Atomic and Molecular gas is starburst/AGN galaxies

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Abstract

We present deci-parsec scale observations of the atomic and molecular gas in several starburst/AGN galaxies that exhibit HI absorption and OH megamaser emission. The basic questions we are addressing is what is the dominant energy source, the starburst or an AGN and what is the connection between the atomic and molecular gas which may be fueling the central engine of the AGN or triggering the starburst.

1 Introduction

Recently, there is mounting evidence for the existence of disk-like radio *continuum* emission from circumnuclear gas on sub-kiloparsec and parsec scales in starburst galaxies, Seyfert galaxies and radio galaxies.

The continuum disk emission is thought to be synchrotron from electrons accelerated by radio supernovae. In fact it has recently been shown that the bright continuum emission in Arp 220 and (probably) in Mrk 273 arises from supernovae (Smith et al 1998, Carilli & Taylor 2000) and not in an AGN.

As well as being interesting in itself for constraining the physical properties of the starburst (eg. starburst energetics, star formation rate), these continuum disks provide an ideal background to observe HI absorption against and constrain the dynamics of these objects on <500 pc scales. Additionally the presence of IR pumping from the active star and a weak diffuse continuum background gives rise to OH megamaser action; providing another way to study the dynamics and physical conditions.

We are involved in the study of the dynamics and physical properties of the atomic and molecular gas in a sample of ULIR/starburst galaxies. that show HI absorption and OH megamaser emission or OH absorption. We are using high resolution centimeter and mm-wavelength observations, to study the distribution and dynamics of the gas, and single dish mm-wave observations to study the physical properties of the molecular gas.

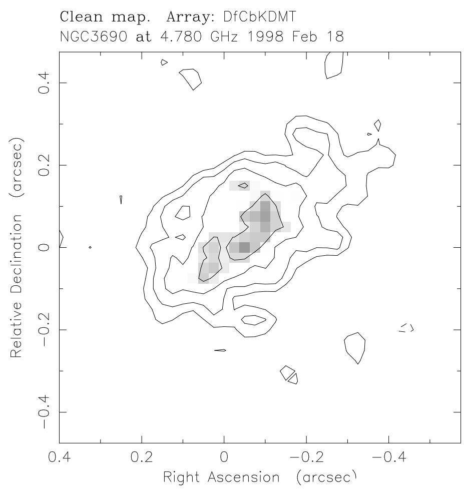
As part of this study we made sub-arcsecond resolution observations with the MERLIN array of the HI absorption and the OH megamaser emission of starburst galaxies. The observations were made between 1998 and in 2001. The data were calibrated and edited in the standard way and both the continuum and the spectral line data-cube were imaged separately.

While the analysis of the data is continuing, here we present the results for the galaxies IC694 and Zw 049.057, both of which are OH megamaser galaxies.

2 IC 694

The merging system Arp 299 (Mrk 171) consists of two interacting galaxies, IC 694 and NGC 3690, at a distance of 42 Mpc (z=0.0103, H_0=75 km s^{-1} Mpc^{-1}). Its far-infrared luminosity of $5.2\times10^{11}L_\odot$ (Soifer et al, 1997) places it in the gap between the nearby starburst galaxies (eg M82) and the more distant and still enigmatic Ultra Luminous far-InfraRed (ULIR) galaxies (eg Arp 220).

The system is rich in molecular gas, with bright CO condensations in the two galactic nuclei, particularly in IC 694, where the molecular gas mass in the inner



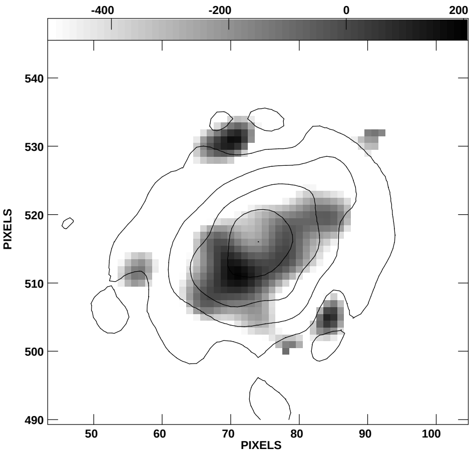


Figure 1a. The full resolution λ6 cm continuum image of IC 694 convolved with a round restoring beam of 55 mas. The contours are 1,2,4,8,16,32,64 $\times$ 0.36 mJy/bm. **Figure 1b.** The spectral index image of IC 694 (grey scale) overlaid on the 150 mas resolution contour image of the λ21 cm continuum. Grey scales are from spectral index -0.005 to 0.186 and contours are from 0.32 mJy/bm $\times$1, 2, 4, 8, 16, 32, 64

280 parsec is $\sim 5\times10^9$ $M_\odot$ (Aalto et al 1999). Furthermore, in the nucleus of IC 694, the mm molecular line rations reveal a highly disrupted molecular ISM with a bulk temperature in excess of 100 K. The detection of OH megamasers and HI absorption in Arp 299 (Baan & Haschick 1990, BH90), further emphasizes the notion of extreme conditions in the ISM.

MERLIN's linear resolution of 10-40 pc approaches the single cloud detection limit and is an order of magnitude higher than that of BH90. These can then be compared with the 200 pc resolution CO interferometric images (Aalto et al 1999) to study the properties and the kinematics of the gas.

Naturally weighted and tapered images of Arp 299 that cover $\sim$40$\times$40 arcsec detect λ21 cm continuum emission at both galaxies in the system, IC 694 and NGC3690, as well as the region of interaction between the galaxies. In contrast, at λ6 cm, emission from only the centres of IC 694 and NGC3690 is detected.

The HI absorption line and the OH megamaser line were clearly detected in spectral plots of the continuum-subtracted datasets. On the contrary, no formaldehyde absorption or emission lines were detected in the 6cm dataset. In this paper we discuss preliminary results for one of the two interacting galaxies, IC 694.

The radio continuum images show a 200 by 250 pc large, elongated structure, orientated at position angle (PA) $\sim 135°$. The overall spectral index of the source is flat between λ6 and λ21 cm. The highest resolution λ6cm image (Figure 2) reveals a 150 parsec long, brighter elongated ridge, surrounded by fainter, diffuse emission (>200pc). This bright ridge is seen to 'break up' in components, with brightness temperatures of the order of 10^5 K, the southwesternmost of which has the most inverted spectral index at $\alpha = -0.169$.

The structure of the source is not that of a typical bright AGN seen at similar resolution; there is no single, bright unresolved core component and the elongated ridge does not have the appearance of a core-jet structure. Instead, the morphology of IC 694 appears consistent with emission from a tilted disk (or torus) with a brighter inner region, similar to those found in several other ULIR galaxies (e.g. Mrk 231, Carilli et al 1998, Mrk 273, Carilli & Taylor 2000), which is thought to be synchrotron emission from electrons accelerated by radio supernovae remnants or hypernovae. Then, at higher resolutions the bright subcomponents may be found to be supernovae remnants.

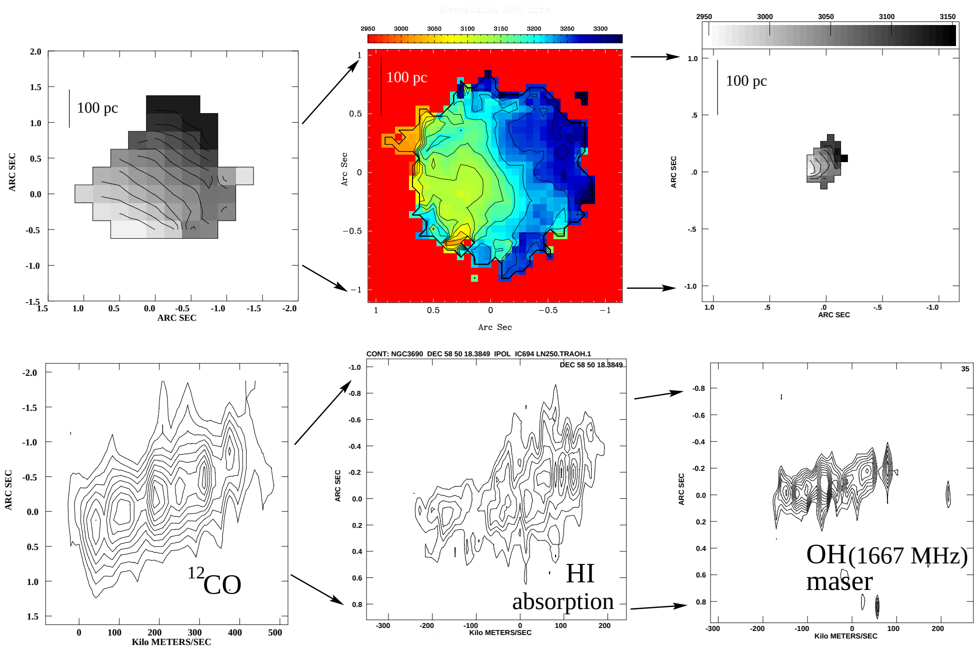


Figure 2: A comparative look of the velocity distribution and the position velocity diagrammes of the CO emission (left), the HI absorption (middle) and the OH megamaser (right) lines of IC 694.

HI absorption is detected against all emission regions of the Arp 299 system, similar to BH90's lower resolution VLA observations. The most pronounced absorption is against the nucleus of IC 694.

The intensity-weighted mean velocity field (Figure 2, middle panel), reveals a fairly regular looking spider diagram in the inner 240 pc (velocity gradient of 2094.4 km/s kpc^{-1}), implying that the HI is located in a rotating disk-like structure with inclination $\sim 60°$, elongated at 135°, along the major axis of the radio continuum, while the Position-Velocity diagramme shows several absorption components along the major axis of the continuum, indicating the clumpy nature of the rotating structure. The optical depth ranges between 0.1 to 0.5 for each clump. The total HI column density is $N_{HI} \sim 1.26 \times 10^{20} T_S$, implying a mass for the HI of $M_{HI} = 3.6 \times 10^6 M_\odot$ (for T_S=100 K), roughly 1% of the dynamical mass.

The turbulence of the HI gas is generally high — it often exceeds 100 km/s - and the highest turbulence does not coincide with the kinematical centre but occurs towards the southeastern part of the source, at the position of the most inverted spectrum continuum component.

OH megamaser emission is only observed in IC 694 in agreement with the VLA observations of BH90. The integrated OH maser spectrum shows both the 1667 MHz and the 1665 MHz transitions. Whereas the 1665 MHz OH line is almost resolved out, the 1667 MHz line emission arises in a 100 pc large rotating structure with a velocity gradient of 2750 km/s kpc^{-1}, orientated at PA=135°. The Position-Velocity diagramme (Fig 2. right panel) shows a clumpy nature for the rotating structure similar to that observed in the HI disk.

The left panel in Figure 2 compares the velocity field of the 200 parsec resolution CO observations of Aalto et al. (1999) and our HI and OH observations. The atomic and molecular gas in the nucleus of IC 694, is located in flattened rotating structures that have the same axis and similar velocity ranges. The CO emission and HI absorption seem to occupy the same space suggesting that the HI and molecular gas phases are mixed. It is possible that the HI is a photodissociation product of the molecular gas. The OH seems to be located further in, in the same

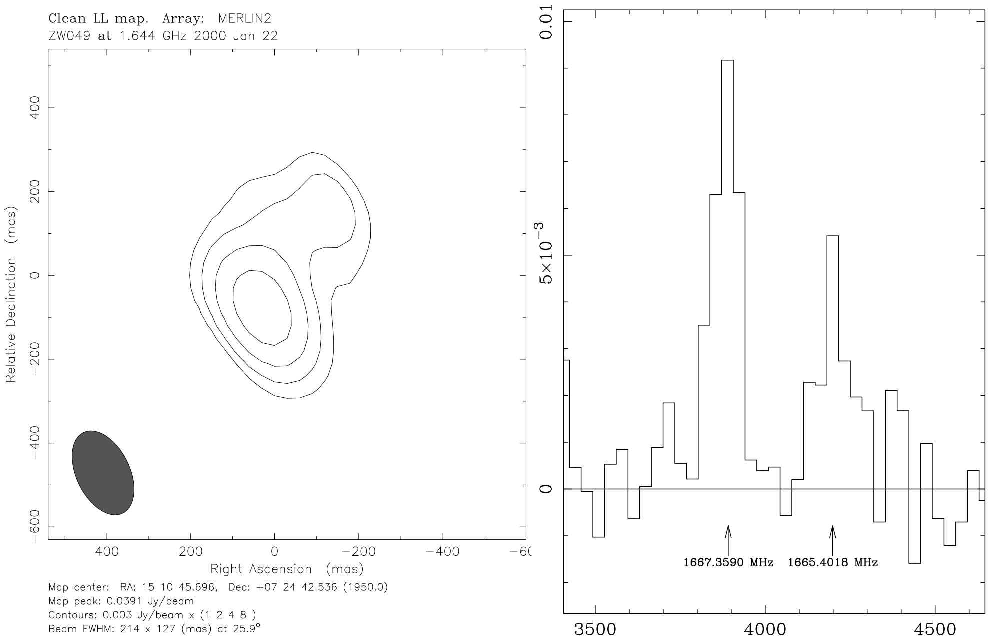


Figure 3a: The 18cm MERLIN continuum image of the megamaser galaxy Zw049.057.Uniform weighting has been used.The contour levels are 3 mJy/bm × 1,2,4,8,16,32,64. **Figure 3b:** The integrated OH megamaser spectrum of Zw049.057 observed with MERLIN.

rotating disk. *The molecular and atomic gas components may thus be mixed on a scale of 100-200 pc.* The turbulence of the gas is generally high. This is consistent with the notion of extremely high gas pressures in the centres of ULIR galaxies with steep potentials.

3 Zw049.057

The galaxy Zw 049.057 hosts one of the weakest OH megamasers (10.9 $L_\odot$ H_0=75, Baan el al 1987) and in addition shows relatively narrow (110 kms^{-1}) HI absorption with a peak optical depth of τ=0.37 (Martin *et al.* 1988).

The MERLIN 18cm continuum image presented in Figure 3 is the first high resolution image of the source and shows a bright central component with a weaker extension to the northwest. The MERLIN OH megamaser spectrum (Fig 3) shows clearly both the 1667 and the 1665 MHz line but recovers only ~60% of the total emission, similarly to all other megamasers that have been imaged at high resolution.

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