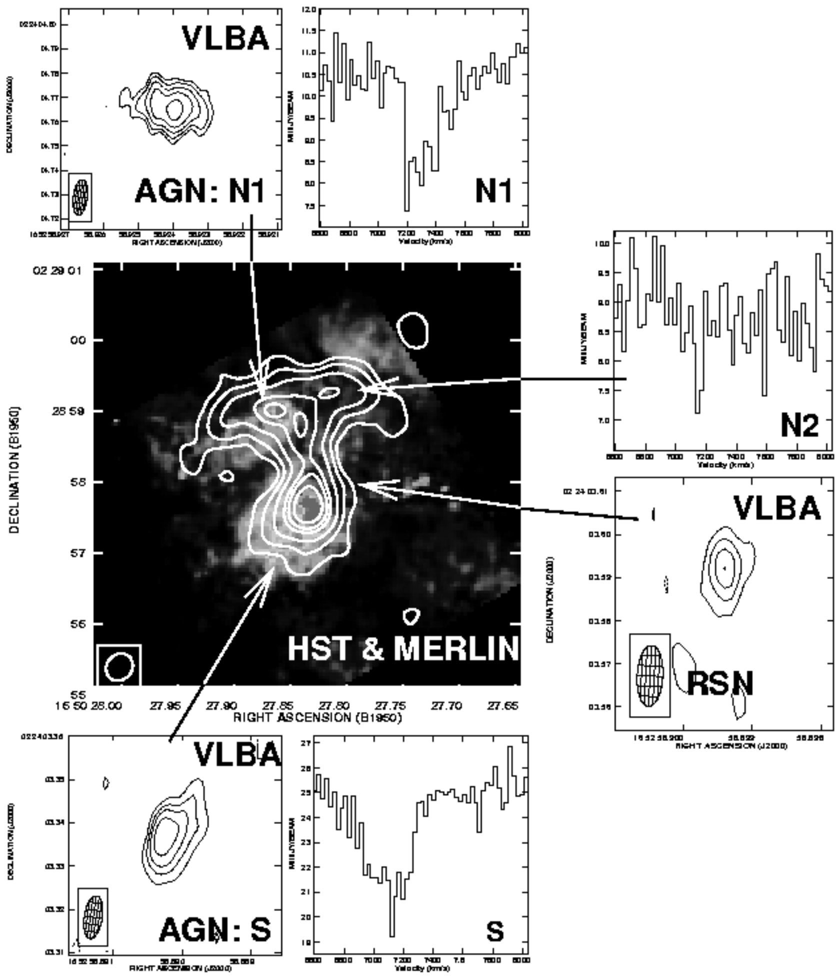

FIGURE 4. A MERLIN 20cm continuum image of the central part of NGC6240. The H1 absorption spectra seen against the north and south nuclei are shown, together with VLBA maps showing compact radio structure associated with the AGN, and a radio supernova (see [27] for details).

does not reveal any anomalous material concentration or velocity in the central region of the galaxy which might indicate an encounter with another galaxy or a far-evolved merger.

Absorption studies of more powerful, distant starbursts

The more powerful starbursts are relatively rare and tend to be at larger distances. Their high starformation rates result in high infrared luminosity ($> 10^{12}L_\odot$) and hence many are classified as ultra luminous infra-red galaxies (ULIRGS). Despite their high infrared luminosity, the 'starburst' regions in many of these galaxies are very compact (eg Arp220 -see below) often smaller than the 0.5kpc starburst in M82 and hence require sub-arcsecond resolution, and currently can only be adequately studied via absorption or masers.

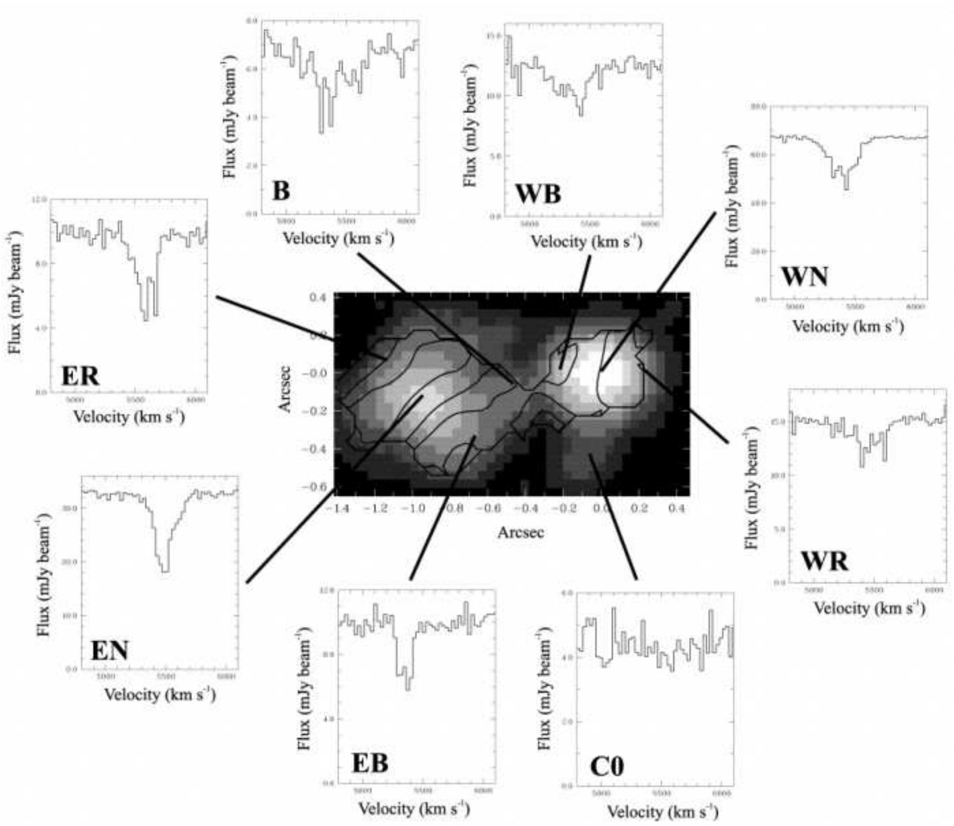

FIGURE 5. A montage of HI absorption spectra seen in Arp220 against the 20cm continuum (shown as a greyscale). Isovelocity contours superimposed on the continuum illustrate the different rotation axes of the two regions (From Mundell et al [34]).

In many cases there have been difficulties in deciding whether the high infrared luminosity of these galaxies is mainly due to starformation, or the presence of an active galactic nucleus (AGN), and neutral gas observations can often be used to distinguish between the two mechanisms In some cases the AGN is clearly separated from the starburst, for example NGC7469 [28] in which the starburst is situated in a clear ring around the AGN. Often, however, the two components are superimposed and embedded within regions of high dust extinction, hindering or preventing optical studies. In the case of Mkn273 infra-red observations [29] were necessary to to identify the AGN, and subsequent observations of its OH mega-maser [30] and HI absorption [31] have shown the neutral gas to be in a $\sim$200pc edge-on disk in orbit around a central mass of $\sim 5 \times 10^8 M_\odot$ which clearly could include a supermassive black hole. NGC6240 is particularly interesting as it appears to contain two AGN embedded within a powerful starburst. A neutral hydrogen study of this object [32] shows broad lines ($300-400$ km s^{-1}) against two compact radio components. Subsequent VLBA observations of these components [27] show them to be AGN, which has been confirmed by X-ray measurements [33].

The starburst in Arp220 is contained in two very compact regions which only extend over $\sim$2 arcseconds (700pc). A 0.2 arcsec resolution MERLIN study of HI absorption against the starburst has been carried out by Mundell et al [34], and shows extensive HI absorption against the two 20cm continuum components (Figure 2). The dynamics of the HI are consistent with two counter-rotating disks of neutral hydrogen, and Mundell et al propose that the two continuum components represent the galaxy cores that have survived the initial encounter and are now in the final stages of merging. The dynamical masses derived for the eastern and western components are $1.1 \times 10^9 (sin^{-2}i)$ and $1.7 \times 10^8 (sin^{-2}i)M_\odot$ respectively, where i is the inclination of each disk. A comparable MERLIN study of OH mega-maser emission from Arp220 has been made by Rovilos et al [35], who noted that the OH masers in the eastern component showed a smaller velocity gradient than the HI, and hence constrained the mass within the central 80pc of this component to be $\sim 10^7$M$_\odot$. Over the years there has been speculation that Arp220 may contain a hidden AGN, however as much of the mass inferred above must be in the form of stars, gas and dust, there seems little possibility that Arp220 contains a $> 10^7$M$_\odot$ black hole normally thought to be required for a powerful AGN. In fact both the eastern and western components have been shown to contain many radio supernovae/remnants [36], with no evidence for inverted spectrum compact sources or collimated ejection symptomatic of an AGN.

If ULIRGs and starbursts do contain supermassive ($\sim 10^7$M$_\odot$) black holes, they should have a measurable effect on the dynamics of the circumnuclear gas. The neutral gas is arguably the best tracer for such studies, as the dynamics of ionised gas are often perturbed by outflows, shocks etc. The OH mega-maser in the starburst IIIZw35 has recently been studied [37] and shown to be a rotating disk with a mass of $< 7 \times 10^6$M$_\odot$ enclosed within the central 22pc. HI absorption studies of the Medusa starburst (NGC4194) imply a central mass of $\sim 10^6$M$_\odot$ within the central 200pc, again putting strong constraints on the mass of any supermassive black hole (R.Beswick –these proceedings).

FUTURE PROSPECTS FOR ABSORPTION WORK

There is no doubt that ALMA will revolutionise neutral gas studies in starburst galaxies. Many molecular species will be studied in emission by ALMA on 0.1 arcsec scales at mm wavelengths, to produce detailed models of the dynamics, gas flows and interactions taking place over many starbursts. Nevertheless there will still be a role for H1 absorption studies to complement these data, particularly when modeling the three dimensional neutral gas distribution in the presence of synchrotron continuum. Its worth noting that even with the advent of the SKA, that subarcsecond resolution studies of neutral hydrogen will still need to be carried using absorption techniques as the SKA resolution for H1 emission will be $\sim$1 arcsecond, although much of this work will be carried out using the SKA which will enable H1 absorption to be detected even against thermal continuum sources.

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