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VLBI STUDY OF 1038+528 A AND B: DISCOVERY OF WAVELENGTH DEPENDENCE OF PEAK BRIGHTNESS LOCATION

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ABSTRACT

VLBI observations of the quasars 1038+528A,B on 1981 March 17 at 3.6 and 13 cm wavelengths with an array of seven antennas were used to obtain a hybrid brightness map of the A quasar and a phase-reference brightness map of the B quasar for each wavelength. Using this phase-reference technique, we determined the relative spatial location of the maps for each wavelength and found that the distance between the peaks of brightness of the quasars is shorter at 13 cm than at 3.6 cm by about 0.7 milli-arcsec. This difference is probably intrinsic to the A quasar and due to wavelength-dependent opacity. Determination of the relative position of the two maps of each quasar, likely reliable to ~0.1 mas, allowed us to make spectral-index maps. The morphology of the spectral-index maps is very similar for both quasars, in sharp contrast to the morphologies of the brightness maps.

Subject headings: interferometry — quasars — radio sources: general

I. INTRODUCTION

The radio sources 1038+528A,B, separated on the sky by approximately 33″, were discovered by Owen, Porcas, and Neff (1978). Optical identification and spectra show the A and B sources to be quasars with $m_v \sim 17.5$ and ~ 18.5 and $z \approx 0.678$ and ≈ 2.296, respectively (Owen, Wills, and Wills 1980). The latter estimate of z, based on four emission lines, seems to be more reliable than the former, which is based on only the Mg II $\lambda 2798$ emission line.

We have studied this pair of quasars primarily with VLBI techniques over a 2 yr span at four different wavelengths. Here, we present the first apparently reliable results for the relative spatial location of compact brightness distributions at two wavelengths. We postpone detailed interpretation to a more extensive publication (Marcaide *et al.* 1984).

II. OBSERVATIONS

The observations were made with the Mark III VLBI system (Rogers *et al.* 1983) on 1981 March 17, at 3.6 and 13 cm wavelengths simultaneously, both with right-circular polarization reception. An array of seven radio telescopes was used whose diameters and locations are: 40 m, Big Pine, California; 100 m, Effelsberg, Federal Republic of Germany; 64 m, Goldstone, California; 43 m, Green Bank, West Virginia; 25 m, Onsala, Sweden; 64 m, Robledo, Spain; and 37 m, Westford, Massachusetts. The telescope at Onsala was able to operate only at 13 cm. The data at each wavelength were recorded with a bandwidth of 28 MHz and correlated with the Mark III processor at the Haystack Observatory in Westford, Massachusetts. The data reduction and calibration procedures used are discussed by Marcaide (1982). Below, we describe only those procedures specific to constructing phase-reference and spectral-index maps.

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III. PHASE-REFERENCE MAPS

For a given interferometer, the observed fringe phase ϕ of a radio source can be written as the sum of several terms:

$$\phi(t) = \phi^g(t) + \phi^{\rm pm}(t) + \phi^{\rm in}(t) + \phi^s(t) , \qquad (1)$$

where ϕ^g, $\phi^{\rm pm}$, $\phi^{\rm in}$, and ϕ^s are, respectively, the contributions to the fringe phase from the geometry, the propagation medium, the instrumentation, and the source structure. The contribution ϕ^s is referenced to the point for which ϕ^g has been computed.

For imaging the radio source, one would like to use the information contained in ϕ^s, but for VLBI observations ϕ^s cannot be extracted directly from ϕ because of the presence of $\phi^{\rm pm}$ and $\phi^{\rm in}$. Several schemes have been developed (Readhead and Wilkinson 1978; Cotton 1979; Schwab 1980; Cornwell and Wilkinson 1981) to estimate ϕ^s subject to the phase-closure condition (Rogers *et al.* 1974). An important drawback of the restriction to use the phase closure is the consequent loss of sensitivity to the position of the source on the sky, resulting from the cancellation of ϕ^g in the formation of the closure phase. As a consequence, it is difficult to register reliably maps of a given source constructed either from observations at the same wavelength but at different epochs or from observations at the same epoch but at different wavelengths. The time and spectral evolution of given source features can therefore not be studied accurately. However, when two or more suitable radio sources lie sufficiently close together in the sky, alternate procedures can be used effectively. One can utilize the facts that $\phi_i^{\rm pm} \approx \phi_j^{\rm pm}$ and $\phi_i^{\rm in} \approx \phi_j^{\rm in}$, where $i \neq j$ denote the various sources. For our observations of 1038+528A,B, the differences in these quantities are each estimated to be under 1° at 3.6 cm (Marcaide 1982). To this accuracy we can therefore write

$$\phi_{\rm B}^s(t) \approx \phi_{\rm B}(t) - [\phi_{\rm A}(t) - \phi_{\rm A}^s(t)] - [\phi_{\rm B}^g(t) - \phi_{\rm A}^g(t)] . \qquad (2)$$

By using equation (2) to estimate $\phi_{\rm B}^s$, we preserve the information on the relative positions of, say, the centers of the maps of the A and B quasars. If one of them were pointlike, then we could uniquely locate the map of the other with respect to it. Virtually every source detectable with VLBI exhibits structure at the milli-arcsecond (mas) level, although typically extended in only one dimension. Thus, the best practical case has sources whose structures are mutually perpendicular, so that plausible registrations are most constrained, especially if easily identifiable features exist in the structure of each. Fortunately, 1038+528 A and B display linear structures with distinct features, and these structures are nearly mutually perpendicular.

We constructed brightness maps of B using A as a phase reference at 3.6 and 13 cm, and using estimates of ϕ_A^s from hybrid maps we had made previously. We also made hybrid maps of B directly. These were of comparable quality to the phase-reference maps because the fractional loss of degrees of freedom by use of closure phases only is not large for a seven antenna array. All hybrid maps were made with Caltech software, kindly made available by M. Cohen and T. Pearson, and modified by one of us (J. M. M.), who also developed the software necessary for the phase-reference mapping.

In Figure 1 we present the A and B maps and their relative positions at 3.6 and 13 cm. We emphasize here only one major result: The angular distance between the peak brightness points in the two maps at 13 cm is about 0.7 mas shorter than the corresponding distance at 3.6 cm. Our use of precision astrometric techniques (Marcaide and Shapiro 1983) confirms this result. The astrometric results from VLBI observations on 1981 February 6 at 18 cm rule out plasma refraction as the cause of the difference. Since this difference is in a direction nearly perpendicular to B's major axis, the correspondence between B's features at the two wavelengths is practically unambiguous. Thus we conclude that the position of the peak brightness of A at 3.6 cm is separated by about 0.7 mas from the position of the peak at 13 cm, as shown in Figure 1. Our spectral-index maps, presented below, support this conclusion.

If we assume that the location of the peak brightness of A with respect to the center of activity in the quasar varies

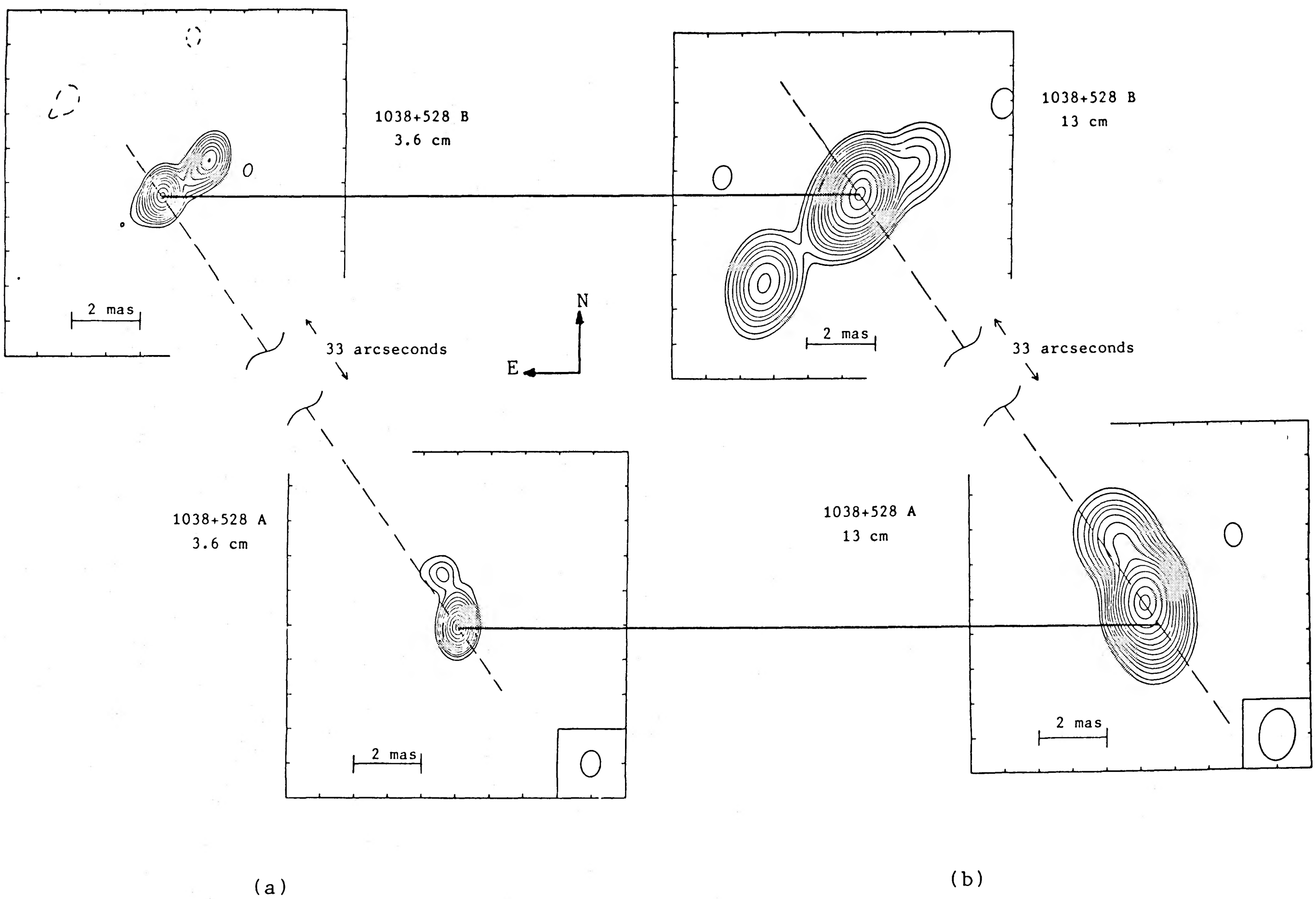
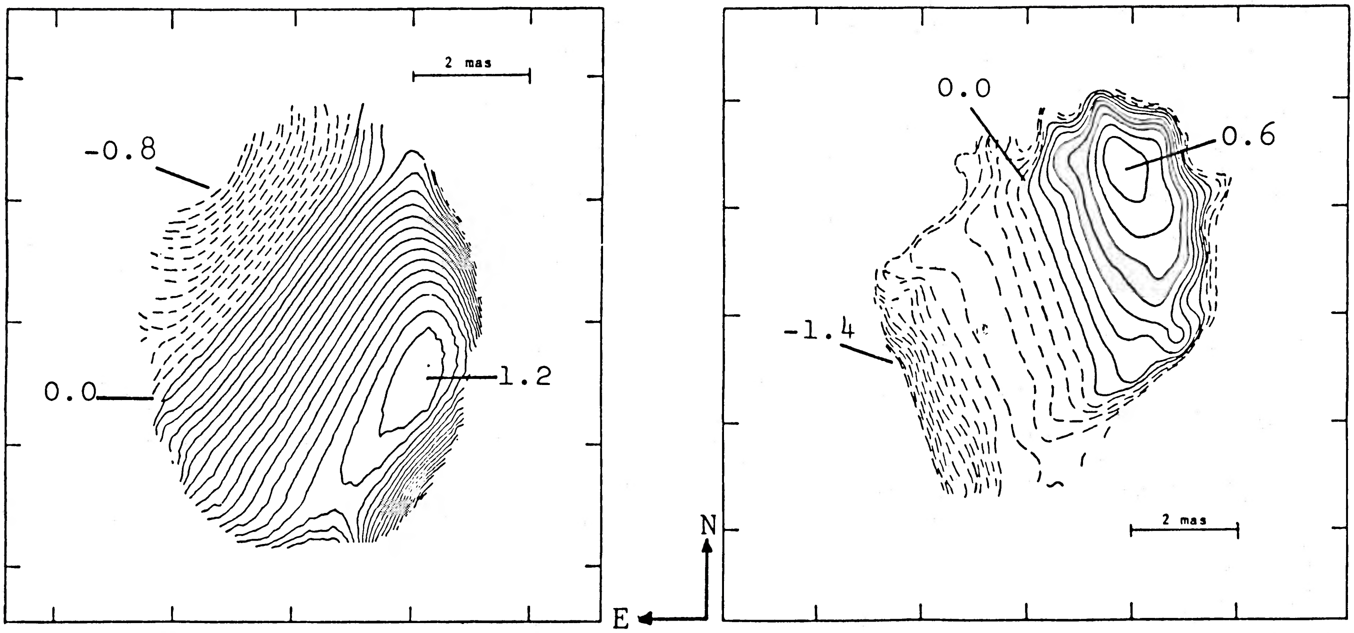


FIG. 1.—Brightness maps and relative position of the quasars 1038+528A,B at 3.6 cm (*a*) and 13 cm (*b*). The continuous lines joining the two sets of maps show that the distance between the peaks of emission of the quasars is shorter for 13 cm than for 3.6 cm. The registration shown here seems the most plausible (see text). The total flux densities in the maps are 440 and 320 mJy for A and 88 and 125 mJy for B, at 3.6 and 13 cm, respectively. The overall calibration error is estimated to be less than 10% at both wavelengths (Marcaide 1982). The contours represent, in percent, are −1 (*broken line*), 2, 4, 6, 10, 15, 22, 30, 42, 60, 80, and 95 and −1 (*broken line*), 2, 3, 5, 7, 9, 12, 16, 21, 27, 35, 45, 60, 80, and 95 of the peak brightness temperature for maps at 3.6 and 13 cm, respectively. (Note that only one map exhibits negative contours at the levels indicated.) The peak brightness temperatures range from about 10^9 K to about 10^{10} K for the different maps. The boxed ellipses show the half-power contours of the Gaussian beams used to "restore" the maps.



(a) (b)

FIG. 2.—Spectral-index maps of the quasars 1038+528A (*a*) and 1038+528B (*b*) obtained from the brightness maps registered as shown in Fig. 1, but with all structure at 2% or less of the peak brightness level discarded. Continuous lines indicate positive spectral indices ($\alpha > 0$, $S \propto \nu^{\alpha}$), and broken lines, negative ones. We estimate the standard error in the absolute values of the spectral indices in the maps to be about 0.09, due to overall calibration uncertainties (Marcaide 1982); corresponding errors in the relative values are about 0.03. In each of the maps the maximum, zero, and minimum values of the spectral index are indicated. Contour increment is $\Delta\alpha = 0.06$ for Fig. 2*a* and $\Delta\alpha = 0.08$ for Fig. 2*b*.

with wavelength as λ^{β}, then we find that $0.7 < \beta < 2$ (see Blandford and Königl 1979 for a related theoretical discussion). VLBI experiments performed in mid-1982, but not yet analyzed, should allow this range to be contracted severalfold.

IV. SPECTRAL-INDEX MAPS

Spectral-index maps are more reliable if made from intensity maps based on data of similar resolution. However, if we were to use the common range of (u, v)-values in our VLBI data for 3.6 and 13 cm [$5 \times 10^6\lambda < d(u, v) < 50 \times 10^6\lambda$, where $d(u, v)$ is the distance of the (u, v) point from the origin], we would have to discard most of the 3.6 cm data and have little left with which to construct the 3.6 cm brightness maps. Hence, to produce spectral-index maps we used only the (u, v) points that met the condition $5 \times 10^6\lambda < d(u, v)$. The $5 \times 10^6\lambda$ cutoff was used to avoid overestimation of the faint extended structure in the 13 cm brightness maps, which could produce spurious structure in the outer part of the spectral-index maps. Thus, we first produced brightness maps from these limited data sets with the same cell size and overall extent at both wavelengths, the latter criterion being met by convolving the 3.6 cm CLEAN components with the 4 times larger diameter of the CLEAN beam from the 13 cm analysis. We used our phase-reference results to align the map pairs and computed the spectral index on a pixel-by-pixel basis. This entire procedure to make spectral-index maps was carried out with the National Radio Astronomy Observatory's Astronomical Image Processing System (AIPS) (Fomalont 1982). The hybrid maps were consistent with those obtained with the Caltech software; however, our version of this software was not sufficiently flexible to allow construction of the spectral-index maps.

In Figure 2 we present the spectral-index maps made with the registration shown in Figure 1. We also shifted the 3.6 cm maps in turn by 0.2 mas along directions parallel to the structures of each of the A and B quasars and made spectral-index maps anew. In neither case do both of these maps (Marcaide 1982) look plausible because either (1) the gradient of the spectral index is perpendicular to the axis of the radio structure, (2) the spectral index is larger at the edges of a map than in its center, (3) the spectral index takes on unacceptably large values (i.e., $\alpha \gg 2.5$, $S \propto \nu^{\alpha}$), or (4) a combination of these effects. Even shifts of 0.1 mas produce "unacceptable" symptoms. Thus we conclude that the registration shown in Figure 1 is likely within about 0.1 mas of the correct one for both quasars.

Despite the very different morphologies of the brightness maps of A and B, the spectral-index maps appear morphologically similar: The spectral-index contours have relatively long, quasi-linear segments oriented normal to the axis of the brightness structure. This "parallelism" is probably not accidental and may provide a useful criterion for making spectral-index maps when one does not have the benefit of a reference source to help determine the correct registration of brightness maps made at different wavelengths. Further, both the sky position and the value of the peak of the spectral-index map are to some degree a product of the imaging process. Consider, for example, the A quasar. The smaller the convolving beam used to obtain the brightness maps, the closer the peak in the spectral-index map will be to the peak in the shorter wavelength brightness map. Thus, to the extent that the selection of a convolving beam is arbitrary, so is the peak value of the spectral-index map and its sky position.

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