Unification scheme and the distribution of neutral gas in compact radio sources

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ABSTRACT

We examine the consistency of H I properties with the unification scheme for radio galaxies and quasars, and any correlation with the symmetry parameters for a sample of compact steep-spectrum (CSS) and gigahertz peaked-spectrum (GPS) sources. In our sample, 15 out of 23 galaxies exhibit 21-cm absorption as against one out of nine quasars, which is broadly consistent with the unification scheme. Also there is a tendency for the detection rate as well as the column density for galaxies to increase with core prominence, $f_c$, a statistical indicator of the orientation of the jet axis to the line of sight. This can be understood in a scenario where radio sources are larger than the scale of the circumnuclear H I disc so that the lines of sight to the lobes at very large inclinations do not intersect the disc. The sources in our sample also exhibit the known anticorrelation between HI column density and source size. This suggests that small linear size, along with intermediate values of core prominence, is a good recipe for detecting 21-cm absorption in CSS and GPS objects. Some of the absorption could also be arising from clouds which may have interacted with the radio jet. The H I column density and velocity shift of the primary absorption component, however, show no dependence on the degree of misalignment and the separation ratio of the radio sources.

Key words: galaxies: active – galaxies: evolution – galaxies: nuclei – quasars: absorption lines – quasars: general – radio lines: galaxies.

1 INTRODUCTION

An understanding of the distribution and kinematics of the different components of the circumnuclear gas in an active galactic nucleus (AGN) is important both for studying the anisotropy in the radiation field and thereby testing the unification scheme (cf. Barthel 1989; Urry & Padovani 1995), and for understanding the fuelling of the radio activity. At radio wavelengths, the ionized component of this gas may be probed via radio polarization measurements of compact components in sources, which reside within the dense interstellar environments of the parent galaxies. Such sources are the radio cores, and the compact steep-spectrum (CSS) and gigahertz peaked-spectrum (GPS) sources. The CSS sources are defined to be those with a projected linear size $\lesssim 15$ kpc ($H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$; Spergel et al. 2003) and having a steep high-frequency radio spectrum ($\alpha \gtrsim 0.5$, where $S(\nu) \propto \nu^{-\alpha}$). The GPS sources are more compact and have sizes $\lesssim 1$ kpc (O’Dea 1998). An important way of probing the atomic gas on subgalactic scales is by studying 21-cm H I absorption towards the compact components of CSS and GPS objects, or the compact radio nuclei of the larger objects (e.g. van Gorkom et al. 1989; Conway & Blanco 1995; Peck et al. 2000; Pihlström 2001; Pihlström, Conway & Vermeulen 2003; Vermeulen et al. 2003; Gupta et al. 2006).

The H I absorption lines associated with CSS and GPS objects exhibit a variety of line profiles, suggesting significant, sometimes complex, gas motions, while the H I column densities have been found to be anticorrelated with source sizes (Pihlström et al. 2003; Vermeulen et al. 2003; Gupta et al. 2006). Pihlström et al. have explored different distributions of the H I gas density to explain this observed anticorrelation, and find that a disc as well as a spherical distribution are consistent with it. To study some of these aspects and to test for consistency with the unification scheme, we examine the dependence of H I column density on relative prominence of the core, $f_c$, which is being used as a statistical measure of the orientation of the source axis to the line of sight (Kapahi & Saikia 1982; Orr & Browne 1982).

In this paper, we have investigated this using a sample of 32 CSS and GPS sources, and have also examined the dependence of H I column density and velocity shift of the primary absorption component relative to the systemic velocity, on source symmetry parameters.

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2 THE SAMPLE OF SOURCES

Our sample consists of all CSS and GPS sources identified with radio galaxies and quasars for which we could compile information on the H\textsc{i} column density and core flux density or an upper limit to it either from the literature or our observations. CSS and GPS sources such as J1347+1217 (4C+12.50) and J1407+2827 (Mrk 668, OQ 208), which have prominent H\textsc{i} absorption lines and well-defined radio structures have not been included because they are classified as Seyferts in the literature (e.g. Gallimore et al. 1999; Hurt et al. 1999). The radio source J1415+1320 (OQ 122) which has an H\textsc{i} absorption line (Carilli, Perlman & Stocke 1992) but has been identified as a BL Lac object possibly residing in a spiral host galaxy (Wurtz, Stocke & Yee 1996) has also not been considered. For this study, a core is defined to be a compact feature between the two outer lobes of emission. For those without a detected core, the upper limits to the core flux density are three times the rms noise in the image, and have been estimated only for those sources whose largest angular size is at least five times the resolution element. The fraction of emission from the core, $f_\text{c}$, or an upper limit to it at an emitted frequency of 8 GHz has been estimated for each source. To estimate this fraction, we have used a spectral index of 0 and 1 for the core and extended emission, respectively, unless information was available in the literature.

The sample consisting of 32 objects of which 14 are GPS and 18 are CSS objects is listed in Table 1. 23 of these are associated with galaxies and nine with quasars. The projected linear size of the sample ranges from 0.02 to 11.3 kpc with a median value of 0.68 kpc, while the 5-GHz luminosity ranges from $1.3 \times 10^{25}$ to $1.2 \times 10^{28}$ W Hz$^{-1}$ with a median value of 7.6 $\times 10^{26}$ W Hz$^{-1}$. The values of $f_\text{c}$ range from $<$0.001 to 0.279 with a median value of 0.011, while those of $N$(H\textsc{i}) range from $<$0.06 $\times 10^{20}$ to 84.2 $\times 10^{20}$ cm$^{-2}$ with a median value which is less than 1.8 $\times 10^{20}$ cm$^{-2}$. In this paper, we will refer to sources with core prominence lesser and greater than the median value as having lower and intermediate values. The sources with the highest values of $f_\text{c}$ are not represented in our sample since they would not be classified as CSS and GPS objects.

3 DEPENDENCE OF H\textsc{i} COLUMN DENSITY ON CORE PROMINENCE

To examine the dependence of H\textsc{i} column density on core prominence and also check for consistency with the unification scheme for radio galaxies and quasars, we plot the H\textsc{i} column density against the core fraction (Fig. 1). In our sample, there is only one H\textsc{i} detection for the nine quasars and 15 detections for the 23 galaxies, consistent with orientation effects playing a significant role in the detection of H\textsc{i} absorption.

The quasars have a higher median value of $f_\text{c}$ of $\sim$0.028 compared with 0.011 for the galaxies. These trends are broadly consistent with the expectations for the unification scheme.

One of the striking features seen in Fig. 1 is that 10 of the 15 galaxies that have a detected H\textsc{i} absorption feature, also have a detected radio core, compared with only two out of eight sources without an H\textsc{i} detection. This suggests that detection of a radio core in galaxies enhances the probability of detecting a 21-cm absorption feature. Dividing the galaxies into two roughly equal groups at the median value of $f_\text{c} \sim 0.011$, nine of the 11 with $f_\text{c} \geq 0.011$ (i.e. intermediate values of core fraction) have a detected absorption feature compared with six out of 12 detections in the other group with lower values of $f_\text{c}$. The median value of $N$(H\textsc{i}), using upper limits as their values, for the intermediate $f_\text{c}$ group is $\sim 3.7 \times 10^{20}$ cm$^{-2}$ compared with $1.5 \times 10^{20}$ cm$^{-2}$ for the lower $f_\text{c}$ group.

A Kolmogorov–Smirnov test shows the distributions to be different at a significance level of $\sim 95$ per cent. Thus for galaxies, there is a tendency for the detection rate as well as the column density to increase with the degree of core prominence. For the nine quasars in our sample, there is only one detection and hence it is not meaningful to do a similar exercise. But clearly, sources with the lowest values of $f_\text{c}$ do not tend to have the higher values of $N$(H\textsc{i}).

It is important to enquire whether such a trend is consistent with the unification scheme for radio galaxies and quasars. The deficit of high column density values for sources with low values of $f_\text{c}$ can be understood in a scenario where the radio source sizes are larger than the scale of the circumnuclear disc which contributes most of the absorbing gas, so that the line of sight to the lobes at very large inclinations (corresponding to small values of $f_\text{c}$) does not intersect the H\textsc{i} disc. For intermediate values of $f_\text{c}$, one would then expect higher detection rates as well as higher values of $N$(H\textsc{i}) as seen in Fig. 1.

For angles close to the line of sight, which would have the highest values of $f_\text{c}$, one would expect small values of $N$(H\textsc{i}) and much lower detection rates due to the line of sight passing largely through the ionization cone and also through regions of the disc with a high spin temperature due to the presence of an AGN (Bahcall & Ekers 1969). Such sources will usually get classified as compact flat-spectrum (CFS) sources and not many of them with similar properties as the sources in our sample have been searched for 21-cm absorption (cf. Gupta et al. 2006).

3.1 Dependence on linear size

The neutral hydrogen column density as a function of linear size for our sample of 32 radio sources is shown in Fig. 2. This shows the anticorrelation between the H\textsc{i} column density and source size reported by Pihlström et al. (2003) and extended to a larger sample of 96 sources by Gupta et al. (2006). Thus detection probability of 21-cm absorption feature is higher for both small sources and those with intermediate values of core prominence. It may be noted that projected linear size and $f_\text{c}$ for this sample show no significant relation.

4 H\textsc{i} AND SYMMETRY PARAMETERS

In addition to the circumnuclear disc, absorption could also occur in neutral clouds that are part of the gas that has been accelerated by interaction with a radio jet. Gas outflows as fast and broad as $\sim 1000$ km s$^{-1}$ have been detected in a number of radio sources in neutral as well as ionized gas (see Morganti, Tadhunter & Oosterloo 2005). The kinematical and spatial properties of these suggest that they are being driven by the same mechanism i.e. interaction with the expanding radio jets. The dynamical interaction of the radio source with these clouds could distort the morphology of the radio source thereby affecting the symmetry parameters such as the separation ratio and the misalignment angle. The separation ratio, $R_\text{s}$, is defined to be the ratio of the separation of the further component from the core to the nearer one, while the misalignment angle, $\Delta$, is defined to be the supplement of the angle formed at the core by the outer hotspots. Such jet–cloud interactions may also affect the velocity of the absorbing cloud relative to the systemic velocity of the galaxy. However, we find no evidence of any significant dependence of the H\textsc{i} column density as well as the relative velocity of the primary absorption component on either the separation ratio or...
The columns are as follows. Columns 1 and 2: source name and an alternative name; columns 3 and 4: optical identification and redshift; column 5: radio luminosity at 5 GHz; column 6: the largest linear size (LLS); column 7: the fraction of emission from the core, $f_c$, at an emitted frequency of 8 GHz; column 8: structural classification where D denotes a double source while T implies a triple source which has a detected core; column 9: the separation of the further component from the core; column 10: the misalignment angle, $\Delta$, defined to be the supplement of the angle formed at the core by the outer hotspots; column 11: the shift of the primary H I component relative to the systemic velocity as measured from the optical emission lines, with a negative sign indicating a blueshift and column 12: references for the radio structure; column 13: radio identification of the sources as CSS and GPS objects; column 14: the misalignment angle, $\Delta$, defined to be the ratio of the separation of the further component from the core to the nearer one; column 15: references for the radio structure; column 16: radio identification of the sources as CSS and GPS objects; column 17: H I column density or a 3 $\sigma$ upper limit to it estimated assuming a spin temperature of 100 K and full coverage of the background source by the absorber; column 18: the shift of the primary H I component relative to the systemic velocity as measured from the optical emission lines, with a negative sign indicating a blueshift and column 15: references for the H I observations. References for structural information are as follows. 1: Tzioumis et al. (2002); 2: Pearson & Readhead (1988); 3: Owsiannik, Conway & Polatidis (1998); 4: Zenius et al. (2002); 5: Baum et al. (1990); 6: Giovannini et al. (2001); 7: Feng et al. (2005); 8: Gupta, Srianand & Saikia (2005); 9: Fanit et al. (1989); 10: Saikia et al. (1995); 11: Sanghera et al. (1995); 12: Fey & Charlot (2000); 13: Dallacasa et al. (1995); 14: Saikia et al. (2001); 15: Stanghellini et al. (2001); 16: Akujor et al. (1991); 17: Saikia et al. (1998); 18: Taylor et al. (1994); 19: Peck & Taylor (2000); 20: Fomalont et al. (2000); 21: Bondi, Garrett & Gurvits (1998); 22: Strom et al. (1990); 23: Läder et al. (1998); 24: Mutel, Phillips & Skuppin (1981); 25: Fey, Clegg & Fomalont (1996); 26: Perlman et al. (1996); 27: Xiang et al. (2002); 28: Ojha et al. (2004); 29: Xu et al. (1995); 30: Taylor & Vermeulen (1997); 31: Fomalont et al. (2003); 32: Polatidis et al. (1995); 33: Taylor et al. (2000).

References for H I observations are as follows. V: Vermeulen et al. (2003); C: Carilli et al. (1998); Gu: Gupta et al. (2006); P1: Peck et al. (2000); M: Morganti et al. (2001); P2: Peck, Taylor & Conway (1999).

5 SUMMARY

For a sample of CSS and GPS objects, we have examined the dependence of H I column density on the degree of core prominence and projected linear size. In our sample, 15 out of 23 galaxies exhibit 21-cm absorption as against one out of nine quasars, which is
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Figure 1. Neutral hydrogen column density as a function of core fraction. The solid symbols (in red) correspond to galaxies while open symbols (in blue) denote quasars. Circles denote GPS objects while triangles denote CSS sources. Upper limits are marked by arrows. The vertical dashed line marks the median value of $f_c$ for galaxies.

Figure 2. Neutral hydrogen column density as a function of projected linear size of the radio sources. See caption of Fig. 1 for the meaning of the various colours and symbols.

Figure 3. Neutral hydrogen column density as a function of radio source symmetry parameters i.e. the separation ratio and misalignment angle. See caption of Fig. 1 for the meaning of the various colours and symbols.

Figure 4. The plot of velocities for the principal HI absorption components with respect to the systemic velocity estimated from optical lines as a function of symmetry parameters. See caption of Fig. 1 for the meaning of the various colours and symbols.

broadly consistent with the unification scheme. The detection rate as well as the H I column density appears to be larger for galaxies with more prominent cores, with the higher column densities occurring in intermediate values of $f_c$ and not in the lowest values of $f_c$. This broad trend can be understood in the unification scheme if the lines of sight towards the lobes of sources with the lowest values of $f_c$, which are inclined at the largest angles to the line of sight, do not pass through the circumnuclear H I disc. This could happen if the source sizes are larger than the scale of the disc. It is interesting to note that 10 of the 15 galaxies with a detected H I absorption feature also has a detected radio core, compared with two out of eight galaxies without any H I detection. Our sample also shows an inverse relationship between the H I column density and the projected linear size, suggesting that both small sizes and more prominent cores enhance the probability of detecting H I absorption in CSS and GPS objects.

In addition to the disc, H I absorption may also be due to clouds of cold gas, some of which may have interacted with the radio jet. We, however, find that the H I column density and the velocity shift of the primary absorption component relative to the systemic velocity show no dependence on the degree of misalignment and the separation ratio.

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