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RADIO OBSERVATIONS OF THE QUADRUPLE LENS 1608+656

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ABSTRACT

VLA observations at 8.4 and 15 GHz of a sample of 119 inverted-spectrum radio sources revealed that one object, 1608+656, consists of four components in a configuration suggestive of gravitational lensing. The maximum separation between individual components is 2"1. An independent discovery of this object was made through the Cosmic Lens All-Sky Survey, as reported in the companion paper (Myers et al. 1995). All four components have similar flat spectral indices, consistent with lensing. The lensed source is found to be the nucleus of a radio galaxy with double-lobed structure of unusually large physical dimensions and a luminosity at the Fanaroff-Riley class I–II transition. The core of 1608+656 has a flat spectrum from 1.4 to 18.5 GHz, but the flux density falls significantly below 1 GHz. The observed core-lobe ratio is about 1:4 at 1.4 GHz. The southwestern lobe is highly polarized, while the northeastern lobe is unpolarized, properties reminiscent of the Laing-Garrington depolarization asymmetry in low-redshift radio galaxies.

Subject headings: gravitational lensing

1. INTRODUCTION

We report the serendipitous discovery of a quadruple radio lens, 1608+656, in a project aimed at studying faint peaked-spectrum radio sources. The object was also discovered independently, two months earlier, as a result of a directed search for radio lenses by the Cosmic Lens All-Sky Survey (CLASS), as described in the companion paper (Myers et al. 1995).

Our discovery was made in the course of analyzing 8.4 and 15 GHz VLA snapshot images of a sample of 119 faint objects with peaked or inverted spectra between 0.325 GHz and higher frequencies. The sample was drawn from source lists taken from the first regions to be completed of the Westerbork Northern Sky Survey (WENSS; de Bruyn et al. 1995) in combination with the 6 cm Green Bank Survey (GB87; Gregory & Condon 1991). WENSS is a major sky survey being carried out at 0.325 and 0.608 GHz with the Westerbork synthesis radio telescope (WSRT). At 0.325 GHz WENSS will cover the sky north of decl. +30° to a 5 σ flux density limit of 15–20 mJy and a resolution of about 1'. At 0.608 GHz, approximately one-third of this area will be observed to a slightly lower flux density limit. A large fraction of the 119 sources have also been observed with the WSRT at 1.4 and 5 GHz and with the VLA at 8.4 and 15 GHz, to measure the spectral shapes more precisely using near-simultaneous measurements. One of the 119 sources, 1608+656 was found to consist of four flat-spectrum components with a configuration not unlike that of several other quadruple lenses. The maximum separation of the individual components is 2"1. Follow-up optical and infrared observations show the same morphology, confirming the lensing hypothesis (Myers et al. 1995).

Radio-selected lenses are important cosmological probes because they point to high mass surface density galaxies, unbiased by optical extinction. The high angular resolution obtainable in the radio also allows the accurate measurement of positions and intensities, crucial parameters for accurate mass modeling. If the lensed object is variable—the probability of which is increased by selecting flat-spectrum radio sources—it may be used to determine the Hubble constant H_0. We will present some evidence that 1608+656 is, indeed, variable.

Close inspection of the WENSS images of 1608+656 at 49 and 92 cm revealed that the radio source was extended, with a size of about 1'. To study the relationship between the compact lensed quadruple and the large-scale structure, we also made a deep synthesis at 1.4 GHz with the WSRT. This Letter describes the discovery, the radio spectrum, and the radio structure of 1608+656. Optical and near-infrared images and spectroscopy, as well as detailed lens models, are described in the companion paper.

2. OBSERVATIONS AND REDUCTIONS

Radio observations of 1608+656 have now been obtained with both single dishes and interferometric arrays over a frequency range from 0.325 to 99 GHz. The data also cover a time span of more than 7 yr. The first detection of 1608+656 was made in 1987 October in GB87 (Gregory & Condon, 1991). The most recent observations are those taken at Owens Valley Radio Observatory (OVRO) at 18.5 GHz in 1994 October. The relevant radio observations are listed in Table 1. A description of the prediscovery, the discovery, and the follow-up observations follows.

2.1. *VLA Observations*

The source 1608+656 was observed with the VLA[6] in B configuration at 8.4 and 15 GHz during the program on faint peaked-spectrum sources, on 1994 July 23. At both frequencies, the object was observed in the standard way using two bands of 25 MHz. Observations of 3C 48 at 8.4 GHz and both 3C 48 and 3C 286 at 15 GHz were used for amplitude

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calibration. We adopted flux densities of 3.297 Jy for 3C 48 at 8.4 GHz and 3.498 and 1.813 Jy for 3C 286 and 3C 48, respectively, at 15 GHz. The phases were calibrated using standard nearby VLA phase calibrators. We obtained total integration times of 90 s at 8.4 GHz and 100 s at 15 GHz, resulting in noise levels of 0.2 and 1.0 mJy beam^{-1}, respectively, close to the expected thermal noise level at 8.4 GHz and slightly higher at 15 GHz. The data were reduced in AIPS using standard procedures. Several rounds of phase self-calibration were used. The final cleaned images are shown in Figures 1 and 2 (Plate L7, *top and bottom*). The angular resolutions of these images are 1″.5 × 0″.8 in P.A. −65° and 0″.8 × 0″.5 in P.A. −68° at 8.4 and 15 GHz, respectively. At 8.4 GHz, we find that the source is unpolarized to a limit of less than 1%. The source 1608+656 was also observed for 30 s with the VLA in A configuration at 8.4 GHz, as part of CLASS, using a bandwidth of 25 MHz (see companion paper). This resulted in an image with a higher angular resolution of ∼0.2″ and a noise level of ∼0.4 mJy.

In order to improve the map fidelity and the relative flux densities of the individual components we have also self-calibrated the B-array data using a starting model derived from the A-configuration data. Table 2 shows the relative flux densities of the various components at 8.4 and 15 GHz, as determined using the AIPS program UVFIT while fixing the positions as determined from the VLA-A 8.4 GHz data (Myers et al. 1995). The two 8.4 GHz data sets will be compared in § 4.

2.2. *WSRT Observations*

The field containing 1608+656 has been observed at 0.325 GHz (92 cm) and 0.608 GHz (49 cm) as part of the WENSS survey (de Bruyn et al. 1995). The source 1608+656 is located in the WENSS minisurvey area near the north ecliptic pole that was singled out for detailed analysis. On the basis of the peak flux density of 42 mJy at 92 cm and the GB87 6 cm flux density of 90 mJy, the source was selected as a potential peaked-spectrum source. At 92 cm the source was found to be extended by about 1′ in P.A. ∼30°; the integrated flux density is ∼66 mJy. At 49 cm the source happens to lie at the boundary of two mosaics observed more than 2 yr apart. The images made for these two mosaics appeared identical, with no evidence for variability, and they were therefore combined. At 49 cm 1608+656 is also extended but more centrally condensed. The peak flux density is 42 mJy, the integrated 47 mJy.

To image the extended structure visible in the 92 cm image at higher angular resolution, 1608+656 was observed at 1.4 GHz with the WSRT for 12 hr on 1994 October 1. Eight bands of 5 MHz between 1377.5 and 1423.5 MHz were used, providing a total bandwidth of 40 MHz. The intense radio source 3C 330 (Laing 1981) is located only 24′ north of 1608+656, which causes some problems in the reduction. The data were reduced using the NEWSTAR software package developed at the Netherlands Foundation for Research in Astronomy (NEWSTAR = Netherlands east west synthesis telescope array reduction). The data were self-calibrated using standard techniques. The absolute flux density scale used was that of Baars et al. (1977). All flux densities given have been corrected for the primary-beam attenuation. The image is shown in Figure 3. It has a noise level of 0.1 mJy beam^{-1}, slightly higher than the 0.06 mJy beam^{-1} thermal noise level. The Stokes Q and U images did reach the expected thermal noise. We find that the core is unpolarized to limits of less than 1% in Q and less than 0.5% in U and V. The southwestern lobe of 1608+656 is highly polarized (15% ± 1.5%), in contrast to the northeastern lobe which is unpolarized. The polarization vectors are shown on top of the continuum emission in Figure 4. Analysis of the Q and U images in the eight spectral bands reveals no frequency-dependent changes, implying an upper limit of 150 rad m^{-2} to the rotation measure of the southern-western lobe polarized emission.

The background source located 2″.5 north of 1608+656 (see Fig. 3) has a 21 cm flux density of 40 mJy. We mention it here because it will confuse, at some low level, single-dish flux density measurements. It has a steep spectrum with a spectral index $\alpha = -0.8$ (where α is defined by $S \propto \nu^{\alpha}$).

In order to improve the 6 cm GB87 measurement, observations were carried out at 6 cm on 1994 May 15, when the WSRT was participating in a VLBI session. Unfortunately, only three telescopes were equipped with 6 cm receivers, and one of them failed during the observations, leaving us with only a single baseline (of 156 m). The source was clearly detected at the expected location with a flux density equal to the GB87 value obtained 7 yr earlier, indicating no large variations. The error in the flux density is, however, relatively

TABLE 1

RELEVANT RADIO OBSERVATIONS OF 1608+656

Frequency (GHz)	Observation Date	Flux (mJy)	Beam Size	Comments
0.3	1992 Feb	66 ± 3	54″	WENSS
0.6	1990 Dec/1993 Mar	47 ± 3	30	WENSS
1.4	1994 Oct 1	63 ± 3	13	WSRT
5.0	1994 May 15	100 ± 10	80	WSRT (1 baseline)
5.0	1987 Oct	90 ± 10	3′.5	GB87
8.4	1994 Mar 1	75 ± 3	0″.3	VLA-CLASS
8.4	1994 Jul 23	85 ± 4	1.5 × 0.8	VLA-GPS
15.0	1994 Jul 23	81 ± 4	0.8 × 0.5	VLA-GPS
18.5	1994 Oct	84 ± 5	2′	OVRO 140 foot
99	1994 Oct 4, 5	38 ± 4	2	OVRO millimeter array

NOTE.—Columns give the observed frequency, the date of observation, the measured flux density and error, the beam size of the telescope, and the survey or telescope used to acquire the data.

TABLE 2

FLUX DENSITIES AT 8.4 AND 15 GHZ AND SPECTRAL INDEX BETWEEN THESE FREQUENCIES FOR EACH COMPONENT OF THE LENSED OBJECT

A. TOTAL AND COMPONENT-B FLUX DENSITY

Component	8.4 GHz (mJy)	15 GHz (mJy)	8.4 GHz (CLASS)[a] (mJy)	$\alpha^{8.4\ \mathrm{GHz}}_{15\ \mathrm{GHz}}$
Total	83 ± 4	81 ± 4	73.2 ± 0.9	+0.0 ± 0.1
B	18.1 ± 0.9	17.1 ± 1.0	17.8 ± 0.4	−0.1 ± 0.2

B. FLUX RATIO (vs. B)

Component	8.4 GHz (mJy)	15 GHz (mJy)	8.4 GHz (CLASS)[a] (mJy)	$\alpha^{8.4\ \mathrm{GHz}}_{15\ \mathrm{GHz}}$
A	2.41 ± 0.17	2.25 ± 0.14	2.06 ± 0.06	−0.20 ± 0.1
B	1.00	1.00	1.00	...
C	0.77 ± 0.12	0.96 ± 0.12	0.85 ± 0.03	+0.3 ± 0.3
D	0.33 ± 0.06	0.30 ± 0.06	0.26 ± 0.03	−0.2 ± 0.2

NOTE.—We adopt the nomenclature for the components suggested in Myers et al. 1995.

[a] From Myers et al. 1995.

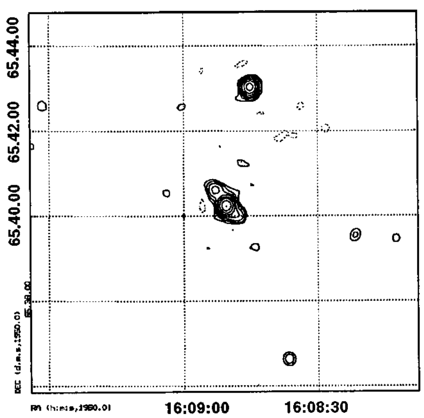

FIG. 3.—WSRT 1.4 GHz map showing 1608+656, with the bright source to the north. The contours are at $0.4 \times (-1, 1, 2, 4, 8, 16, 32, 64,$ and $96)$ mJy.

large. The fringe spacing was 80″, implying that the lobe emission was included in the flux density estimate.

2.3. *OVRO Observations*

The lens 1608+656 was also observed with the OVRO 40 m radio telescope at a frequency of 18.5 GHz. The measurements were made during 1994 October and give a flux density of 84 ± 5 mJy (assuming 19.5 Jy for DR 21 and 6 Jy for NGC 7027). Observations were also made with the OVRO millimeter array at a frequency of 99 GHz on 1994 October 4 and 5, when a flux density of 38 ± 4 mJy was recorded.

3. DISCUSSION OF STRUCTURE AND POLARIZATION

The quadruple radio structure of the core of 1608+656 is similar to that of several quadruple-lens systems (e.g., Patnaik 1992). The flux densities of the components range from 6 to 44 mJy at 8.4 GHz and from 5 to 39 mJy at 15 GHz. All four components have flat radio spectra (see Table 2). A fifth component, which is predicted by the lens modeling (see companion paper) to be somewhere in the middle, is not detected. Limits (3 σ) to its flux density are about 1 mJy at both 8.4 and 3 mJy at 15 GHz. When the core is subtracted, the WSRT 21 cm image (Fig. 4) reveals a classical double source with an overall size of ∼50″. The precise value for the core flux density is somewhat subjective since it blends with diffuse emission bridging the region between the lobes. The adopted core flux density is 51 ± 2 mJy, which includes the uncertainty in the base level. The peaks in the lobes, at 12″ resolution, are separated by 45″ in P.A. 38°. The core is located 26″ from the northeastern lobe, yielding an arm ratio of 1.5. The locations of peak brightness in the two lobes are misaligned by about 10° when connected to the core. The southwestern lobe is clearly extended, with a suggestion of a connection curving in to the core. This feature could well hide a curved jet when observed at higher resolution. The peak brightness of both lobes is about 4.5 mJy, and the integrated flux density of the extended emission is 12 ± 2 mJy.

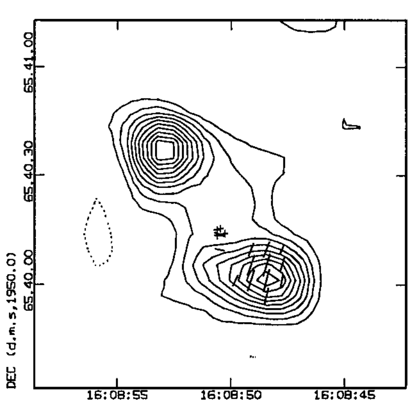

FIG. 4.—Detail of the WSRT 1.4 GHz map. The core (51 mJy) has been subtracted at the location of the four crosses indicating the four components of the quadruple lens. The contours are at $0.4 \times (-1, 1, 2, 3, 4, 5, 6, 7, 8, 9,$ and $10)$ mJy. Polarization vectors are also shown.

The strong polarization asymmetry between the two lobes is reminiscent of that seen in many double radio sources (Conway & Strom 1985; Strom & Jägers 1988). This asymmetry has been investigated in detail by Laing (1988) and Garrington et al. (1988), who suggest that it is due to beam depolarization in the radiation from the more distant lobe seen through a gaseous halo of the parent galaxy (see also Garrington & Conway 1991). If the curved structure in the southwestern lobe is in fact a jet, then 1608+656 also fits the Laing-Garrington explanation because the jet would be relativistically boosted on the near, i.e., polarized, side. Higher resolution observations are needed to study the polarization asymmetry and possible jetlike structure. What is noteworthy about the polarization asymmetry is that it is present at rather large physical separation; the northeastern lobe is separated, in projection, from the core and the lensing galaxy by about 200 kpc (for all $0.9 < z < 3$; we assume $q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1}). (We note that the redshift of the lensed object has not yet been determined but that possible values are 0.9 and 2.3; cf. Myers et al. 1995.)

The lens 1608+656 has the appearance of an edge-brightened (FR II) radio source. If the radio source is at a redshift $z = 2$, its luminosity $P_{178\ \mathrm{MHz}} \approx 2 \times 10^{26}$ W Hz^{-1} would place it just above the transition luminosity between FR I's and the more powerful FR II's (here we assumed the lobe emission dominates the emission at a rest frequency 178 MHz).

The models presented in Myers et al. (1995) suggest a total magnification factor of 6 for the core of the radio galaxy. The core-lobe ratio that would have been observed in the absence of a lens would then be about 1 at 1.4 GHz (or about 5 GHz rest frequency for $z = 2$). This is a rather high value (see, e.g., Orr & Browne 1982), suggesting that the core emission is boosted due to relativistic motion close to the line of sight. The overall size of the radio source could therefore be larger still by an order of 2. This would make 1608+656 a truly giant radio source for such a large redshift and raises interesting questions related to the energy loss due to inverse Compton scattering of the microwave background photons.

Large-scale radio emission associated with a gravitationally lensed source has been seen previously in 0957+561 (Greenfield, Roberts, & Burke 1985) and 0218+357 (O'Dea et al. 1992; Patnaik et al. 1992). Source 0957+561 appears to have the same radio morphology as 1608+656: a bright core with a jet feeding a double-lobed source. Both the angular and linear scales of the extended radio emission are ∼4 times smaller (∼12″, $z = 1.413$). The structure of 0218+357 is more complex, with a very dominant core, a jet, and a 30″ halo. We note that 0218+357 and 0957+561 were first discovered in the Jodrell Bank 968 MHz survey, at which frequency the extended structure dominates. In the case of 1608+656, it was the flat/inverted lensed core that led to the discovery.

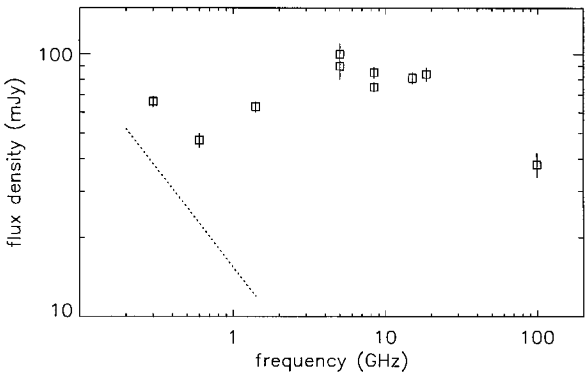

FIG. 5.—Radio spectrum of 1608+656 from 0.3 to 19 GHz: *squares*, integrated flux densities. The contribution from the lobes is indicated by the dotted line.

4. RADIO SPECTRUM AND EVIDENCE FOR VARIABILITY

Disentangling the radio spectrum of 1608+656 is complicated by the different angular resolutions of the various measurements and the different spectral indices of the core and lobes. The double-lobe contribution at 5 GHz is about 5 mJy, assuming a spectral index of $\alpha = -0.8$ for the extended emission. The flux densities of the lobes at 0.325 GHz would then be about 25 mJy at 0.608 GHz and 40 mJy at 0.325 GHz. This leaves about 24 mJy at 0.608 GHz and 25 mJy at 0.325 GHz for the core flux densities. All other measurements at frequencies of 1.4 GHz and higher refer to the core. A graphical decomposition of the spectra of the lensed core and extended emission is presented in Figure 5. The core spectral index is inverted between 0.325 and 5 GHz, but may be flat or weakly undulating above this frequency. This spectral decomposition assumes no variability in the core. The two WENSS flux density points at 0.608 GHz, taken 2.5 yr apart, differ by less than the noise (peak flux densities of 40 and 45 mJy). There is, however, some evidence for modest variability at a frequency of 8.4 GHz. The two VLA observations at 8.4 GHz taken almost 5 months apart are different in total flux density. This difference can almost completely be attributed to the brightest component (A), which has changed from 36 to 44 mJy, a 20% increase, which we consider to be significant. This increase is also reflected in the A/B ratio, which increased from 2.06 to 2.38 (cf. Myers et al. 1995), a ratio not affected by errors in the absolute flux calibration. None of the other components has changed significantly in this time span. No signs of variability are seen in the OVRO 18.5 GHz data taken through the month of October, although the quality of the data is not sufficient to place reliable limits on anything less than gross variability (<20%).

Flux density variations in the cores of radio sources are generally accompanied by spectral index variations. In the presence of differential time delays, the individual components of the quadruple lens should then also show variations in spectral index. However, the spectral index between 8.4 and 15 GHz of the four components of the quadruple are consistent with no variation, but the errors are rather large in these snapshot images. The 5 GHz WSRT and GB87 flux densities, taken 6.5 yr apart, are consistent with no variation of more than about 15% (1 σ).

5. CONCLUSIONS

The radio source 1608+656 has been shown to be a high-redshift radio galaxy with radio power $P_{178\ \mathrm{MHz}} < 2 \times 10^{26}$ W Hz^{-1} and to have rather large physical dimensions. Its core has been magnified by lensing, but even without the lens magnification the core of the radio source is rather strong with a core-lobe ratio of ~1 at the observed frequency of 1.4 GHz. The core emission is therefore likely to be relativistically boosted. Cores of radio sources seen close to the line of sight are generally variable. When comparing our data with those obtained by Myers et al. (1995) we find some evidence for variability in the brightest component (A); in the future such variations may be used in time delay studies to determine the Hubble constant. VLBA observations have been proposed to provide a first-epoch image for time delay and proper-motion studies and for detailed study of the structure and polarity of the four lensed components. Due to the magnification, any relative motion of substructure within the components will be sped up. If it were possible to measure motion of individual jet features in the images, this would provide an independent means of determining a time delay, even if the source is not highly variable.

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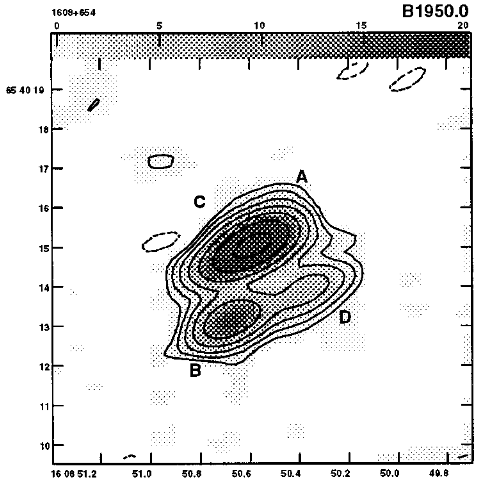

FIG. 1.—Arcsecond-scale structure of 1608+656 observed with the VLA in B configuration at 8.4 GHz. The beam size is 1″.5 × 0″.8 in P.A. −65°. The contours are at 0.2 × (−3, 3, 6, 12, 24, 48, and 96) mJy.

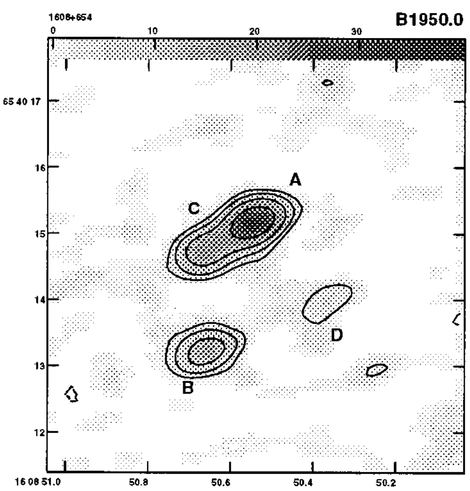

FIG. 2.—Arcsecond-scale structure of 1608+656 observed with the VLA in B configuration at 15 GHz. The beam size is 0″.8 × 0″.5 in P.A. −68°. The contours are at 1 × (−3, 3, 6, 12, 24, 48, and 96) mJy.

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