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H I ABSORPTION IN THE STEEP-SPECTRUM SUPERLUMINAL QUASAR 3C 216

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ABSTRACT

The search for H I absorption in strong compact steep-spectrum sources is a natural way to probe the neutral gas contents in young radio sources. In turn, this may provide information about the evolution of powerful radio sources. The recently improved capabilities of the Westerbork Synthesis Radio Telescope have made it possible to detect a 0.31% (19 mJy) deep neutral atomic hydrogen absorption line associated with the steep-spectrum superluminal quasar 3C 216. The redshift ($z = 0.67$) of the source shifts the frequency of the 21 cm line down to the ultra–high-frequency (UHF) band (850 MHz). The exact location of the H I–absorbing gas remains to be determined by spectral line VLBI observations at 850 MHz. We cannot exclude that the gas might be extended on galactic scales, but we think it is more likely to be located in the central kiloparsec. Constraints from the lack of X-ray absorption probably rule out obscuration of the core region, and we argue that the most plausible site for the H I absorption is in the jet-cloud interaction observed in this source.

Subject headings: galaxies: active — galaxies: ISM — quasars: absorption lines — quasars: individual (3C 216) — radio lines: galaxies

1. INTRODUCTION

Interferometric observations of H I–absorbing gas in the strong compact steep-spectrum (CSS) sources probe the interstellar medium (ISM) kinematics and distribution in young radio sources. In turn, this may provide information about the evolution of powerful radio sources. We are searching for H I absorption in samples of such sources with the Westerbork Synthesis Radio Telescope (WSRT; Vermeulen et al. 1999). Here we present an intriguing result on the compact steep-spectrum superluminal quasar 3C 216.

The quasar 3C 216 ($z = 0.670$; Lawrence et al. 1996) has been classified as a blazar (e.g., Angel & Stockman 1980) because of its high and variable polarization (12%–21%; Kinman 1976 and Moore & Stockman 1981) and optical variability (Kinman 1976). According to orientation-based unification schemes, blazars are supposed to be seen end-on, with the radio jets more or less aligned with the line of sight (Antonucci 1993). Projection effects may then enhance a small real bending of one of the jets, which appears to be the case in 3C 216 where a misalignment of more than 90° is observed between the jet axis on milliarcsecond and arcsecond scales (Fejes, Porcas, & Akujor 1992). An end-on orientation of 3C 216 is further supported by the superluminal motion observed in its milliarcsecond radio jets: $v_{\rm app} = 5.9c$ (Venturi et al. 1993) implies an upper limit of $\theta_{\rm max} < 20°$.[4]

However, 3C 216 is unusual for a blazar in that it possesses an overall steep spectrum. Since it has a modest total projected linear size (~15 kpc), 3C 216 also belongs to the sample of CSS sources of Fanti et al. (1990). In these sources, the very compact (≤15 kpc) size is usually not explained by projection effects but rather by the fact that the sources may be in an early evolutionary state prior to the larger scale classical doubles (Fanti et al. 1995; Owsianik & Conway 1998). Furthermore, for a quasar, 3C 216 shows surprisingly weak ionization levels in its optical spectrum: the flux ratio [O II]/[O III] = 1.2 (Lawrence et al. 1996). While such a ratio may indicate a high thermal pressure and has been taken to infer cooling flows (e.g., Forbes et al. 1990), it is also a fairly common property in the physically small CSS and compact symmetric object (CSO) classes (Gelderman & Whittle 1994). We are therefore unsure of the real overall physical size of 3C 216; perhaps its small angular extent is a combination of projection effects and an intrinsically modest size.

On milliarcsecond scales, the radio jet emanates from the core to the southeast out to 140 mas (0.85 kpc), where, after a sharp turn, at least in projection, the jet is directed toward a southwest lobe. Recent polarimetric observations by Venturi & Taylor (1999) suggest that a bow shock produces high rotation measures at the location of the sharp bend. The central bright core-lobe continuum features in 3C 216 extend over 2.″5 (15 kpc) and are oriented southwest to northeast (Pearson, Perley, & Readhead 1985). They are embedded in a fainter radio halo that subtends over 8″ (~48 kpc; Barthel, Pearson, & Readhead 1988). Polarization observations (Taylor, Ge, & O'Dea 1995) reveal higher depolarization of the northeast arcsecond-scale lobe (which is assumed to be the more distant one) than what is found over the core and southwest arcsecond lobe components.

2. WSRT OBSERVATIONS

At the WSRT, the recently installed multifrequency front ends (called MFFEs) incorporate so-called UHF-high receivers that cover the 700–1200 MHz band, allowing access to the H I 21 cm line redshifted between $z = 0.2$ and $z = 1.0$. A neutral atomic hydrogen absorption line associated with 3C 216 was detected in 1998 July during a search for H I absorption in CSOs and CSSs at high redshifts ($z > 0.2$). At the time of our observations, 10 telescopes were operational, and the resulting angular resolution was 24″. After a first detection of the line using a 10 MHz–wide band, the source was observed on two additional occasions (in total 13 hr) with a bandwidth of 5 MHz, covering ~1760 km s^{-1}. Careful editing to remove

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[4] We use $H_0 = 65$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ in Friedmann cosmology throughout this Letter.

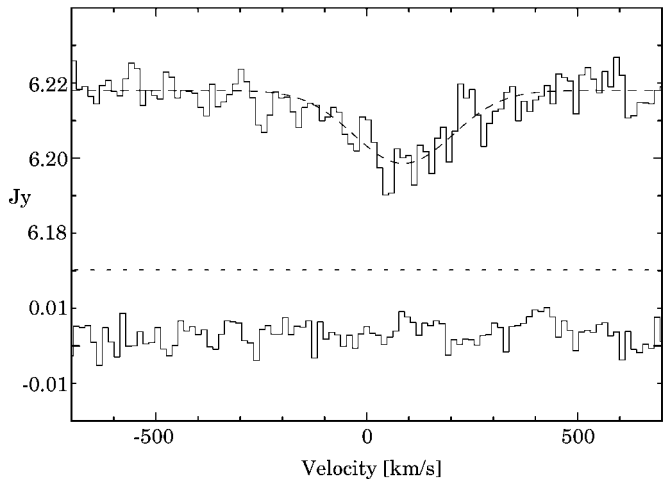

FIG. 1.—The top spectrum plots total neutral atomic hydrogen absorption toward 3C 216 averaged over the whole continuum. The dashed line represents a single-fitted Gaussian of depth 19 mJy and FWHM = 280 km s^{-1}. The bottom spectrum is taken at a location well away from any continuum emission and is representative of the rms noise in our spectral cube. Due to bad band-edges, we only show the inner 1400 km s^{-1}. Zero velocity denotes the optical velocity of the source.

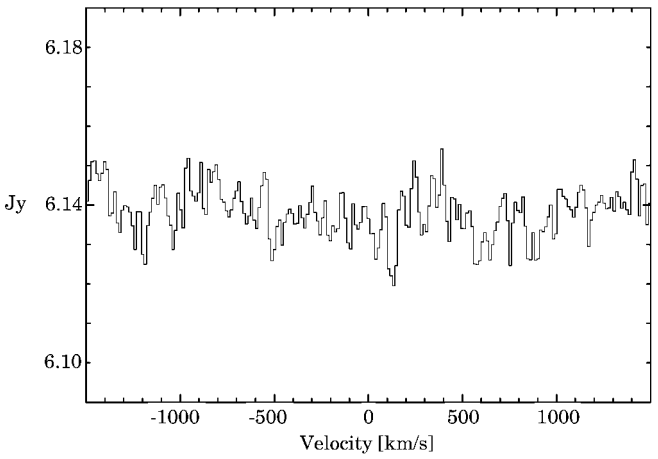

FIG. 2.—Spectrum toward 3C 216 at the redshift of the possible damped Lyα absorber. Zero velocity corresponds to a redshift of $z = 0.63$. No significant line features are present.

narrowband radio-frequency interference in a few spectral channels took place in DIFMAP (Shepherd, Pearson, & Taylor 1994). A complex bandpass and flux density calibration was performed in the Astronomical Image Processing System (AIPS) using scans on strong celestial calibrator sources. We used DIFMAP to create a model of the continuum source that was used to self-calibrate the spectral line data in AIPS. After subtracting the continuum using UVLIN, the 256 spectral channels were finally imaged within AIPS.

The resulting H I absorption spectrum on the (unresolved) source is shown in Figure 1, with the zero velocity marking the optical redshift of the quasar, $z = 0.670$ (Lawrence et al. 1996). In order to display the rms noise in the spectral cube, we insert (below the absorption line) a second spectrum in Figure 1, which is taken at a position well away from any continuum source. The absorption line is consistent with a single Gaussian (best fit shown as a dashed line in Fig. 1) of depth 19 ± 1.3 mJy ($0.31\% \pm 0.02\%$) and a FWHM velocity width of 280 ± 22 km s^{-1}. If this integrated absorption of the H I–absorbing gas were to uniformly cover a fraction f of the total flux density, then the atomic hydrogen column density would be $N_{\rm H\,I} = 1.6 \times 10^{18} T_{\rm sp}(1/f)$ cm^{-2}, where $T_{\rm sp}$ is the spin temperature in kelvins. The H I absorption appears to be slightly redshifted ($\sim 86 \pm 9$ km s^{-1}) with respect to the optical velocity. However, given the quoted uncertainty of the optical velocity of 70 km s^{-1} (Lawrence et al. 1996), in addition to the fact that the systemic velocity may not be reliably measured by emission lines, we do not consider this velocity difference to be significant.

In the ultraviolet spectrum of 3C 216 published by Wills et al. (1995), we saw a hint of a possible damped Lyα absorption system at $z \approx 0.63$. We spent an additional 12 hr of observing 3C 216 at the WSRT with a 10 MHz–wide band centered at the corresponding frequency for the redshifted H I 21 cm line (869 MHz). No absorption was found at a 3 σ line peak level of 10 mJy for a line width of 13 km s^{-1} (see Fig. 2).

3. LOCATION OF THE ABSORBING GAS

Given the radio structure of 3C 216, the spatial resolution ($24'' = 145$ kpc) of our WSRT data is not enough to resolve the location of the H I absorption. It might be extended over the whole radio source, perhaps associated with the normal ISM of the host galaxy. Alternatively, the absorption may be confined to a milliarcsecond-scale region near the quasar nucleus, either associated with circumnuclear gas around the central engine or perhaps related to the region where the jet bends. We consider these options in turn.

3.1. *Absorption on Galactic Scales*

The absorption might extend fairly uniformly over a large part of the kiloparsec background continuum that is seen at, e.g., 8.5 GHz (Taylor et al. 1995) and 1.4 GHz (Barthel et al. 1988). Typical values of the spin temperature of neutral gas in high-redshift galaxies are not readily available. The only observations to date are for damped Lyα systems, which may not be directly comparable to the host galaxy of 3C 216; they yield $T_{\rm sp} > 1000$ K (Carilli et al. 1996). Most likely, on kiloparsec scales, the spin temperature is simply determined by collisions ($T_{\rm sp} = T_k$), and if we assume the local kinetic temperature to be $T_k \sim 100$ K, the resulting H I column density for gas uniformly covering the whole radio source would be $1.6 \times 10^{20}(T_k/100\ {\rm K})$ cm^{-2}.

The absorption line is well approximated by a Gaussian of FWHM = 280 km s^{-1}. This far exceeds the velocity width of a single ISM cloud in our Galaxy (a few km s^{-1}; Mebold et al. 1981 and Dickey, Salpeter, & Terzian 1978) but could be the result of a fairly large population of clouds with a few hundred km s^{-1} velocity distribution covering the source fairly homogeneously; galactic rotation could account for some of the line broadening. However, within a deprojected radius of around 25 kpc (where we have used $\theta_{\rm max} = 20°$ from the superluminal motion), the total mass of atomic hydrogen would equal $3 \times 10^9\ M_\odot$. Such a substantial gas mass would be unexpected, given that K-band imaging of 3C 216 shows a fuzz similar to radio galaxies that have an elliptical host galaxy (Carballo et al. 1998).

3.2. *Central Obscuring Gas*

In several active galactic nuclei (AGNs), partly atomic H I gas has been found to occur on scales less than 1 kpc from the central engine (e.g., in the FR II galaxy Cyg A by Conway & Blanco 1995 and in the Seyfert 1.5 galaxy Mrk 6 by Gallimore et al. 1998). In the CSO 1946+708, a rapidly rotating circumnuclear disk- or torus-like structure has been found by its H I absorption signature (Peck, Taylor, & Conway 1999).

Unification models assume that circumnuclear gas preferentially occupies the equatorial plane, with outflowing jets along the polar axis, thus creating aspect-dependent obscuration. If the H I absorption in 3C 216 is found to cover the nuclear region, the expected end-on orientation of 3C 216 naturally requires that such a distribution of gas is geometrically thick very close to the central engine. Consistent with this idea is the fact that the Mg II and Hβ lines in the optical spectrum obtained by Lawrence et al. (1996) are relatively narrow (FWHM $\approx$ 1100 km s^{-1}) and weak (EW $\leq$ 4 Å). The UV lines in the spectrum plotted by Wills (1995) are also feeble. Moreover, the optical ionization level is very low for a quasar (a flux ratio of [O II]/[O III] = 1.2; Lawrence et al. 1996). The optical/UV spectrum could be explained simply by postulating that a large part of the ionized region in the inner parts close to the active nucleus is hidden from our direct view. Therefore, in 3C 216, the torus might be unusually geometrically thick, with an unusually small polar opening angle, so as to hide the broad-line region and nuclear continuum despite the inclination shown by the superluminal motion.

It takes only a small column depth of H I to absorb Lyα emission completely. Therefore, we suggest that the Lyα emission is from star-forming regions along the jet, which could be supported by the core isophotes of the optical emission that appear to be somewhat extended and aligned with the milliarcsecond radio jet axis toward the southwest (de Vries et al. 1997).

In contrast to the Lyα emission, we believe that at least a significant fraction of the observed X-rays (Sambruna 1997) probably arise in a region close to the central engine. Assuming a power-law energy spectrum, Sambruna (1997) finds that the observed excess of hard X-rays in 3C 216 can be accounted for by a Galactic absorbing column depth of 1.4×10^{20} cm^{-2}, which implies a strict limit of the amount of H I absorption local to 3C 216. Similar column depths are implied by the analysis of Pearson & Worrall referenced in Taylor et al. (1995). We assume that the core spectral index ($S_\nu \propto \nu^{-\alpha}$; $\alpha = -0.6$) derived from Venturi & Taylor (1999) between 8.4 and 4.8 GHz is still similar down to 0.85 GHz. This predicts a core flux density of 0.2 Jy, which is a factor $f = 0.03$ of the total flux density of 3C 216. This estimate cannot be off by more than a factor of a few. Thus, even if we assume $T_{\rm sp}$ = 100 K (in fact, this close to the central source $T_{\rm sp}$ = 8000 K is more likely; Maloney, Hollenbach, & Tielens 1996; Neufeld, Maloney, & Conger 1995; Lepp et al. 1985), then $N_{\rm H\,I} = 5.2 \times 10^{21}(T_{\rm sp}/100\ {\rm K})(0.03/f)$ cm^{-2} would be needed to explain the observed 21 cm line if it arises in front of the core. Hence, this is ruled out by more than an order of magnitude if the X-ray emission is predominantly from the AGN.

Another interpretation of the weak optical/UV features may be that there simply is no prominent broad-line region, only a comparatively faint (but variable) source of nuclear continuum. A similar scenario has been suggested on the basis of optical spectropolarimetry by Cohen et al. (1997) for another compact steep-spectrum radio source with variable optical polarization: the narrow-line radio galaxy PKS 0116+082. Its subkiloparsec-scale radio morphology shows a sharp bend, remarkably resembling that in 3C 216. Perhaps then, these optical properties find their counterpart in the overall steep-spectrum character of the radio source, which might be explained by the lobes being unusually bright rather than the core being obscured.

3.3. *Jet-Cloud Interaction*

The third possible site of absorption, which we believe is the most plausible, is at the 140 mas (0.85 kpc) jet-bending. In the more nearby Seyfert galaxies, there appears to be a trend of neutral gas lying in rotating disks of a few hundred parsec radii (Gallimore et al. 1999). It is unlikely, however, that any absorption seen against the jet in 3C 216 is tracing such gas, since we believe this jet is feeding into the southwest lobe, which we think is approaching us in view of the polarization asymmetry (Venturi & Taylor 1999). Instead we find it reasonable that the H I absorption is the result of a jet-cloud interaction, as is probably the case in the more nearby radio source 3C 236 (Conway & Schilizzi 1999). In this source, an $\sim$130 km s^{-1} wide (e.g., van Gorkom et al. 1989) absorption line is seen toward the tip of one of the kiloparsec-scale lobes (Conway 1999). The radio jet could be driven into a cloud at the location of the large observed bend, 140 mas away from the core, and this might create a shell of ionized and atomic hydrogen in front of the jet, which can be seen in H I absorption. Venturi & Taylor (1999) suggest that the high Faraday rotation measures that they found in VLA observations arise in this vicinity. The (5 GHz) VLBI image of Venturi & Taylor (1999) shows that it is not unreasonable to adopt an absorbing region of, say, $\sim$20 mas (120 pc) that covers (uniformly, we will assume) a fraction $f \sim 0.24$ of the total flux density at 850 MHz, giving a column density of $N_{\rm H\,I} = 6.5 \times 10^{20}(T_{\rm sp}/100\ {\rm K}) \times (0.24/f)$ cm^{-2}. Further estimates of physical parameters like the density become uncertain since we do not know the structure of such an absorbing region; it could, for instance, be a homogeneous spherical cloud, shell-like or perhaps filamentary. Possibly, the wide velocity width (280 km s^{-1}) of our absorption line has its origin in entrainment by the superluminal jet. If the model of the H I absorption being connected to the jet-bending region is confirmed by VLBI observations, we may reveal information about the dynamics of jet-cloud interactions.

4. SUMMARY

Using the new multifrequency receivers at the WSRT, we have detected a broad (FWHM $\sim$ 280 km s^{-1}) H I absorption line in the steep-spectrum superluminal quasar 3C 216. The peak line depth is 19 mJy, which is 0.31% of the total flux density of 3C 216. If a fraction f of the total flux density is uniformly covered, we obtain a column density of $N_{\rm H\,I} = 1.6 \times 10^{20}(T_{\rm sp}/100\ {\rm K})(1/f)$ cm^{-2}. While the WSRT observations lack the resolution to exclude the possibility that the absorption occurs on galactic scales ($f \sim 1$), we feel that it is more likely that the absorption is localized ($f \ll 1$ and $N_{\rm H\,I}$ correspondingly higher). If the X-ray emission of 3C 216 comes predominantly from the AGN, then its spectrum rules out a column depth against the core that would be adequate to explain the 21 cm line. Instead, we prefer an explanation where the H I absorption arises in a cloud interacting with, and bending, one of the jets; such a cloud may also cause the observed high

Faraday rotation measures. Spectral line VLBI observations are planned in order to resolve the absorption region.

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