THE ASTRONOMICAL JOURNAL VOLUME 88, NUMBER 6 JUNE 1983

VLBI OBSERVATIONS OF THE QUASARS CTD20 (0234+285), OJ248 (0827+243), AND 4C19.44 (1354+195), AND THE MILLIMETER-X-RAY CONNECTION

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Received 10 September 1982; revised 14 March 1983

ABSTRACT

We have obtained limited VLBI data on the quasars CTD20, OJ248, and 4C19.44 at 2.8 cm. CTD20 was also observed at 6 and 18 cm. All three sources contain multicomponent structure, and rather large fractions of the 2.8-cm flux densities arise in unresolved regions. All of the radio flux density of CTD20 originates in compact components. 4C19.44 is dominated at low frequencies by a steep-spectrum component which exceeds about 7 mas in size. Above 2 GHz the spectrum is flat and variable owing to several compact components. CTD20 and OJ248 belong to a sample of millimeter-excess quasars which were shown by Owen, Helfand, and Spangler to have highly predictable ratios of 90 GHz to 2-keV flux densities. A self-Compton explanation of this relationship is supported by the existence of unresolved radio components. However, the rapid 90-GHz variability of OJ248 and other quasars with strong millimeter emission should destroy the observed tight correlation except under special circumstances. A synchrotron origin of the radio-to-x-ray emission requires that any variations in the radio should be time delayed relative to the x-ray.

I. INTRODUCTION

We have obtained limited Very-Long Baseline Interferometer (VLBI) observations of three quasars, CTD20 (0234 + 285), OJ248 (0827 + 243), and 4C19.44 (1354 + 195). Although these sources were used primarily for calibration purposes, each is interesting in its own right. CTD20 and OJ248 are millimeter-excess quasars, a class of objects whose x-ray fluxes were found to correlate extremely well with mm-wavelength flux densities (Owen, Helfand, and Spangler 1981). Moreover, all three quasars are variable in the radio. Because of the paucity of *u-v* coverage, we can discuss the source structures only in a rough manner.

II. OBSERVATIONS

We have observed all three sources at 2.8 cm on 9 April 1980, using a 4-element VLB array composed of the 100-m telescope at Effelsburg, West Germany (referred to as "BONN"); the 37-m antenna at Haystack (HSTK), Massachusetts; the 43-m dish at the National Radio Astronomy Observatory* (NRAO) in Green Bank, West Virginia; and the 40-m antenna of Owens Valley Radio Observatory (OVRO) near Big Pine, California. We also observed CTD20 at 2.8 cm on 8 June 1981, using the same array minus HSTK and adding the 26-m dish at Harvard Radio Astronomy Station in Fort Davis (FDVS), Texas; at 6 cm on 17 August 1981 using BONN, HSTK, FDVS, and OVRO; and at 18 cm on 9 October 1981 using BONN, HSTK, NRAO, FDVS, OVRO, and the 26-m antenna at Hat Creek (HCRK), California. Processing of the video tapes and subsequent data analysis were performed at Caltech using the JPL-CIT processor and VAX computer. Total flux density measurements were obtained at BONN (R. Porcas and I. Pauliny-Toth, private communication, 1980 & 1981). Antenna and system temperature calibrations were made at all stations except HSTK, FDVS, OVRO, and HCRK, where pre-determined gain curves of antenna temperatures versus zenith angle were used. Our final calibration of correlated flux densities was found to be self-consistent at the 10% level at 2.8 and 6 cm and at the 5% level at 18 cm.

III. RESULTS

a) CTD20 (0234+285)

CTD20 is a quasar with redshift $z = 1.213$ and optical magnitude $m = 18.5$ (Hewitt and Burbidge 1980). It is mildly variable at centimetric wavelengths (Medd *et al.* 1972; Webber *et al.* 1976; Dent and Balonek 1982), is totally unresolved to the VLA at 6 and 20 cm (Perley 1982), and has a radio spectrum which is flat up to 90 GHz (Owen, Spangler, and Cotton 1980).

Our VLBI observations of CTD20 are listed in Table I. The *u-v* coverage is quite scanty; and the data are insufficient to allow us to uniquely model the source

*NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE I. Visibility data for CTD20.

Baseline[a]	Length ($10^6\lambda$)	PA	S_c (Jy)	Triangle[a]	Closure phase
a) 2.8 cm April 1980 ($S_\nu = 2.64 \pm 0.10$ Jy)					
B − K	195	77°	1.55 ± 0.16	B − K − G	− 5° ± 3°
	138	42°	1.53 ± 0.15		3° ± 3°
B − G	223	75°	1.48 ± 0.15	B − K − O	− 52° ± 5°
	166	43°	1.20 ± 0.12		0° ± 3°
K − G	28.5	71°	2.55 ± 0.25	B − G − O	− 50° ± 5°
	29	50°	2.50 ± 0.25		− 5° ± 3°
B − O	286	88°	1.00 ± 0.10	K − G − O	− 5° ± 4°
	258	63°	1.40 ± 0.14		0° ± 4°
K − O	102	109°	1.23 ± 0.13		
	139	84°	1.68 ± 0.17		
G − O	82	121°	1.35 ± 0.14		
	117	92°	1.55 ± 0.16		
b) 2.8 cm June 1981 ($S_\nu = 2.54 \pm 0.10$ Jy)					
B − G	225	81°	1.80 ± 0.18	B − G − F	− 5° ± 5°
B − F	278	84°	1.45 ± 0.15	B − G − O	− 10° ± 3°
G − F	55	96°	1.60 ± 0.16	B − F − O	− 15° ± 5°
B − O	273	93°	1.54 ± 0.15	G − F − O	− 10° ± 5°
G − O	69	134°	1.38 ± 0.14		
F − O	43	186°	1.32 ± 0.27		
c) 6 cm August 1982 ($S_\nu = 2.53 \pm 0.10$ Jy)					
B − K	93	80°	2.17 ± 0.22	B − K − F	− 13° ± 2°
B − F	132	83°	1.26 ± 0.13	B − K − O	− 30° ± 2°
K − F	39	88°	2.56 ± 0.26	B − F − O	− 20° ± 2°
B − O	130	91°	1.10 ± 0.11	K − F − O	− 3° ± 2°
K − O	43	116°	2.15 ± 0.21		
F − O	20	3°	2.05 ± 0.20		
d) 18 cm October 1981 ($S_\nu = 2.15 \pm 0.10$ Jy)					
B − K	31	80°	1.82 ± 0.10	B − K − G	2° ± 2°
B − G	35	79°	1.74 ± 0.09	B − K − F	1° ± 4°
K − G	4.3	74°	2.05 ± 0.20	B − G − F	1° ± 2°
B − F	44	83°	1.63 ± 0.08	K − G − F	4° ± 3°
K − F	13	88°	2.03 ± 0.15	B − K − O	− 3° ± 2°
G − F	9.0	94°	2.01 ± 0.10	B − G − O	− 3° ± 1°
B − O	43	92°	1.58 ± 0.08	K − G − O	1° ± 2°
K − O	14	117°	1.77 ± 0.18	B − F − O	− 5° ± 2°
G − O	11	130°	1.78 ± 0.09	K − F − O	0° ± 5°
F − O	6.6	4°	1.82 ± 0.09	G − F − O	0° ± 2°
B − H	42	94°	1.50 ± 0.08	B − G − H	− 3° ± 1°
G − H	12	141°	1.64 ± 0.16	B − F − H	− 4° ± 1°
F − H	9.0	9°	1.56 ± 0.16	G − F − H	0° ± 1°
O − H	2.6	27°	1.93 ± 0.19	B − O − H	− 4° ± 1°
				G − O − H	− 4° ± 2°
				F − O − H	− 5° ± 2°

[a] Baseline abbreviation key: B = BONN, K = HSTK, G = NRAO, F = FDVS, O = OVRO, H = HCRK.

structure. At 2.8 cm, the longer baseline data seem to indicate that the most compact feature resolved by the array is a double of spacing near 3 milliarseconds (mas) and position angle (PA) 171°. This is determined by plotting the amplitude data against baseline length projected onto PA 171°; the correlated flux densities display a minimum near $35 \times 10^6 \lambda$ and a secondary maximum near $70 \times 10^6 \lambda$ projected baselines. (The often nonzero closure phases also indicate that multicomponent structure exists.) This behavior is indicative of an unequal double source of the quoted spacing, with one component having roughly three times the flux density of the other. Other, more extended emission also exists. The data are certainly insufficient to map the source, and even the rough description given above is of questionable uniqueness. (This is especially true since the model structure is elongated at nearly right angles to the PA of maximum resolution.)

The 6- and 18-cm data are even more limited. Again, the amplitudes and closure phases indicate the presence of multiple components.

A radio spectrum of CTD20 from 0.43 to 90 GHz was obtained by Owen, Spangler, and Cotton (1980) at epoch 1978.1. The spectrum is rather flat with a broad maximum near 10 GHz. Subsequent total flux density measurements by us, Perley (1982), and Dent and Balonek (1982) indicate that the flux density has since risen at 1.5 GHz and declined by up to ~30%, then risen (although to a lower level than at 1978.1) at frequencies higher than about 5 GHz.

b) OJ248 (0827+243)

OJ248 is a quasar with $z = 0.939$ and $m = 17.5$ (Hewitt and Burbidge 1980). As described below, the source exhibits wild variations at centimetric wavelengths. Our April 1980 2.8-cm observations were taken during a relatively low point, and the total flux density was only 0.48 ± 0.05 Jy at 2.8 cm, 0.59 ± 0.03 Jy at 6 cm, and 0.62 ± 0.03 Jy at 20 cm (last two observations obtained 2–5 months earlier by Perley 1982).

Table II lists the correlated flux densities for our six baselines. The source was only marginally detected on the baselines which do not include BONN; this causes the closure phases to be rather unreliable and they cannot be distinguished from 0° (symmetric structure). The u-v coverage is extremely scanty, so we can discuss the structure only in a most sketchy manner. About half the flux density is contained in a component which is unresolved on our longest baseline (BONN – OVRO), and hence less than about 0.2 mas in size. The remaining emission originates from a region essentially unresolved on our shortest baselines (HSTK – NRAO), fully resolved on the BONN – OVRO baseline, and partially resolved on the intermediate baselines. It is therefore of order 2 ± 1 mas in size (major axis FWHM) and is noncircular (as evidenced by the higher correlated flux density on the BONN – HSTK and BONN – NRAO baselines relative to the shorter HSTK – OVRO and NRAO – OVRO baselines).

Some larger scale structure in OJ248 has been resolved by Perley (1982). He finds a single, steep-spectrum, secondary component located 7.″9 in PA 200° from the compact, dominant component. Our poor VLBI coverage prevents us from comparing the axis of the compact structure with that of the arcsecond structure. We can, however, determine whether our data allow to exist a simple model in which the milliarsecond axis lies along PA 200°. This is certainly not possible for any simple model, however, since the correlated flux density along PA 116°, nearly perpendicular to PA 200° (or equivalently, 20°), is lower (and hence the source is more heavily resolved) than that at longer baselines oriented more closely toward PA 200°. In fact, our data can be fit quite well by a core-halo (or jet) model if the more extended component is elongated along PA 141°, nearly 60° from the direction of the secondary component.

A maximum of about 0.25 Jy is emitted from regions which are resolved on our longest baseline (i.e., with sizes $\gtrsim 0.15$ mas). The radio spectra obtained in 1977.1 by Owen, Porcas, Mufson, and Moffett (1978) and 1978.1 by Owen, Spangler, and Cotton (1980) indicate that OJ248 was at a high flux level at these epochs relative to 1979 and 1980 (Perley 1982; Owen, Helfand, and Spangler 1981; this paper). In fact, the 2.8-cm flux density (estimated by interpolation at the earlier epochs) dropped by a factor of 3 from early 1978 to early 1980 and the 90-GHz flux density declined by a similar factor

TABLE II. 2.8 cm correlated flux densities for OJ248.

Baseline	Length ($10^6 \lambda$)	PA (N through E)	S_c (Jy)
BONN – HSTK	158 to 115	61° to 32°	0.37 ± 0.04
	193	77°	0.25 ± 0.05
BONN – NRAO	162 to 141	49° to 35°	0.38 to 0.33 (± 0.04)
	222	76°	0.22 ± 0.05
HSTK – NRAO	29 to 27	52° to 44°	0.45 ± 0.04
	29	69°	0.44 ± 0.04
BONN – OVRO	279 to 250	73° to 64°	0.22 to 0.24 (± 0.04)
	289	85°	0.26 ± 0.04
HSTK – OVRO	139	84°	0.26 ± 0.04
NRAO – OVRO	117	92°	0.28 ± 0.04
	80	116°	0.27 ± 0.04

from 1978.1 to 1979.3. Such rapidly variable emission most likely originates in very compact regions. This implies that less than about 15% of the 2.8-cm flux density from OJ248 can be resolved when its flux density is 1.5 Jy.

c) 4C19.44 (1354+195)

4C19.44 is also a quasar, with an emission redshift $z = 0.720$ and $m = 16.0$ (mildly variable) (Hewitt and Burbidge 1980; Pica *et al.* 1980). Weymann, Williams, Peterson, and Turnshek (1979) have also discovered a Mg II absorption system at redshift $Z_{\text{abs}} = 0.457$. The radio spectrum is dominated by a steep spectrum component at low frequencies and becomes flat above 2 GHz. This "centimeter excess" component is variable (Medd *et al.* 1972; Altschuler and Wardle 1976).

We observed 4C19.44 continuously from 0200 to 0530 UT on 9 April 1980 at 2.8 cm. Bad weather at BONN occurred between 0420 and 0530, and this caused us to delete poorly calibrated data taken from 0430 to 0500 on the BONN baselines. We did not detect fringes on the BONN-OVRO baseline between 0300 and 0400. As is indicated by the trend of the data obtained at later times, this is almost certainly due to a correlated flux density which is below the detection limit, ~ 0.1 Jy. The data are shown in Fig. 1.

The data are rather limited but yield enough information for us to give a rough description of the source structure. The total flux density was 1.26 ± 0.06 Jy. A certain fraction of this, 0.36 ± 0.06, originates in a region which is totally resolved on our shortest baseline, and hence has an angular size $\gtrsim 7$ mas. The very deep minimum of the correlated flux density on the BONN-OVRO baseline indicates that the most compact structure consists of a nearly equal double. A model fit (which is shown by the solid line in Fig. 1) indicates that each component is unresolved ($\lesssim 0.2$ mas) with a flux density to 0.25 Jy. The separation is 0.75 mas along PA $- 29°$. The remaining 0.4 Jy originates in a region of size ~ 1 mas, although we cannot determine the position and eccentricity of this component. The nominal model fit illustrated in Fig. 1 centers this component on the SE end of the double; however, it is clear that the closure phases which involve the short HSTK-NRAO baseline (which best defines this feature) are not reproduced by this model (difference $\sim 10°$).

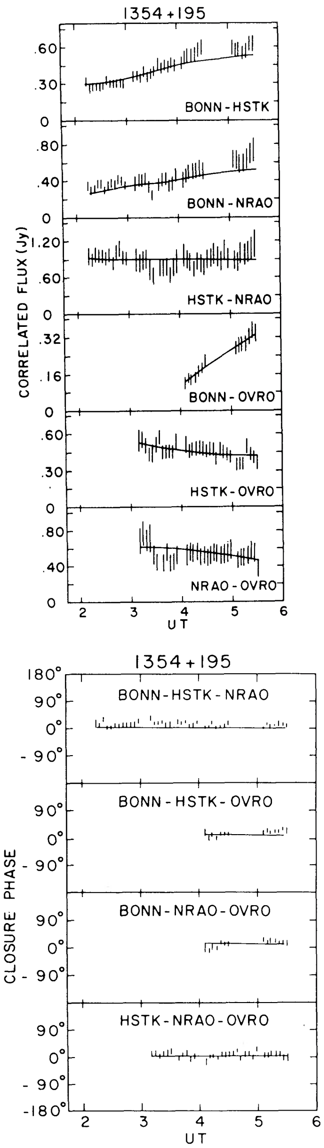

FIG. 1. (a) Correlated flux densities and (b) closure phases at 2.8 cm of 4C19.44 (1354 + 195). Curve drawn corresponds to model described in text. The correlated flux density on the BONN-OVRO baseline was too weak to be detected from 0300 to 0400 UT.

The low-frequency spectrum of 4C19.44 is dominated by a steep-spectrum component with spectrum $S_\nu \propto \nu^{-0.81}$ (Kuehr *et al.* 1981; Dennison, Broderick, Ledden, and O'Dell 1982; Perley 1982). An extrapolation of the low-frequency spectrum to 2.8 cm yields 0.32 Jy as the flux density of this component. This agrees quite well with the flux density which is fully resolved by our shortest baseline. Perley (1982) and Miley and Hartsuijker (1978) have found at 6 and 20 cm a secondary component which lies 16″ at PA $- 15°$ from the primary. This differs by only 14° from the PA of the compact double. Still, $\sim 55\%$ of the steep spectrum emission originates in the primary, with angular size $0\overset{''}{.}007 \lesssim \theta \lesssim 1''$.

Above 2 GHz the radio spectrum is quite flat, with flux density between 1.0 and 2.0 Jy at all frequencies up to 90 GHz (Perley 1982; Geldzahler and Witzel 1981; Ulvestad, Johnston, Perley, and Fomalont 1981). This centimeter-excess component is variable (Medd *et al.* 1972; Altschuler and Wardle 1976) at the 50% level with characteristic time scale of one to a few years. We apparently observed 4C19.44 during a low period.

IV. DISCUSSION

Owen, Helfand, and Spangler (1981) have found that one can predict the x-ray flux of a quasar with strong millimeter emission to within a factor of 2 from a measurement of the 90-GHz flux density. They interpret this relationship as an indication that self-Compton scattering is the mechanism by which most of the x rays are generated in these objects. Two of the objects observed by us, CTD20 and OJ248, are included in the sample of Owen, Helfand, and Spangler. Indeed, in both objects a large fraction of the flux density at 2.8 cm originates in very compact regions, with $\theta \lesssim 0.2$ mas, as is required by self-Compton models. An obvious reason for the millimeter-x-ray correlation then presents itself: strong millimeter emission is an indicator of very compact structure, which in turn should correlate with efficient Compton x-ray production.

There is a difficulty with this interpretation, however. Many, if not most, millimeter-excess quasars have variable 90-GHz flux densities. In the case of OJ248, the flux density dropped by a factor of about 3 in less than two years. This factor is even higher for the most compact regions, which are almost surely responsible for this rapid variability. The problem is that the self-Compton flux should be extremely sensitive to changes in the parameters which affect the synchrotron emission. Let us consider the example of a change in the number of relativistic electrons N_{re}, with all other factors held constant. A decrease of N_{re} by a factor of 3 would decrease the radio flux density also by a factor of 3, but the Compton x-ray flux would decrease by a factor $3^2 = 9$. The small scatter in 90-GHz to 2-keV flux density ratio should therefore be destroyed by variability unless the change in physical parameters is such that there is a one-to-one coupling of synchrotron to Compton flux density. From the example above, merely changing the injection rate of relativistic electrons does not satisfy this criterion, and it is straightforward to show that bulk expansion or contraction of the emission region violates it even more severely. If the source originates in a relativistic outflow (Blandford and Königl 1979; Marscher 1980), a change in the bulk Lorentz factor would alter both the synchrotron and self-Compton flux densities by about the same factor. However, since a detailed model of relativistic beams is still lacking, it is not clear what other physical changes would accompany variations in bulk Lorentz factor.

As mentioned by Owen, Helfand, and Spangler (1981), a synchrotron origin of both the millimeter and the x-ray emission could be expected to yield a nearly constant 90-GHz to 2-keV flux density ratio. The difficulty which they cite, viz., that variability time scales differ from one region of the spectrum to another, can be overcome if the emission at high frequencies originates in a region which is smaller than, but still connected to, the volume responsible for the lower frequency radiation (see, e.g., Marscher 1980). One would then expect time delays, with changes in the x ray preceding those at 90-GHz. The limited monitoring ability of the *Einstein* satellite did not allow this prediction to be tested.

The authors wish to thank the staffs at the observatories used in the VLBI experiments for their *in absentia* support of our observations, and at Caltech for their assistance in the data reduction process. D. B. Shaffer suggested that the sources observed by us might be interesting. We are grateful to W. Dent, T. Balonek, and R. Perley for communicating data prior to publication. I. Pauliny-Toth and R. Porcas kindly provided us with total flux density measurements. J. J. B. was supported by the National Science Foundation and by the VPI Educational Foundation. The National Science Foundation also supports radio astronomy at Berkeley (HCRK), Caltech (OVRO), Harvard (FDVS), and Haystack (HSTK, operated by the Northeast Radio Observatory Corporation).

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