The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
Proceedings IAU Symposium No. 222, 2004
T. Storchi-Bergmann, L. C. Ho & H. R. Schmitt, eds.

DOI: 10.1017/S1743921304002820

The interplay between radio jets and atomic hydrogen gas seen in 21cm H I absorption

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Abstract. Atomic gas in the central kiloparsec of young radio galaxies is quite prevalent, as revealed by 21cm H I absorption line observations using the WSRT. The column depths are anti-correlated with the linear sizes of the radio sources, but VLBI reveals that sometimes the neutral hydrogen is situated in a disk or torus on parsec or sub-kiloparsec scales around the central engine, while in other cases the H I is probably associated with star-forming regions along the jets. NGC 1052 is a nearby example, in which, next to some isolated clouds along the jets, there appears to be an atomic and molecular torus with a radius of a few parsecs, but with a central hole of about 0.5 pc, in which the gas is mostly ionised.

1. Introduction

For Seyfert galaxies, there is an increasingly large body of work, to which many of the papers presented at this conference bear witness, probing the interplay between nuclear starbursts and infalling gas. This gas eventually powers the central engine, in turn is influenced by its radiation, and also interacts with the jets. For powerful radio galaxies, however, much less is known, perhaps because these tend to be at larger redshifts, and thus less amenable to detailed study.

This paper deals with Compact Steep Spectrum (CSS) sources and Compact Symmetric Objects (CSO), in which the radio emission is confined to galactic ($<$ 15 kpc) or sub-galactic ($<$ 1 kpc) scales, respectively (e.g. Wilkinson *et al.* 1994; Fanti *et al.* 1995). Many of these small radio sources have a Gigahertz Peaked Spectrum (GPS, e.g. O'Dea 1998), due to either synchrotron self-absorption, free-free absorption by ionised gas surrounding the radio source, or a combination of both mechanisms (e.g. Bicknell *et al.* 2003; Snellen *et al.* 2003). Most of these sources are likely to be compact because they are young, and for a number of CSOs, kinematic ages have now been derived, which range from as low as a few 100 years up to 3000 years (e.g. Owsianik, Conway & Polatidis 1998; Polatidis & Conway 2003). The temporal evolution of the luminosity and linear size of the radio structure is thought to be influenced by interaction and ram-pressure confinement by the galactic medium, of which the density quite plausibly drops with distance from the centre (e.g. Snellen *et al.* 2003). While the surrounding medium is unlikely to be dense enough to "frustrate" the radio sources in their growth permanently, interactions in the narrow line region of the inner galaxy could well be dynamically important.

Thus, in order to understand processes of active galaxy formation, and, for example, feedback of the central activity on star formation, it is important to investigate the properties of the circumnuclear gas and the wider inner galactic medium. The upgraded Westerbork Synthesis Radio Telescope (WSRT) now allows high resolution broad-band 21 cm H I absorption line studies of the atomic gas in radio galaxies at arbitrary redshifts out to $z \sim 1$, with a column depth sensitivity dependent only on the flux density of the radio emission behind the gas being probed. Follow-up imaging with VLBI offers the potential to study these regions at parsec-scale or even higher resolution.

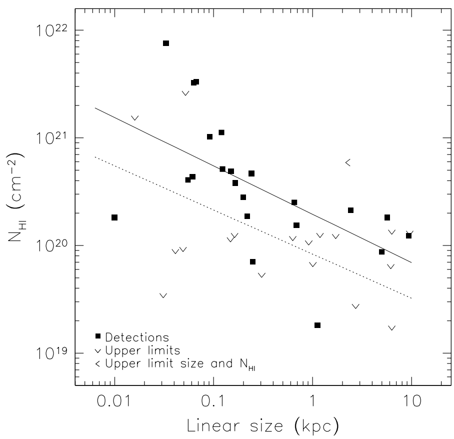


Figure 1. Distribution of atomic hydrogen column depths in compact radio galaxies, from Pihlström *et al.* (2003). The fitted anti-correlations with linear size are shown as thin and thick lines when including or excluding upper limits, respectively.

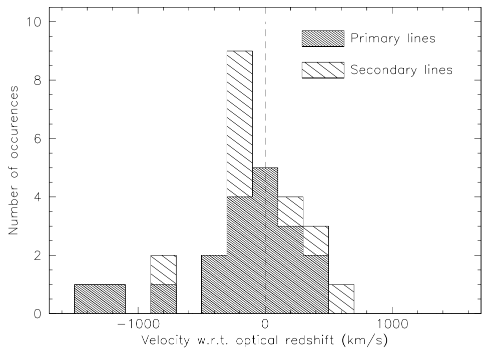


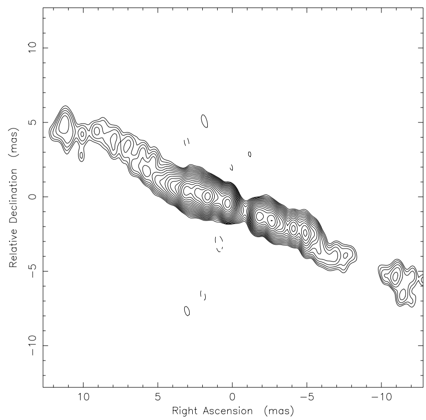
Figure 2. Distribution of atomic hydrogen line velocities in compact radio galaxies, from Pihlström *et al.* (2003). Positive velocities are infalling to the host galaxy.

2. H I absorption line survey at the WSRT

Vermeulen *et al.* (2003a) report on the largest survey to date of H I absorption in compact radio galaxies. Atomic gas was detected in 33% (19/57) of the sources. Pihlström, Conway, & Vermeulen (2003), taking all of the well-defined CSO and CSS sources from this survey plus several from other papers, have shown an anti-correlation between the absorbing column of atomic hydrogen and the linear size of the radio source, roughly as $N(\mathrm{H}) \simeq 10^{20.2} L^{-0.33}$ cm^{-2}, where L is in kiloparsec; this is illustrated in figure 1. However, the relationship is statistical only, with a broad scatter for individual galaxies. There is no evidence that the line widths are correlated with linear size. The FWHM are typically around 100 km s^{-1}, but they can be as large as 400 km s^{-1}. Some line profiles are highly non-Gaussian, and there can be narrow ($\sim$10 km s^{-1}) sub-components.

An anti-correlation between atomic gas column density and linear size fits well with the ideas about compact radio galaxies enveloped in an accreting medium, with density increasing towards the central black hole. However, the kinematic evidence from the H I line profiles shows that the medium is often quite complex. Furthermore, Pihlström *et al.* (2003) have shown that, next to models with a spherical gas distribution, models with the neutral hydrogen situated in a disk or torus around the central engine are also viable. Earlier, Van Gorkom *et al.* (1989) found that all 8 of the nearby galaxies in which H I absorption was then detected, had the gas infalling with respect to the host galaxy, and typically not faster than 200 km s^{-1}. However, in the new Pihlström *et al.* (2003) sample, there are as many infalling as outflowing velocities, and they range typically to 500 km s^{-1}, sometimes even in excess of 1000 km s^{-1}, as shown in figure 2.

While these compact radio galaxies are unresolved using the WSRT, with VLBI imaging the spatial distribution and kinematics of the H I absorbing gas can be studied, to probe whether and how this gas might be accreting onto the central engine, and how the interplay between the radio source and the surrounding medium operates.



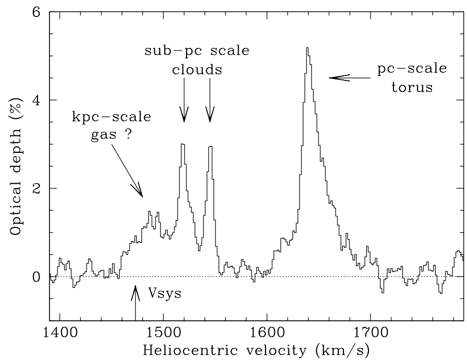


Figure 3. 15 GHz VLBA image from July 1997, showing two-sided jets in NGC 1052 (Vermeulen *et al.* 2003b). The resolution of 0.5×1 mas corresponds to 0.05×0.1 pc. The flux density contours increase in factors of $\sqrt{2}$, starting at 0.7 mJy/beam; the peak flux density is 425 mJy/beam.

Figure 4. H I absorption line spectrum of NGC 1052 in July 1998 obtained with VLBI by Vermeulen *et al.* (2003b). The location of the absorbers is indicated.

3. The shroud around the twin jets of NGC 1052

The LINER galaxy NGC 1052 is at a distance of only 22 Mpc, and has a bright radio source (1–2 Jy with a fairly flat spectrum). Thus, VLBI offers the opportunity for in-depth studies of its surrounding medium at linear resolutions better than 0.1 pc. The total extent of the double-lobed radio source is 3 kpc, which resembles a CSS source, but VLBI imaging (Vermeulen *et al.* 2003b, see figure 3) has shown that it is dominated by a central twin-jet structure spanning a few parsecs, in which features on both sides move away from the centre with an apparent velocity near $0.26c$.

Detailed study of the jet component flux densities, at a broad range of frequencies, and as a function of distance, shows variable and sometimes highly inverted radio spectra, strongly suggesting free-free absorption. There is evidently a clumpy, geometrically thick, ionised torus, with central density $n_e \sim 10^5$ cm^{-3}, through which, given the relative absorption depths, the eastern jet is approaching and the western jet is receding from us.

Vermeulen *et al.* (2003b) have also determined the locations at which H I absorption occurs along the radio jets of NGC 1052; this is shown in figure 4. A broad ($\sim$100 km s^{-1}) absorption feature near the systemic velocity of NGC 1052 is detectable against the entire parsec-scale radio structure, and could well be due to atomic hydrogen on galactic scales. Several narrower ($\sim$10 km s^{-1}) line features arise in clouds each spanning a few tenths of a parsec along the eastern jet. Most intriguing is a broad ($\sim$20 km s^{-1}) line redshifted by $\sim$150 km s^{-1} w.r.t. the stellar and (optical emission line) gas systemic velocity. The peak observed column depth is $N(\mathrm{H}) = 4 \times 10^{20}(T_{\mathrm{spin}}/100)$ cm^{-2}. The absorber spans at least 2 pc and can be seen towards both jets, possibly with a velocity gradient of $\sim$10 km s^{-1} per parsec, but it is absent in the central 0.5 pc. Thus it has is the geometry of a torus, and furthermore, the size of the central hole in the neutral gas matches well to the extent of the ionised gas seen by its free-free absorption ! It is of course plausible that the

https://doi.org/10.1017/S1743921304002820 Published online by Cambridge University Press

neutral gas is more ionised by the central engine in the innermost region than at larger distances. However, there is no satisfactory explanation for the $\sim$150 km s^{-1} velocity offset of the entire toroidal structure from the systemic velocity of the host galaxy. All four 18cm OH lines have been detected by Vermeulen *et al.* (2003b) using the WSRT, and their kinematics suggest that there is molecular gas in the same toroidal structure as the atomic and ionised gas; this will be verified with VLBI.

4. Generalisation and speculation

Several other nearby radio galaxies (see e.g. van Langevelde *et al.* 2000, and Peck & Taylor 2001) also show a circumnuclear, possibly toroidal or disk-like distribution of H I absorbing gas. However, in yet other systems, H I absorption occurs at off-nuclear jet-cloud interaction regions, for example as discussed at this conference by Morganti.

Motivated largely by the wish to allow H I VLBI imaging of objects at larger redshifts, so-called UHF or 30cm receivers were developed at a number of radio telescopes. VLBI data are now available for 6 of the 7 CSOs from the Pearson-Readhead survey. In 0108+388 and 2352+495 there is probably an H I torus, but in 0404+768 and 1358+624 the absorbing H I gas is likely to be off-nuclear, and while in 1031+557 and 2021+614 no H I absorption is seen, the radio cores are very faint, suggesting that the circumnuclear gas in these objects may be extensively ionised, leading to free-free absorption.

Tori surrounding the central engines are likely to be very common indeed, based on many lines of evidence. They may well usually contain atomic gas, at distances dependent on the power of the central ionising radiation. This gas will be detectable through H I absorption when there is a sufficiently bright radio core, or a radio jet or lobe appropriately positioned in the background. In addition, the jets and lobes can also back-light off-nuclear clouds, either by chance superposition, or because they are co-located and interacting. NGC 1052 shows that circumnuclear and off-nuclear H I can sometimes be seen in the same galaxy. With better statistics one could learn more about the covering factor of such clouds and the rate of occurrence of interactions.

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