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Redshifts and Neutral Hydrogen Observations of Compact Symmetric Objects in the COINS Sample

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ABSTRACT

Compact Symmetric Objects (CSOs) are young radio galaxies whose jet axes lie close to the plane of the sky, and whose appearance is therefore not dominated by relativistic beaming effects. The small linear sizes of CSOs make them valuable for studies of both the evolution of radio galaxies and testing unified schemes for active galactic nuclei (AGN). A parsec-scale region of gas surrounding the central engine is predicted by both accretion and obscuration scenarios. Working surfaces, or "hot spots," and the radio jets of CSOs are close enough to the central engines that this circumnuclear gas can be seen in absorption.

The CSOs Observed in the Northern Sky (COINS) sample is comprised of 52 CSO candidates identified in three VLBI surveys. Of these, 27 have now been confirmed as CSOs. Optical redshifts are available in the literature for 28 of the CSO candidates, and H I absorption has been detected toward four. We present new optical spectroscopic redshifts for three of the candidates and summarize the current status of optical identifications. We further report on the discovery of H I in absorption towards the CSO J1816+3457 and summarize the results of neutral hydrogen absorption studies of the sources in this sample.

1. Introduction

Unified schemes for active galactic nuclei (AGN) seek to explain several classes of objects with a smaller number of source types viewed at different orientations (see the review by Antonucci (1993)). A critical ingredient of all unified schemes is an obscuring disk or torus which hides the

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nucleus when the source is viewed edge-on. An accretion disk is also required to feed the AGN and probably plays a role in collimating the bipolar jets. Although the composition of the obscuring material in the torus may be varied, it seems likely that at some radii and scale heights, there will be significant amounts of neutral atomic hydrogen gas (Neufeld & Maloney 1995). This should be detectable in H I absorption towards the core and inner jets of radio-loud AGN. Sources with symmetric parsec-scale jets are ideal for testing the model. Broad (>100 km s^{-1}) lines are expected this close to the bottom of the potential well of the galaxy. Such broad absorption lines have thus far been detected towards a few moderate power radio galaxies such as Hydra A (Taylor 1996), 3C 84 (Crane, van der Hulst & Haschick 1982) and PKS 2322−123 (Taylor et al. 1999), and in the compact symmetric objects (CSOs) 0108+388 (Carilli et al. 1998), 1146+586 (van Gorkom et al. 1989; Peck & Taylor 1998), PKS 1413+135 (Carilli, Perlman & Stocke 1992) and 1946+708 (Peck, Taylor & Conway 1999).

In the inner regions of the disk a large fraction of the gas must be ionized by the central engine. This will result in free-free absorption of the radio continuum at frequencies below ∼5 GHz as seen in 3C 84 (Walker et al. 1998), Hydra A (Taylor 1996), 1946+708 (Peck, Taylor & Conway 1999), and PKS 2322−123 (Taylor et al. 1999). Another result of the dense ionized gas, if it is magnetized, could be extremely high Faraday rotation measures (RMs). Owing to the lack of any polarized flux in these systems, it has not been possible to directly measure the RMs in any source with H I absorption, but the presence of very high RMs could explain why no polarized flux is detected from these sources (Taylor et al. 1999; Peck & Taylor 1999).

We are engaged in an ongoing project to use VLBI observations of H I absorption to study the densities, kinematics, and scale heights of the neutral gas in the obscuring torus in a moderate size sample of compact objects. This sample is known as the CSOs Observed in the Northern Sky (COINS) sample, although to date only 27 have been securely classified as CSOs. Since CSOs are rare (∼2% of compact objects; Peck & Taylor 1999), it is necessary to start with large VLBI surveys and go to moderately low flux density levels (∼100 mJy at 5 GHz) in order to obtain the 52 CSO candidates that make up the COINS sample. Follow-up multifrequency and polarimetric VLBI observations must then be made in order to identify the center of activity in each source and thus distinguish the true CSOs from core jet sources with "compact double" morphologies. Once the CSOs are identified, their redshifts must be determined before they can be searched for H I in absorption. Low spatial resolution observations can then be carried out at the frequency of the redshifted neutral hydrogen line, and detections can be followed up with extremely high spatial and spectral resolution VLBI studies. Multifrequency continuum observations can also be used to image the free-free absorption in suitable candidates, providing an additional means of determining the geometry of the circumnuclear material.

We present the current status of the COINS survey project in §2 of this paper. §3 outlines our recent observations which provide three new redshifts and one new H I detection. These new results, and their importance to future work, are discussed in §§ 4 and 5.

2. The COINS Sample

The sources in the COINS sample have been identified based on images in the Pearson-Readhead (PR; Pearson & Readhead 1988), Caltech-Jodrell Bank (CJ; Polatidis et al. 1995; Taylor et al. 1994) and VLBA Calibrator (VCS; Peck & Beasley 1997) Surveys. The majority of the CSO candidates were chosen from the VCS based on criteria outlined in Peck & Taylor (1999), while the sources chosen from the PR and CJ surveys conformed to very similar criteria described in Readhead et al. (1996) and in Taylor, Readhead & Pearson (1996).

The sources in the COINS sample are described in Table 1. Column (1) lists the J2000 convention source name of the CSO candidate. Column (2) provides an alternate name, with those prefaced by PR or CJ indicating selection from that survey. Columns (3) and (4) show the optical identification and magnitude of the source. Column (5) lists the redshift of the source, references for which are provided in the table caption. The last column in Table 1 lists the status of the H I absorption detections toward the source, providing the optical depth or upper limit of any H I absorption observation published to date.

3. Observations and Data Reduction

The optical data were taken in two observing runs on the 200 inch telescope at Palomar Observatory, 1998 March 30 and 1999 April 10. Both runs used the Double Spectrograph with a 5200 Å dichroic beamsplitter and a $2''$ slit. All target sources were observed for 1500 seconds each. The total effective wavelength coverage was approximately 3500–9200 Å with a resolution of 4.9 Å. The spectra were extracted using standard IRAF techniques. Wavelength calibration was performed using exposures of arc lamps taken at intervals throughout the observations. Observations of the standard star Feige 34 were used to remove the response function of the chip. The conditions were not photometric on either run so the flux calibration in the spectra shown should not be regarded as absolute.

On 1998 December 6, the source J1110+4817 was observed for 6 hours on the Westerbork Synthesis Radio Telescope (WSRT) using the UHF-high receivers in dual linear polarization. With the new DZB correlator we obtained 256 spectral channels over a 10 MHz bandwidth (formal resolution 47 kHz), centered at the frequency of the H I line predicted by the optical redshift. There were 10 operational telescopes. Calibration of the bandpass shape and the flux density scale was based on a brief scan of 3C286 (1328+307). The initial phase calibration was refined by a few self-calibration and modelfitting loops, in which the 20 brightest continuum sources in the field were found. The spectrum of J1110+4817 shown in Fig. 2a was then produced by vector averaging (over time and baselines) all of the cross-correlation spectra; J1110+4817 is unresolved with the WSRT and was at the phase center of the data. The spectrum of J1816+3457 shown in Fig. 2b was obtained in an analogous procedure from a 12-hour observation on 1999 June 17.

4. Results

4.1. Redshifts

The spectra of the three CSO candidates for which redshifts were obtained are shown in Figure 1. Gaussian fits to the spectral lines used to determine the redshifts for the three new CSO candidates are summarized in Table 2.

J1111+1955 is a galaxy with a redshift of 0.299±0.001. Some indication of stellar absorption features is seen (Ca H & K, Balmer break), but these fall at the location of the dichroic and so the identifications are tentative.

J1311+1417 is a quasar at a redshift of 1.995±0.003.

J1816+3457 is a radio galaxy at a redshift of 0.2448±0.0003. Here again, stellar features are visible, but have not been fitted.

4.2. Neutral Hydrogen

Figure 2 shows the spectra of the redshifted 21cm hydrogen toward two of the CSO candidates.

J1110+4817 has been identified as a quasar by Hook et al. (1996). The upper limit for H I absorption at the redshift of the source is $\tau \leq 0.009$.

J1816+3457 exhibits H I absorption with an optical depth of $\tau \sim 0.035$. This line is centered at 1.1418 GHz (cz=73151 km s^{-1}). Applying the relativistic correction required at this redshift, the radial velocity of the H I absorption line is v=64434±10 km s^{-1}, which is 184 km s^{-1} blueward of the optical emission line radial velocity of v=64618±70 km s^{-1}. This difference of a couple of hundred km s^{-1} should not be overinterpreted, given that the optical redshift is determined from emission lines, which can be influenced by outflow or infall. A VLBI study of the H I absorption in this source is currently underway.

5. Summary

The compact size, orientation, and high rate of H I detection in compact symmetric objects make these sources highly valuable in the study of accretion, evolution and the unified scheme of AGN. Unfortunately, the scarcity of these sources thus far has resulted in too few extensive studies on which to base any general conclusions. The COINS survey is an attempt to ameliorate this situation by identifying a larger sample of CSOs which can be comprehensively studied using VLBI techniques. The first phase of this project, the identification at radio wavelengths of CSO candidates from large, high resolution surveys, has been completed. Multi-frequency VLBI follow-up observations to eliminate core-jet sources masquerading as CSOs in the finding survey have been carried out by Peck & Taylor (1999).

A requisite next step in the process is to obtain the redshift of the COINS sources by optical spectroscopy. Including the three redshifts presented herein, our redshift completeness for the sample is 32 of 52 (61%). Of these 32, low spatial resolution (kpc-scale) observations to look for the presence of H I absorption are available for 6 sources (4 referred to in the introduction, 2 new ones presented here). J1110+4817 is the only 1 of the 6 in which there is no absorption line exceeding 1% peak depth. Clearly, H I studies are very profitable for CSOs. The detection rate in this class of sources is far higher than that found in the nearby radio galaxies of "normal" size surveyed for H I absorption by van Gorkom et al. (1989), which yielded 4 detections for 29 galaxies.

Continuing work on this project involves using optical spectroscopy to obtain redshifts for the remaining CSOs, many of which are extremely faint at optical wavelengths. Once this has been accomplished, H I absorption studies can be undertaken, providing a necessary complement to free-free absorption and jet expansion studies.

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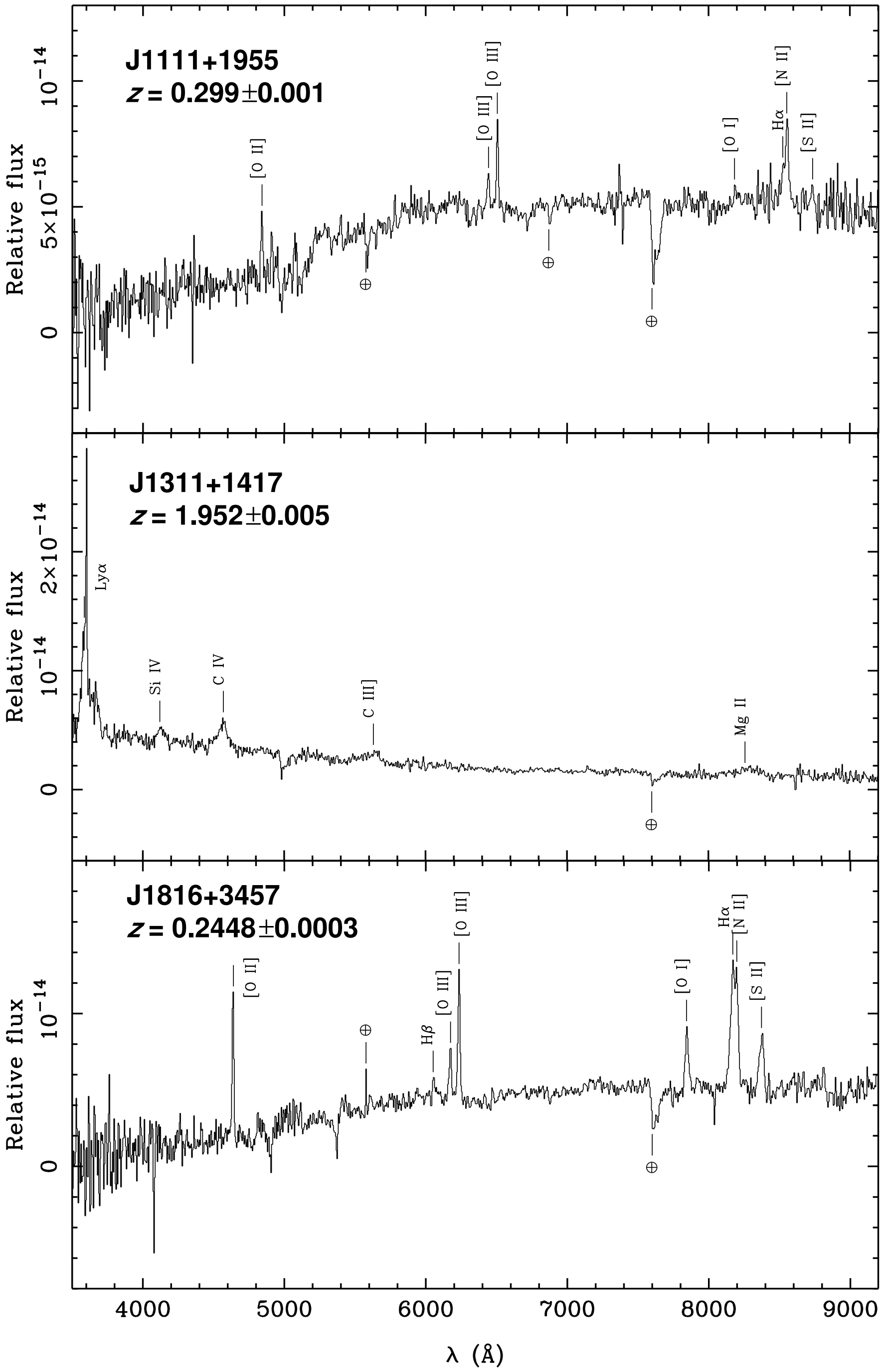

Fig. 1.— Redshifts obtained for three of the CSO candidates. Gaussian fits to the lines used in redshift determination are shown in Table 2.

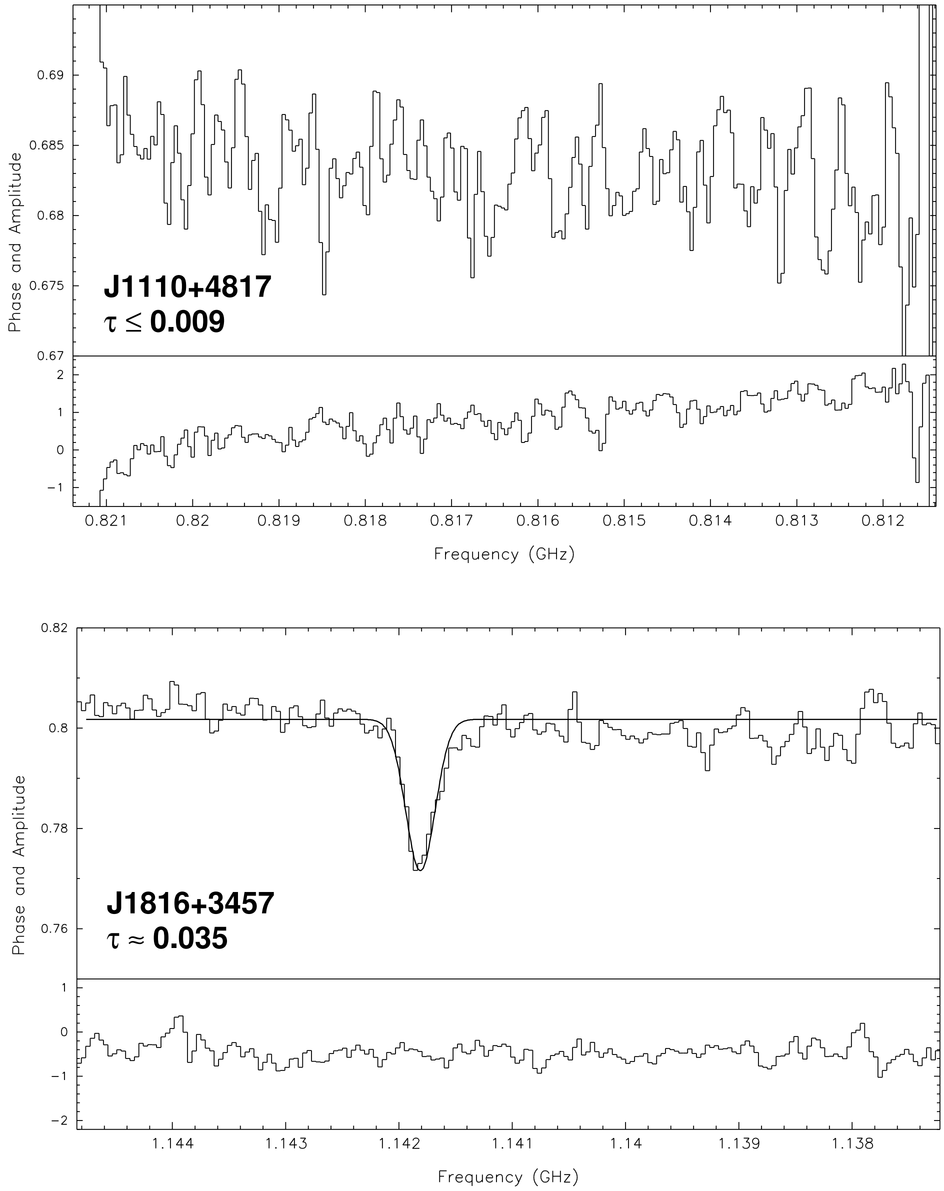

Fig. 2.— WSRT spectra obtained for two of the CSO candidates. (a) The spectrum of J1110+4817 represents a six hour observation. The rms noise in each channel was ∼5 mJy/beam. The upper limit on H I optical depth is $\tau \leq 0.009$. (b) The spectrum of J1816+3457 represents a twelve hour observation. The rms noise in each channel was ∼5 mJy/beam. The optical depth of the H I is $\tau \sim 0.035$. The line is centered on cz=73151 km s^{-1} and has a FWHM of ∼80 km s^{-1}.

Table 1. The COINS Sample

Source Name (1)	Alternate Name (2)	ID (3)	m (4)	z (5)	$\tau_{\rm HI}$ (6)
J0000+4054	4C 40.52	G	20.0	...	...
J0003+4807		...	EF	...	...
J0029+3456	CJ 0026+346	G	20.4	...	...
J0029+0509		QSO	20.0	1.63[1]	...
J0111+3906	PR 0108+388	G	22.0	0.6703[2]	0.44[3]
J0132+5620		...	EF	...	...
J0204+0903		...	EF	...	...
J0207+3152	5C 06.008	G	16.8	1.21[4]	...
J0332+6753		...	EF	...	...
J0400+0550		...	18.5	...	...
J0410+7656	PR 0404+768	G	22.0	0.5985[2]	...
J0424+1442		...	EF	...	...
J0427+4133		...	EF	...	...
J0518+4730		...	EF	...	...
J0620+2102		...	EF	...	...
J0650+6001	CJ 0646+600	QSO	18.9	0.455[5]	...
J0713+4349	PR 0710+439	G	19.7	0.5180[2]	...
J0753+4231	CJ 0749+426	QSO	18.1	3.59[6]	...
J0754+5324		...	EF	...	...
J0842+1835		QSO	16.4	1.27[7]	...
J0925+0019		QSO	18.1	1.72[7]	...
J0954+7435		G	21.7	...	...
J1035+5628	PR 1031+567	G	20.3	0.4597[2]	...
J1107+7232		QSO	18.9	2.10[7]	...
J1110+4817		QSO	19.2	0.74[6]	<0.009[8]
J1111+1955		G	18.5	0.299[8]	...
J1143+1834		...	EF	...	...
J1148+5924	CJ 1146+596	G	11.0	0.011[9]	0.04[10]
J1227+3635		QSO	21.5	1.97[11]	...
J1244+4048	CJ 1242+410	QSO	19.0	0.813[11]	...
J1311+1417		QSO	19.5	1.952[8]	...
J1311+1658		...	EF	...	...
J1357+4353	CJ 1355+441	G	21.6	...	...
J1400+6210	PR 1358+624	G	20.9	0.4310[2]	...
J1414+4554		G	19.9	0.19[12]	...
J1415+1320	PKS1413+135	QSO	20	0.25[13]	0.34[14]
J1546+0026		G	20	0.55[15]	...
J1651+0129		...	21.2	...	...
J1734+0926		G	20.7	...	...
J1737+0621		QSO	17.9	1.21[9]	...
J1810+5649	7C1809+5648	...	18.0	...	...

Table 1—Continued

Source Name (1)	Alternate Name (2)	ID (3)	m (4)	z (5)	$\tau_{\rm HI}$ (6)
J1815+6127	CJ 1815+614	QSO	22.0	0.601[16]	...
J1816+3457		G	18.7	0.245[8]	0.035 [8]
J1826+1831		...	EF	...	...
J1823+7938	CJ 1826+796	G	16.7	0.224[17]	...
J1845+3541	CJ 1843+356	G	21.9	0.764[18]	...
J1944+5448	CJ 1943+546	G	17.6	0.263[19]	...
J1945+7055	CJ 1946+708	G	18.0	0.101[19]	0.05[20]
J2022+6136	PR 2021+614	QSO	19.5	0.2280[2]	...
J2203+1007		...	EF	...	...
J2245+0324		QSO	19.0	1.34[21]	...
J2355+4950	PR 2352+495	G	20.1	0.2383[2]	...

Note. — The initial list of CSO candidates observed in the northern sky: References are as follows: (1) Perlman et al. 1998; (2) Lawrence et al. 1996; (3) Carilli et al. 1998; (4) Willott et al. 1998; (5) Stickel & Kühr 1993a; (6) Hook et al. 1996; (7) Hewitt, A. & Burbidge, G. 1988; (8) this paper; (9) Karachentsev 1980; (10) van Gorkom et al. 1989; (11) Xu et al. 1994; (12) Falco et al. 1998; (13) McHardy et al. 1991; (14) Carilli et al 1992; (15) Heckman et al. 1994; (16) Vermeulen & Taylor 1995; (17) Henstock et al. 1997; (18) Vermeulen et al. 1996; (19) Stickel & Kühr 1993b; (20) Peck et al. 1999; (21) Wolter et al. 1997.

Table 2. Redshifts for CSO candidates

Source Name	z	Integ. (s)	Line ID	λ_{obs} (Å)	EW (Å)	FWHM (Å)
J1111+1955	0.2991±0.001	1500	[O II] λ3727.6	4840	20.20	15.6
			[O III] λ4960.3	6443	5.48	18.4
			[O III] λ5008.2	6507	10.70	13.8
			[O I]λ6300.0	8189	3.50	20.6
			H α λ6562.8	8531	Blend	
			[N II] λ6548.1	8556	Blend	
			[S II] λ6725.5	8733	4.5	25.4
J1311+1417	1.952±0.005	1500	Ly α λ1215.7	3596	102	40.5
			Si IV λ1396.7	4128	22.1	64.5
			C IV λ1549.1	4568	43.1	70.8
			C III] λ1908.7	5641	24.3	78.9
			Mg II λ2799.8	8292	105	164.4
J1816+3457	0.2448±0.0003	1500	[O II]λ3727.6	4637	78.7	13.1
			[O III] λ4960.3	6173	15.1	19.3
			[O III] λ5008.2	6234	33.2	16.9
			[O I]λ6300.0	7844	26.9	30.1
			H α λ6562.8	8172	Blend	
			[N II] λ6585.2	8200	Blend	
			[S II] λ6725.5	8371	44.9	44.8