Outflows from nearby active galaxies

Ananda Hota[1,2], D.J. Saikia[2] and Judith A. Irwin[3]

[1] **Joint Astronomy Programme, Indian Institute of Science, Bangalore 560 012, India**

[2] **National Centre for Radio Astrophysics, TIFR, Ganeshkhind, Pune 411 007, India**

email : hota@ncra.tifr.res.in and djs@ncra.tifr.res.in

[3] **Department of Physics, Queen's University, Kingston, K7L 3N6, Canada**

email : irwin@astro.queensu.ca

Abstract

We present results of H I and radio-continuum observations with the GMRT and VLA of three galaxies with extra-planar emission. The radio-continuum observations have shown evidence of outflow of non-thermal plasma in NGC4438 and NGC6764, while in NGC1482, only the central starburst and disk emission are seen. In NGC1482 and NGC6764, the blue-shifted H I-absorption spectra show kinematic effects of the nuclear activity on the cool-gas. In NGC4438, a massive elongated structure in H I-emission and diffuse radio-emitting plasma are seen on the western side of the stellar disk. These features could be due to a combination of ram pressure stripping, tidal interactions and outflow from the central source. Our observations provide important information towards determining which of these processes plays a dominant role in producing the extended features.

1 INTRODUCTION

Outflows from galaxies could be due to an intense starburst in the circumnuclear region, an active galactic nucleus (AGN) or a combination of both these phenomena. Starburst-driven superwind outflows from galaxies carry away about a million $M_\odot$ of gas to the halo of the galaxy with typical velocities of $100-1500$ km s^{-1}, and also help enrich the intergalactic medium (IGM). A metal-enriched mass outflow rate of $1-100$ $M_\odot$ yr^{-1}, can supply a significant fraction of metals, mass and heat to the IGM or intracluster medium (ICM)[1]. Jet-driven outflows in galaxies with an AGN can also carry away metal-enriched gas, besides relativistic plasma and magnetic fields. In addition to these two processes, gas may also be removed from the disk of the galaxy by ram pressure of the ICM and tidal interactions with companion galaxies[2]. We are studying a few galaxies in radio continuum and H I with the Giant Metrewave Radio Telescope (GMRT) and the Very Large Array (VLA) to examine the extent and kinematical signatures of the outflow at radio frequencies, and to search for ways to distinguish between the different processes.

2 NGC 1482

NGC 1482, an SA0/a galaxy at a distance of 24.7 Mpc, is a remarkable superwind galaxy with an hourglass-shaped optical emission line outflow seen in Hα and N II with a velocity of $\sim$250 km s^{-1}. The energy in this outflow is at least 2×10^{53} ergs[3]. The ionization ratios of the gas in the superwind have been interpreted to be due to shock formation in the outflow. The soft X-ray image from the Chandra Observatory also exhibits bipolar emission along a similar axis to that of the optical hourglass-shaped structure[4].

We have studied this galaxy at radio continuum wavelengths ranging from 335 MHz to 14965 MHz as well as in H I[5]. The high-frequency, high-resolution radio images show a prominent peak with more extended emission around it from the circumnuclear starburst. The radio peak is co-incident with the IR peak but not with the optical which could possibly be due to extinction by the interstellar medium (ISM) of the galaxy. The radio peak appears to have a steep spectrum, and it is difficult to distinguish whether it is an AGN or non-thermal emission from a compact starburst region. Optical spectroscopic observations show no evidence of an AGN[6].

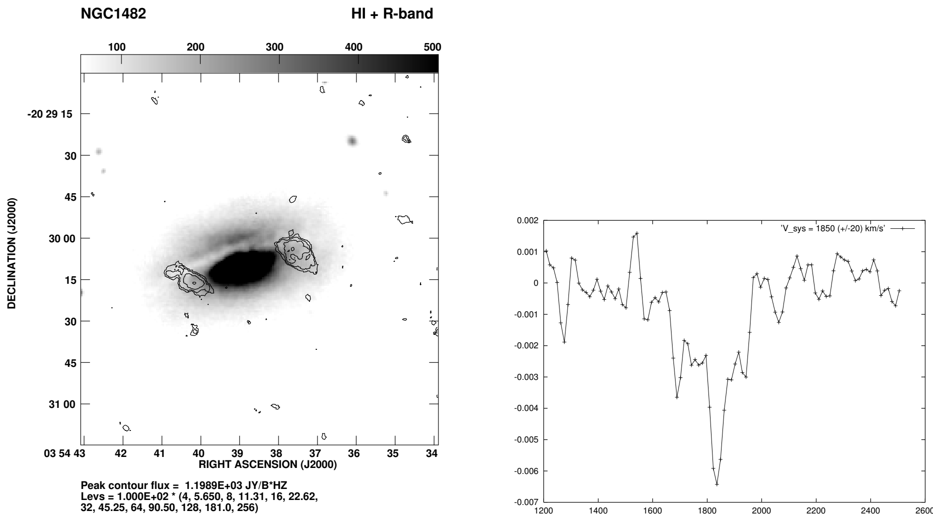

Figure 1: Left panel: The GMRT H I total-intensity contours superimposed on an optical R-band image. Right panel: The H I absorption spectrum towards the central radio source.

The low-frequency images trace the relatively smooth non-thermal emission due to relativistic particles generated largely in the starburst. There is no evidence of significant non-thermal emission along the optical hourglass-shaped or X-ray outflows. From radio observations we have estimated the supernova rate and find it to be similar to other well-known starburst galaxies. Although the supernovae have enough energy to drive the Hα outflow, an estimate of the total energy in all the different components of the outflow is required before determining whether the energy in the supernovae is adequate to drive the superwind.

The H I gas is expected to be kinematically affected by the circumnuclear starburst. Our observations show that H I is depleted in the central region, possibly due to the nuclear starburst, and there exists two emission blobs located on opposite sides of the centre of the galaxy, roughly perpendicular to the outflow axis (Fig. 1). These blobs have a mass of $\sim$15 and 13.5$\times10^7$ M$_\odot$ and are located at $\sim$2 kpc from the centre. The western blob has a maximum red shift of $\sim$190 km s^{-1} relative to the systemic velocity of 1850 km s^{-1}, while the maximum blue shift for the eastern one is 220 km s^{-1}.

In addition, H I is also seen in absorption towards the central radio source. The H I absorption profile shows multiple components with the deepest absorption feature at $\sim$1840 km s^{-1}, consistent with the systemic velocity of the galaxy (Fig. 1). The H I mass estimated from the absorption profile is 6.3$\times10^6$ M$_\odot$. Relative to the systemic velocity, there is a suggestion of a mild asymmetry in the absorption profile which could be due to H I clouds hydrodynamically affected by the superwind, in addition to the effects of galactic rotation[5].

3 NGC 4438

The galaxy, NGC4438 (VV188, Arp 120), which is located only about 1° ($\sim$300 kpc for a distance of 16 Mpc) from the densest part of the Virgo cluster, is highly inclined, and has a very disturbed disk with stellar debris scattered to the west of the disk. Some have suggested that this might be due to interactions with the ICM of the Virgo cluster, since the relative velocity of NGC4438 is about 1000 km s^{-1}. A tidal encounter with the SBO galaxy NGC4435 at a projected distance of $\sim$4.3 arcmin ($\sim$20 kpc) is also likely to affect NGC4438. Kenney et al.[7] have suggested that most of the features of the disturbed ISM are likely to be due to a high-velocity ISM-ISM collision between NGC4438 and 4435. Numerical simulations suggest that the nuclei of these two galaxies have passed within 5 kpc of each other in the last 10^8 yr [8]. Keel & Wehrle[9] have proposed that matter and energy ejected from an active nucleus may be responsible for the disturbed ISM. They point out that the region of emission 70 arcsec west of the nucleus is in a similar position angle to the bubbles of radio continuum emission near the nucleus imaged by Hummel & Saikia[10].

Here we present the results of GMRT 1.4-GHz and H I observations. The continuum image at 1.4 GHz clearly shows the diffuse region of emission to the west of the disk (Fig. 2), while the H I total-intensity image shows an elongated structure again to the west of the galaxy and more diffuse emission towards the south-western side (Fig. 2). The elongated

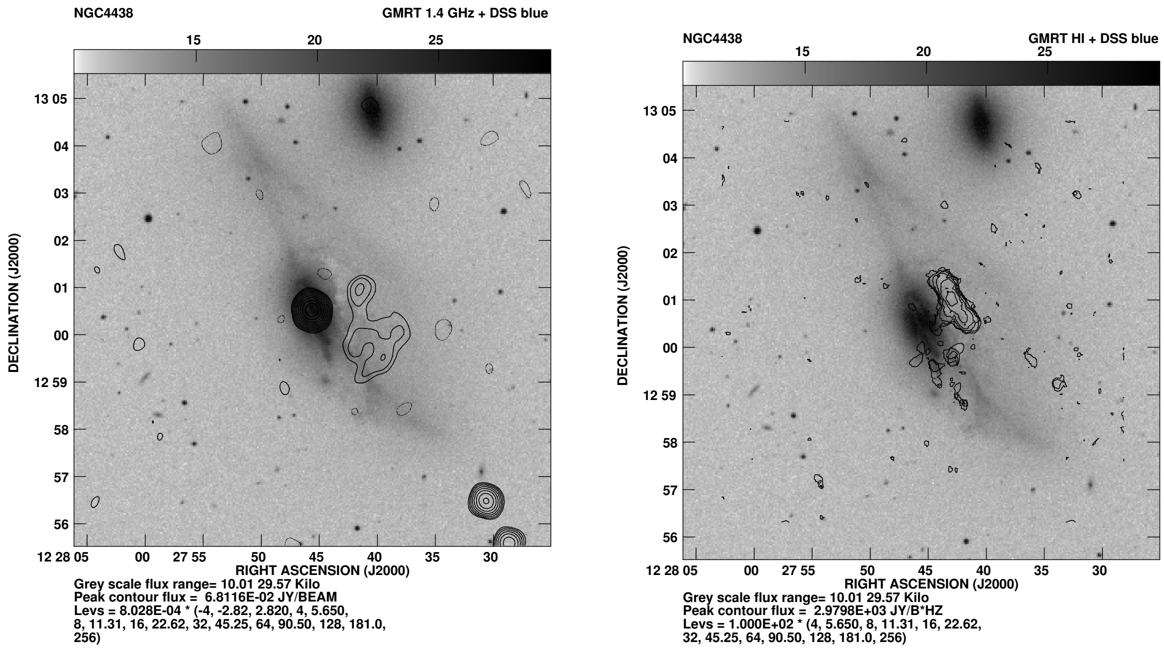

Figure 2: The GMRT 1.4−GHz radio-continuum contours (left panel) and the H I total-intensity contours (right panel) superimposed on the DSS blue-band image.

structure extends for $\sim$6 kpc and has a mass of $2\times10^7 M_\odot$. Most of the H I gas appears red-shifted with respect to the systemic velocity of the galaxy[13]. The elongated H I feature is close to the position of the extra-planar CO emission, which has been interpreted to be due to a combination of tidal interactions and ram presssure stripping[8]. A similar interpretation seems likely for the H I feature[13]. The diffuse extended continuum emission on the western side could also be stripped by ram pressure of the ICM.

The nuclear region (central 1kpc) of this galaxy show two lobes of emission in radio-continuum, Hα and X-rays to the east and west of the nucleus identified from optical and infrared observations[10, 11, 12]. The western lobe is brighter and closer to the nucleus than the eastern one. This could be due to the higher density ISM on the western side[11].

4 NGC 6764

NGC 6764 is a barred galaxy (SBb) at a distance of $\sim$34 Mpc and has a mild AGN as well as a young starburst[15]. We have studied this galaxy at various radio frequencies ranging from 15 GHz down to 325 MHz and also in H I[14]. The high-frequency, high-resolution VLA images show the nuclear peak and poorly collimated structures approximately along the major axis of the galaxy. These nuclear structures appear to bend towards the north and south, and connect to the large-scale bubbles of radio emission seen with coarser resolution (Fig. 3).

A comparison of the radio images with an Hα one show some similarities [18, 14]. The western side of the nuclear region is brighter in Hα as well as at radio frequencies. In addition, some of the filamentary structures seen in Hα appear co-incident with radio features seen in the lower-resolution images of the bubbles (Fig. 3). The similarities are suggestive of an interaction between the expanding radio bubble and the ISM. A plume of CO emission is also seen at the north-eastern side of the radio bubble where a prominent Hα filament is seen[16]. A CO J(2−1)/J(1−0) line ratio map with a resolution of $\sim$20 arcsec show higher ($\sim$1.0) values along the axis of the radio bubbles, whereas it falls down to $\sim$0.5 perpendicular to it[17]. The ratio is much higher ($\sim$2.0) for a component of CO gas blue-shifted by $\sim$140 km/s[16]. We also detect a weak H I-absorption feature at the same blue-shifted velocity which is possibly due to the outflowing ISM driven by the nuclear or circumnuclear activity[14].

We have presented new, sensitive radio-continuum and H I observations of three galaxies illustrating the diverse processes by which gas may be either removed from the disk or kinematically affected by the nuclear activity.

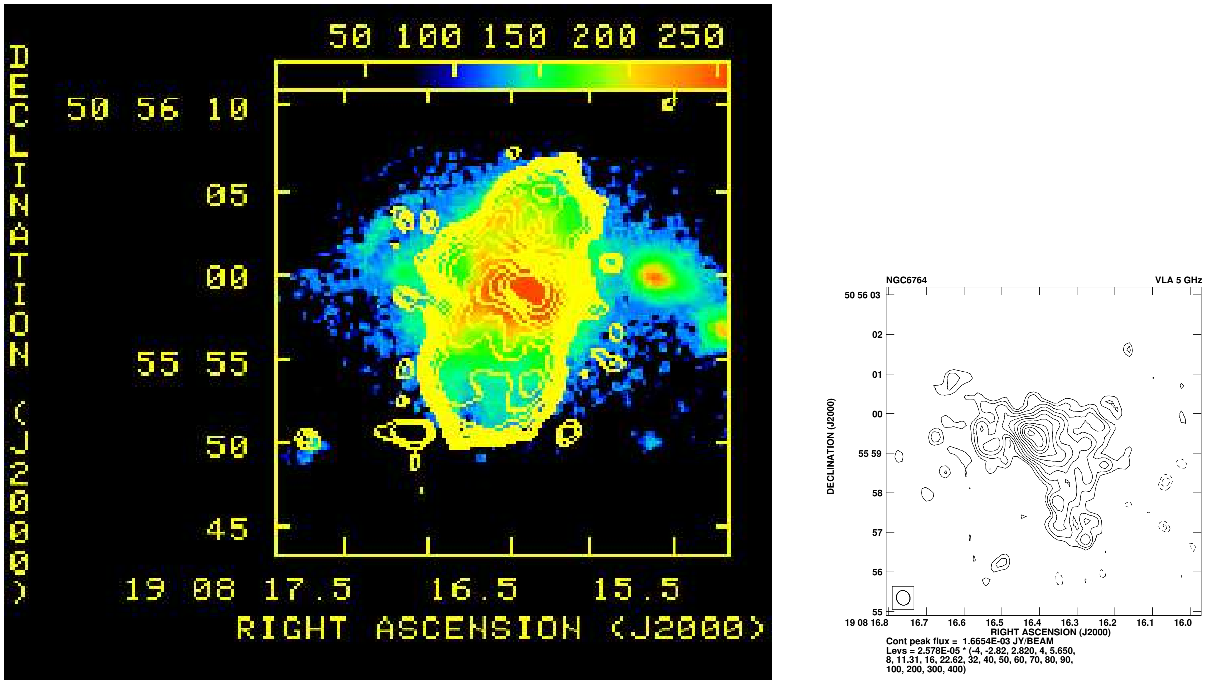

Figure 3: Left panel: The VLA 1.4−GHz radio continuum contours of the bubbles have been superimposed on the Hα-image of the central region. Right panel: The VLA 5-GHz radio continuum contours of the nuclear region.

References

[1] T.M. Heckman, L. Armus, G.K. Miley, "On the nature and implications of starburst-driven galactic superwinds," *Astrophys. J. Suppl.*, vol. 74, pp. 833−868, 1990.

[2] J.E. Gunn, J.R. Gott III, " On the Infall of Matter Into Clusters of Galaxies and Some Effects on Their Evolution," *Astrophys. J.*, vol. 176, pp. 1−19, 1972

[3] S. Veilleux, D.S. Rupke, "Identification of Galactic Wind Candidates Using Excitation Maps: Tunable-Filter Discovery of a Shock-excited Wind in the Galaxy NGC 1482," *Astrophys. J.*, vol. 565, pp. 63−66L, 2002.

[4] D.K. Strickland, T.M. Heckman, E.J.N. Colbert, C.G. Hoopes, K.A. Weaver, "A High Spatial Resolution X-Ray and Halpha Study of Hot Gas in the Halos of Star-forming Disk Galaxies. I. Spatial and Spectral Properties of the Diffuse X-Ray Emission," *Astrophys. J. Suppl.*, vol. 151, pp. 193−236, 2004.

[5] A. Hota, D.J. Saikia, "A radio study of the superwind galaxy NGC 1482," *Mon. Not. Roy. Ast. Soc.*, vol. 356, pp. 998−1008, 2005.

[6] L.J. Kewley, C.A. Heisler, M.A. Dopita, R. Sutherland, R.P. Norris, J. Reynolds, S. Lumsden ,"Compact Radio Emission from Warm Infrared Galaxies," *Astrophys. J.*, vol. 530, pp. 704−718, 2000.

[7] J.D.P. Kenney, V.C. Rubin, P. Planesas, J.S. Young, "Gas filaments in the collisional debris of NGC 4438," *Astrophys. J.*, vol. 438, pp. 135−154, 1995.

[8] B. Vollmer, J. Braine, F. Combes, Y. Sofue, "New CO observations and simulations of the NGC 4438/NGC 4435 system," *astro-ph/0507252*, 2005

[9] W.C. Keel, A.E. Wehrle, "The dynamic interstellar medium in NGC 4438," *Astron. J.*, vol. 106, pp. 236−244, 1993

[10] E. Hummel, D.J. Saikia, "The anomalous radio features in NGC 4388 and NGC 4438," *Astron. & Astrophys.*, vol. 249, pp. 43−56, 1991.

[11] J.D.P. Kenney, E.E. Yale, "Hubble Space Telescope Imaging of Bipolar Nuclear Shells in the Disturbed Virgo Cluster Galaxy NGC 4438," *Astrophys. J.*, vol. 567, pp. 865−874, 2002

[12] M.E. Machacek, C. Jones, W.R. Forman,"Chandra Observations of NGC 4438: An Environmentally Damaged Galaxy in the Virgo Cluster," *Astrophys. J.*, vol. 610, pp. 183−200, 2004.

[13] A. Hota, D.J. Saikia, J.A. Irwin, "Extra-planar relativistic plasma and H I in NGC4438," 2005, (unpublished).

[14] A. Hota, D.J. Saikia, "A radio study of NGC 6764," 2005, (unpublished).

[15] E. Schinnerer, A. Eckart, T. Boller, "The Young Starburst Nucleus of the Wolf-Rayet LINER Galaxy NGC 6764," *Astrophys. J.*, vol. 545, pp. 205−215, 2000.

[16] S. Leon, A. Eckart, S. Laine, E. Schinnerer, "Molecular outflow in the composite galaxy NGC6764," *astro-ph/0211280*, 2002.

[17] A. Eckart, M. Cameron, J.M. Jackson, R. Genzel, A.I. Harris, W. Wild, H. Zinnecker, "The molecular interstellar medium and the near-infrared continuum of the barred liner NGC 6764" *Astrophys. J.*, vol. 372, pp. 67−80, 1991.

[18] A. Zurita, M. Rozas, J.E. Beckman, "The origin of the ionization of the diffuse interstellar medium in spiral galaxies. I. Photometric measurements," *Astron. & Astrophys.*, vol. 363, pp. 9−28, 2000.