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Neutral hydrogen absorption at milliarcsecond resolutions: The radio galaxy 3C 293

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Abstract. We present new milliarcsecond resolution observations of the HI absorption against the kiloparsec scale inner jet of the radio galaxy 3C 293. Using a combination of observations obtained with global VLBI, MERLIN and the VLA we have imaged the strong and extensive neutral hydrogen absorption against the radio core and jet of this source across a wide range of angular scales.
In this proceedings we will present these new combined milliarcsecond scale VLBI results alongside our previous lower resolution MERLIN studies of the HI absorption in this source. This study will allow us to investigate the distribution and dynamics of the HI absorption in the centre of this source from scales of arcseconds to a few milliarcsecond.

1. Introduction

The study of the physical properties of the dust and gas at the centres of active galaxies is of great observational interest. Its significance is inextricably linked to the activity observed in these sources since it is the gas and the dust that is ultimately the fuel for the activity. The dust distribution can be studied using optical and infrared imaging. The atomic gas can be studied using the 21-cm line of neutral hydrogen (HI). As well as giving clues to formation of active galaxies, dust and gas may obscure the direct view to the active galactic nuclei (AGN) and thus affect our ability to view the central optical continuum and broad-emission-line region.

With present day instruments sub-arcsecond optical observations of the ionised gas and radio observations of the synchrotron emission are relatively routine. There are relatively few methods by which the abundances and kinematics of the components within neutral ISM can be studied in galaxies with high angular resolution. Components, such as dust, preclude optical observations of the hearts of these sources and the present array of mm-wavelength instruments do not currently provide the angular resolution to study molecular gas at great detail. Unfortunately atomic hydrogen emission can only be observed by integrating over large areas - typically tens of arcsec - because of its low ($\sim$100 K) brightness temperature and the current sensitivities of decimeter arrays. However, provided the neutral gas is in front of a strong source of radio continuum, absorption studies can be used to study the atomic hydrogen on milliarcsecond scales. Atomic hydrogen absorption observations allow the derivation of parameters such as the transverse velocity gradients and structure of the neutral gas can then contribute to an understanding of the dynamics of the nuclear regions of active galaxies.

The radio galaxy 3C 293 is a nearby (D=180 Mpc) moderately large two-sided Fanaroff-Riley type-II radio source with a disturbed optical morphology and an unusually bright steep-spectrum extended core component (Akujor et al 1996).

The interstellar medium (ISM) of 3C 293 is particularly rich. Strong detections of molecular gas, for example CO 1$\rightarrow$ 0 observed in both emission and absorption by Evans et al (1999) and extensive deep and extremely broad HI absorption detected against the kiloparsec scale inner jet and core components (Haschick & Baan 1985; Beswick, Pedlar & Holloway 2002; Morganti et al 2003). In this proceedings we will present milliarcsecond observations using global VLBI, combined with MERLIN and VLA, data to trace this deep absorption against the inner jet of 3C 293.

2. Observations & Data Reduction

3C 293 was observed independently using the UK's Multi-Element Radio Linked Interferometric Array (MERLIN) on April 8th 1998, a Global VLBI on November 18th 1999 and using the VLA, in it's A-configurationand including the VLBA antenna at Pie Town on December 15th 2000. All of these observations were made at 1359 MHz, the frequency of the redshifted 21 cm line HI at 3C 293.

Standard phase and amplitude calibration were applied to each of these three data sets individually, using OQ208 as a phase calibration source in all cases (as described in Beswick et al. 2002, 2004). The global VLBI data and VLA+PT data were averaged in frequency to correspond with the lower velocity resolution MERLIN data, and the central frequencies were shifted slightly so that the frequency range and channel numbers in all data-sets matched exactly. The data-sets were then concatenated by combining the VLA+PT and MERLIN data, and then the VLBI data, with iterations of self-calibration at each stage. The relative weights for the data from each array were also checked during the process. The combined data were subsequently Fourier transformed and deconvolved using a cir-

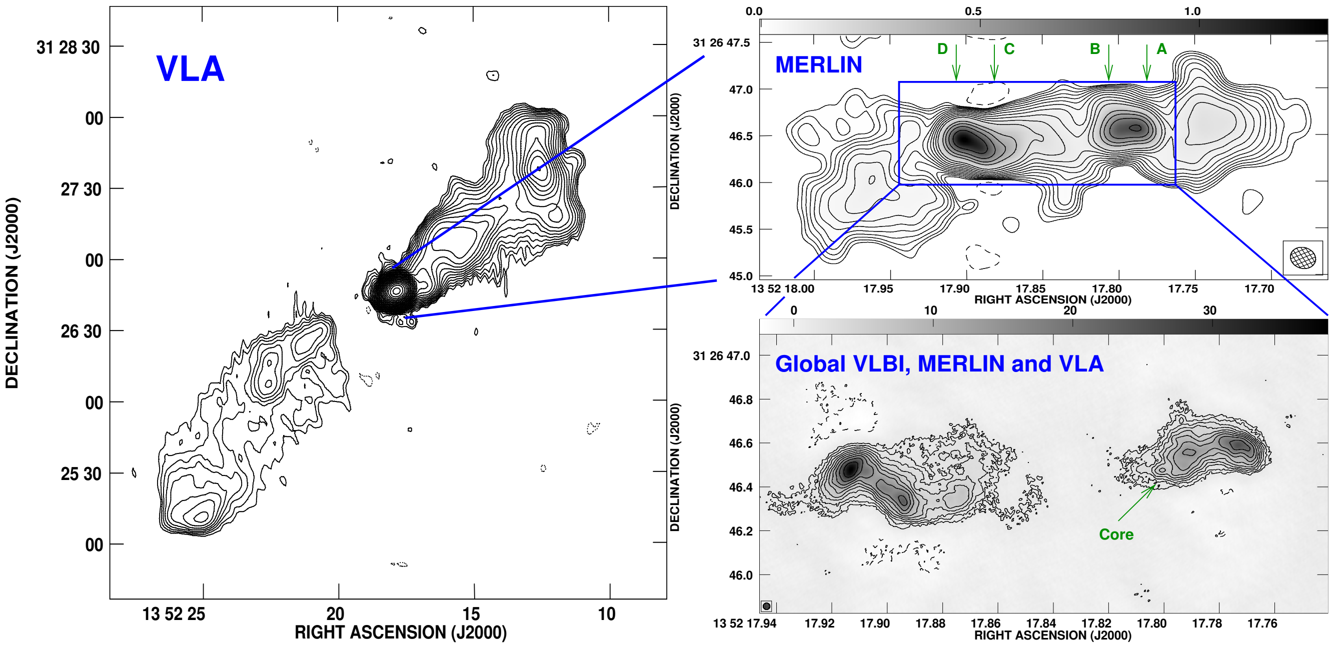

Fig. 1. From kpc to pc: the multi-scale sub-arcsecond 1.359 GHz radio continuum structure of the inner jet in 3C 293 as seen by the VLA, MERLIN and VLBI. The right-hand upper panel shows a MERLIN image with a synthesised beam of 0.″23×0.″20. This image is contoured at $\sqrt{2}$ multiples of 5mJy beam^{-1}. The right-hand lower panel shows the radio structure with a 30 mas angular resolution, derived from the combination of VLA, including Pie Town, MERLIN and Global VLBI observations. This image is contoured at multiples of $\sqrt{2}$ times 1.3 mJy beam^{-1}. Whereas the left-hand image shows the large scale radio structure of 3C 293 as observed with the VLA.

cular 30 mas restoring beam to form a 2048×2048×23 spectral line cube to which standard spectral line routines within AIPS were applied.

3. Results & Discussion

3.1. The radio continuum jet structure

In Fig. 1 the radio structure of the jets of 3C 293 are shown on scales ranging from several tens of kiloparsec to a few parsces (1 arcsec= 815 pc). As can be seen on the MERLIN and VLBI scales the inner radio jet in 3C 293 follows an almost east-west orientation. The orientation of these inner hotspots and jet are misaligned by ∼ 45 deg to the large-scale FR-II radio lobes (Fig. 1 left hand panel; Bridle et al 1981; Beswick et al 2004). In the 0.″2 angular resolution MERLIN 1.3 GHz observations, the inner jet of 3C 293 shows at least four distinct radio components (labelled A, B, C & D in Fig. 1a) with two more diffuse lobe-like components extending on either side of the central region. At this resolution and frequency it is unclear which radio continuum component is coincident with the AGN. However, due 3C 293's steep spectrum $\alpha \approx -1$ ($S_\nu \propto \nu^{-\alpha}$) (Akujor et al 1996), the position of the core becomes apparent at higher frequencies.

On the largest observed scales (Fig. 1) the ∼ 10 kiloparsec scale jet has a P.A.∼ 45°. This jet trajectory is significantly discordant with that of the inner jet structure implies a large position angle change of the jet emission during the lifetime of the radio source. This position angle change is indicative of the radio emission having undergone multiple (at least two) phases of jet emission, implying that the inner radio emission observed at sub-arcsecond angular resolutions is a younger outburst. In this scenario the large scale jet emission has arissen from an outburst ∼ 10^5 years old.

3.2. The sub-kiloparsec scale absorption structure

In earlier studies of the HI absorption against 3C 293 using WSRT (Shostak et al 1983), the VLA (Haschick & Baan 1985) and MERLIN (Beswick et al 2002), deep, multi-component HI absorption was detected against inner jet region. More recent high sensitivity, broad bandwidth observations using WSRT by Morganti et al (2003) have also shown that this nuclear HI absorption possess an extremely broad blueshifted wing of ∼1000 km s^{-1}. In this study (see Beswick et al 2004) we investigate further the deep and 'relatively' narrow HI absorption against the inner jet with milliarcsecond angular resolution.

Beswick et al (2002) imaged the HI absorption against the inner jet of 3C 293 (see Fig. 1 top right) at ∼0.″2 with MERLIN. At these angular resolutions it possible to separate two absorbing components. Against the eastern half of the inner jet structure the absorption line-widths are ∼40 km s^{-1} compared to the considerably broader line structure observed against the western portion of the source. Consequently in the following to sections we will discuss each of these spatially resolved components separately.

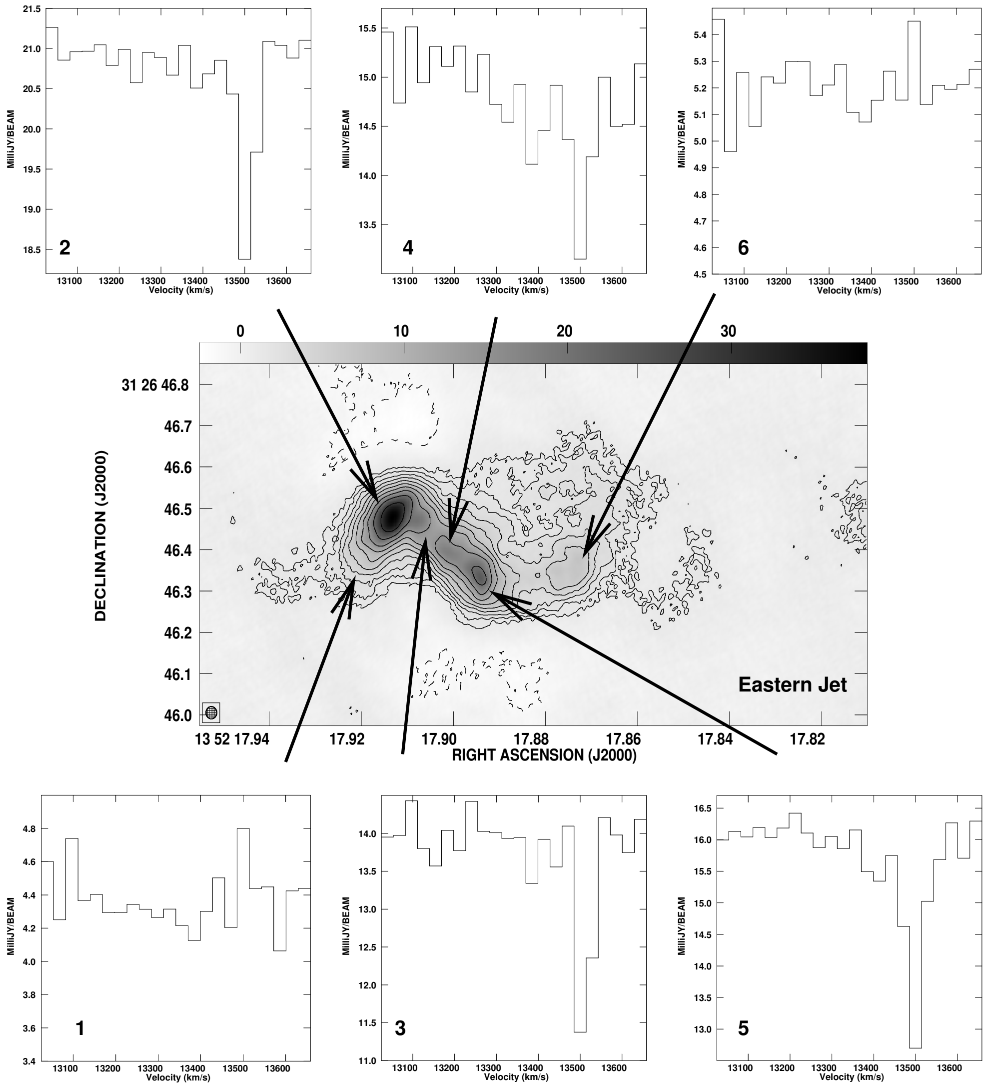

Fig. 2. A montage of the eastern half of the inner radio jet along with seletced Hɪ absorption spectra.

3.2.1. Against the eastern inner jet: Narrow Hɪ absorption

As can be seen in Fig. 2 the absorption against the eastern jet components has narrow line-widths (~40 km s^{-1}) and is centred approximately on the rest velocity of 3C 293 (~13500 km s^{-1}). In general this narrow absorption is often attributed to more ambient, less disturbed foreground gas which is lying at some distance from the centre of a galaxy. In the case of 3C 293 this seems the most likely explanation for this narrow component. However with these new high resolution observations its is clear that this gas is not a homogeneous screen but shows distinct spatial correlation with the positions of a cross nuclear dust lane seen in *HST* observations (Beswick et al 2002, 2004). The correlation of the lines of sight of these two components (Hɪ and dust) suggests that both are probably physically associated. In addition these new high resolution data, resolve a shallow velocity gradient of ~46 km s^{-1} arcsec^{-1} along a P.A.~ 60 → 65°. This is consistent with a velocity gradient of ionised gas traced out to a radius of ~10″(~8kpc) using long-slit spectroscopy (van Breugel et al. 1984). Consequently it can be reasonable concluded that the dust, narrow Hɪ component and the ionised gas are associated, situated at similar radii away from the centre of the galaxy and are most likely undergoing galactic rotation.

3.2.2. Against the western inner jet and core: Broad Hɪ absorption

Against the western portion of the inner radio jet and the region associated with the core broad, multi-component Hɪ absorption is detected (see Fig. 3). In the close vicinity of the core and western jet region the absorption predominately displays two velocity components. Although, especially in these VLBI data, much of the illuminating background radio continuum is resolved away, this complex absorption does show some velocity structure on linear scales ranging from ~0.5 kpc to ~50 pc. These absorbing structures can be interpreted in two ways either as, consistent with two unrelated Hɪ gas systems along the line of sight to the core, or with a steep velocity (~410 km s^{-1} ≈0.34 km s^{-1} pc^{-1}) centred upon the core. If the latter is assumed to be correct then the mass enclosed by this

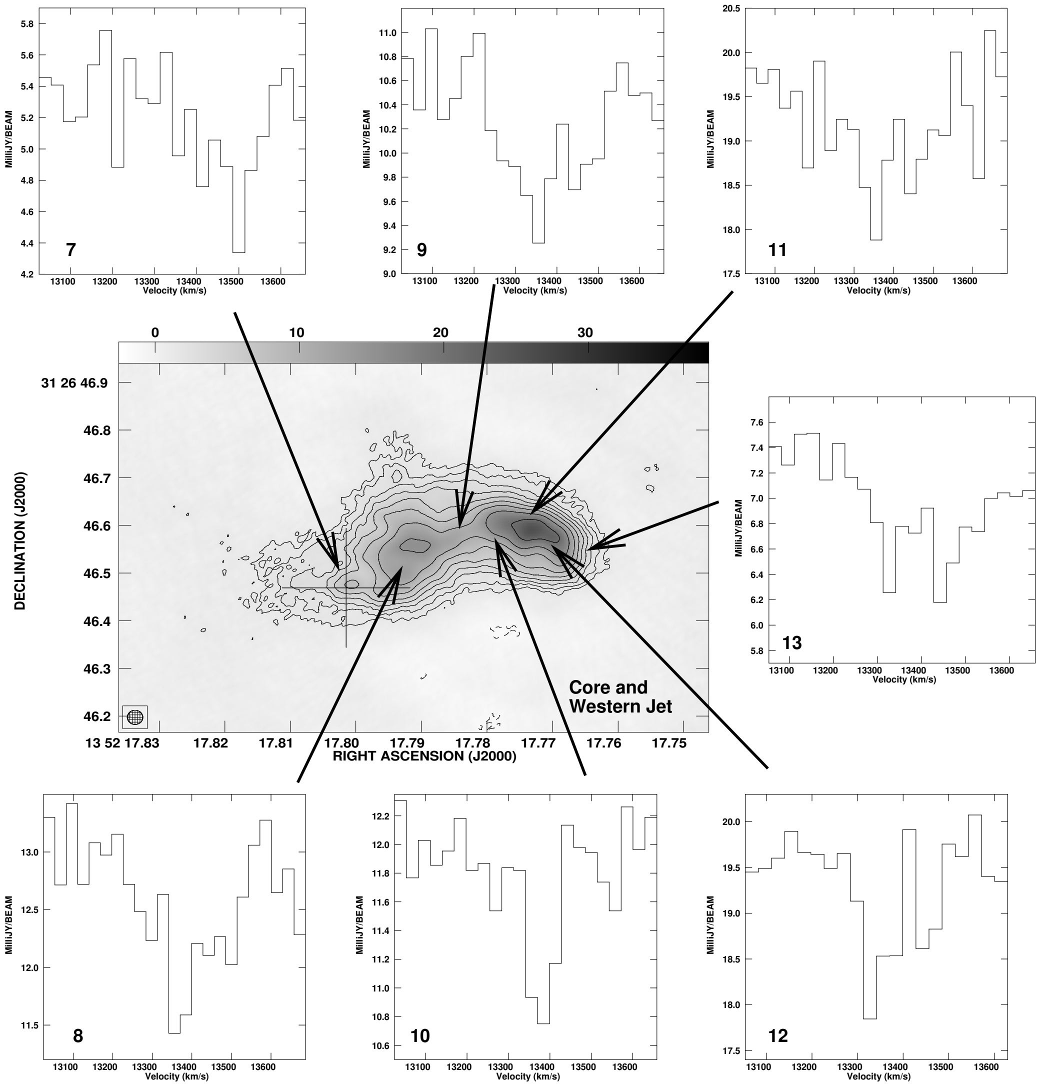

Fig. 3. A montage of the western half of the inner radio jet along with seletced HI absorption spectra. The position of the core, as measured at 5 GHz with MERLIN by Akujor et al (1996) is marked by a cross.

rotating gas ring would be at least $1.7\times10^{9}\,M_\odot$ within 400 pc of the core.

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