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RADIO OBSERVATIONS OF A CANDIDATE COSMIC STRING GRAVITATIONAL LENS

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ABSTRACT

The "twin-galaxies" field was tentatively suggested by Cowie and Hu as a candidate for gravitational lensing by a cosmic string. We present observations of the field made at $\lambda = 20$ cm with the A array of the VLA. We detect radio emission apparently associated with one galaxy of one of the pairs. The power and morphology are typical of a common class of radio sources, and there is nothing unusual about the properties of the radio emission to suggest that it is influenced by gravitational lensing or due to emission from the cosmic string itself. These observations make the lensing interpretation appear unlikely. However, in the absence of optical data of higher resolution and more precise registration of the radio and optical images, they cannot rule out all possible string lens models. We note that a straight string cannot accommodate the widely varying position angles of the pairs, and that the small dispersion in the measured image separations is unlikely in the case of a convoluted string.

Subject headings: early universe — gravitational lenses — radio sources: galaxies

I. INTRODUCTION

The formation of cosmic strings is a prediction of some theories of the early universe. If cosmic strings exist, they may play an important role in the formation of galaxies and large-scale structure (Vilenkin 1985 and references therein). Some directly observable consequences of cosmic strings have been proposed: temporal fluctuations in pulsar signals due to gravitational radiation from decaying cosmic strings (Vilenkin 1981*b*; Hogan and Rees 1984), fluctuations in the microwave background (Kaiser and Stebbins 1984; Gott 1985; Bouchet, Bennett, and Stebbins 1988) gravitational lensing (Vilenkin 1981*a*; Gott 1985; Hiscock 1985; Vilenkin 1984, 1986; Hogan and Narayan 1984), and, if cosmic strings are superconducting, the emission of nonthermal radiation along the string (Witten 1985; Chudnovsky *et al.* 1986; Thompson 1990). Pulsar timing and microwave background measurements have already placed limits on the properties of cosmic strings. Cosmic strings are commonly parameterized by $\mu = G\lambda/c^2$, where λ is the linear mass density, and present observational limits indicate that $\mu < 5 \times 10^{-6}$ (Bouchet, Bennett, and Stebbins 1988; Rawley *et al.* 1987). The space surrounding a cosmic string is locally flat, yet globally exhibits an angle deficit in the azimuthal angle, which makes possible the formation of gravitationally lensed double images of background sources. For cosmic strings with $\mu = 10^{-6}$, image separations of extragalactic objects are of order one to several arc seconds. The formation of many pairs of images stretching along a cosmic string is a unique property of strings, and at least one deliberate search for this signature has been proposed (Hogan 1987). Cowie and Hu (1987) recently reported the serendipitous discovery of a field of twin galaxies, which they noted had many of the properties which would be produced by lensing by a cosmic string. This unusual collection of galaxies in a $45'' \times 45''$ field consists of four or five (one pair is very faint) pairs of galaxies with very similar pairwise properties. Each pair is remarkable in that the magnitude difference in the R band is less than 0.10, except for one pair in which it is 0.13; in three pairs for which redshifts have been measured they are the same within the measurement error of 100 km s^{-1} (Hu and Cowie 1990); and both the galaxies of one pair show emission lines at the same relative intensities. These unusual properties could be explained by the presence of a cosmic string, including the small magnitude difference in one pair which is likely when extended objects (such as galaxies) are only partly imaged by the string. The observed dependence of the "image" separations on redshift agrees with that predicted by stationary string models, though such predictions must be viewed with caution given the geometry of the system (see § IV below).

An alternative explanation for the properties of the field is that we are seeing an unusual collection of binary galaxies. Cowie and Hu consider this explanation and conclude, based on previous counts of binary galaxies (Turner 1976), that one expects only three groups of four twins in the entire sky. However, as Cowie and Hu point out, if just 10% of galaxies in groups and clusters have as many binary galaxies as was estimated by Struble and Rood (1983) for A2244, the probability of the twins' being binary galaxies is roughly equal to the probability of lensing calculated in cosmic string models. This estimate of the frequency of occurrence of binaries does not require that the binaries have similar properties. Nevertheless, the binary galaxy hypothesis is a plausible alternative to that of lensing by a cosmic string, and given the far-reaching implications of a demonstration of the existence of a cosmic string, it is important to carry out tests that can distinguish between the two hypotheses. There are three tests that can be carried out at radio wavelengths: (1) a determination of whether there are any radio objects that are lensed, (2) a measurement of the fluctuations in the microwave background predicted by string models, and (3) the detection of nonthermal radiation that may be produced by a superconducting cosmic string. The second test would require a great deal of telescope time and may not be justified without further evidence that the twin galaxies field harbors a cosmic string. The uncertainty in the properties of a superconducting cosmic string makes a quantitative prediction of the brightness of nonthermal emission very difficult, although the morphology may change in a characteristic way with frequency and distance along the string (Thompson 1990). The first test, however, is straightforward

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and prompted us to image the twin-galaxies field at radio wavelengths with the National Radio Astronomy Observatory Very Large Array.[4]

II. RADIO OBSERVATIONS

We observed the twin galaxies field with the A configuration of the VLA at L band ($\lambda = 20$ cm) during a 4 hr observing run on 1988 November 30. The phase center was at R.A. $02^h49^m23^s.00$, decl. $18°25'32''.0$ (B1950), and we recorded two continuum channels, each with 50 MHz bandwidth, at right and left circular polarizations. Calibration of the antennas was based on observations of 0237−233, and the flux densities were referred to 3C 48 using the scale of Baars *et al.* (1977). Images of the sky were constructed using the NRAO Astronomical Image Processing System (AIPS) software package. Initial mapping of the data showed evidence for low levels (amplitude of <1 mJy) of interference on the short baselines. Therefore, data at projected baselines smaller than 4000 wavelengths were discarded in subsequent mapping, reducing the sensitivity of the observations to extended structure (objects $\sim 25''$ or larger are severely attenuated), but lowering the noise level in the maps. A $4' \times 4'$ field about the phase center was mapped, once giving the visibility points equal weight thereby maximizing the sensitivity to point sources, and once applying a Gaussian taper with a 50% radius of 70,000 wavelengths in the U-V plane, increasing the sensitivity to extended structure. Phase stability was exceptionally good, and the noise in the image is 30 μJy per beam without self-calibration. Two sources were detected with brightnesses greater than 5 σ. One is unresolved with flux density 0.5 ± 0.1 mJy, at R.A. $02^h49^m22^s.00$, decl. $18°24'17''.0$ (1950). The other is a double-lobed radio source with classical Fanaroff and Riley (1974) Type I (FRI) morphology and integrated flux density of 3.3 ± 0.4 mJy. No emission was detected from the quasar UM 679 which lies within the field. The quoted uncertainties in the flux densities are internal errors due to noise in the map; the systematic uncertainty in the calibration of the flux density scale is probably less than 3%. No polarization was detected in either source. In Figure 1 the radio data are superposed on an optical image (I band) of the twin-galaxies field acquired with the University of Hawaii 88 inch (2.2 m) telescope on Mauna Kea. Figure 1*a* presents a radio image of the resolved source (henceforth referred to as 0249−184), constructed giving all the visibility points equal weight ("natural" weighting) and CLEANing the resulting image. The restoring beam is an elliptical Gaussian with axes of $2''.3 \times 1''.4$ (FWHM) at a position angle of 14°. The peak brightness of 0249−184 is at $02^h49^m22^s.15$ $-18°26'01''.0$ (1950), and the radio emission appears to be associated with the A1–A2 (following the nomenclature of Cowie and Hu) galaxy pair. The redshift of the A1–A2 pair is 0.43 (Cowie and Hu 1987), giving an intrinsic power of the radio source, assuming isotropic emission, of $9 \times 10^{22} h^{-2}$ W sr^{-1} Hz^{-1} and a linear size of $\sim 70 h^{-1}$ kpc ($H_0 = 100h$ km s^{-1} Mpc^{-1}; $q_0 = \frac{1}{2}$), which are consistent with the range usually seen in FRI radio sources (Faranoff and Riley 1974; Shaver *et al.* 1982). The radio power is brighter than that usually seen in optically selected elliptical galaxies (Hummel, Kotanyi, and Ekers 1983). The distortion of the radio lobes is typical of the "C-type" distortion often seen in radio sources (Ekers *et al.* 1981). In Figure 1*b* we display a plot of the positions of all CLEAN components associated with peaks of 4 σ or more identified during the CLEANing of the map of Figure 1*a*. With 33,024 pixels plotted, we expect just two CLEAN components, because of noise.

III. COMPARISON OF RADIO AND OPTICAL DATA

To compare the optical and radio data a registration of radio and optical images must be carried out. Since the accuracy of this procedure is important in our analysis, we describe it in some detail. In the CCD frame, there are no stars bright enough to appear in catalogs of positional standards. Therefore, we measured positions of the brighter stellar objects visible on the CCD frame relative to bright positional standards on the Palomar Sky Survey plate. This was accomplished with the ASTRO astrometric plate-fitting program at the National Optical Astronomy Observatories' Kitt Peak National Observatory[5]; a six-parameter fit yielded a plate solution with a standard error of $0''.5$. The VISTA (Lauer, Stover, and Terndrup 1983) plate fitting program was used to determine a plate solution with the bright stellar objects on the CCD frame; the standard error of a six-parameter fit was $0''.3$. The coordinates of the radio map are referred to 0237−233, for which the position is known to $\sim 0''.03$. The astrometric accuracy of A array, L band observations are affected by the ionosphere; we calculate that for our observations the effect is not larger than $0''.05$, depending on the activity in the ionosphere (Bignell and Perley 1986). Finally, differences as large as $0''.2$ between the optical and radio reference frames have been measured (de Vegt and Gehlich 1982). Thus, we estimate an overall positional uncertainty of $0''.6$. The northern radio point source is coincident with a marginally resolved object on the CCD frame. This identification provides a further check of our plate solutions; we measure no difference in right ascension and a difference of $0''.4$ in declination.

In the image of Figure 1*a*, it appears that the radio lobes lie along the edge of the optical galaxy A2. However, the higher resolution of Figure 1*b* indicates that the lobes point directly at the nucleus of A2. The apparent misalignment of the lobes and the nucleus of the galaxy in Figure 1*a* is probably due either to the uncertainty in the registration of the images, or to the absence of emission from the core of the galaxy combined with the distortion of the lobes and the finite resolution of the image. The angular separation of the A1 and A2 galaxies is $2''.45$; for the jets to be aligned with A1 rather than A2 would require a shift in the coordinates of $\sim 4\ \sigma$.

IV. DISCUSSION

The most straightforward interpretation of the data is that the radio source 0249−184 is physically associated with the A1–A2 galaxy pair, and consists of radio lobes caused by activity in the nucleus of A2. The source's power and morphology are typical of a common class of radio sources. The different radio properties of the A1 and A2 galaxies do not support the lensing interpretation of the twin-galaxies field. There is nothing unusual about the source to suggest that we are seeing a double image of a radio source with an angular separation of $\sim 2''$, or that we are seeing radio emission from the cosmic string itself. A stationary string falling in front of a linear structure such as a radio jet would cause a break in the structure

[4] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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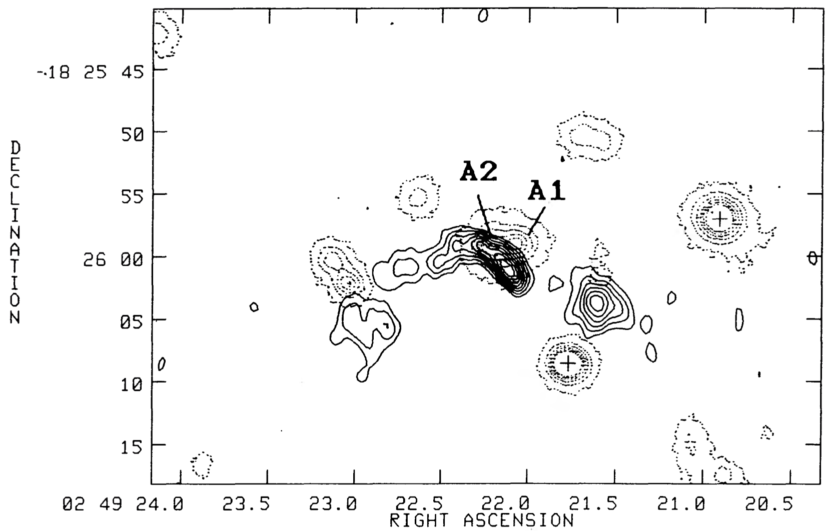

FIG. 1*a*

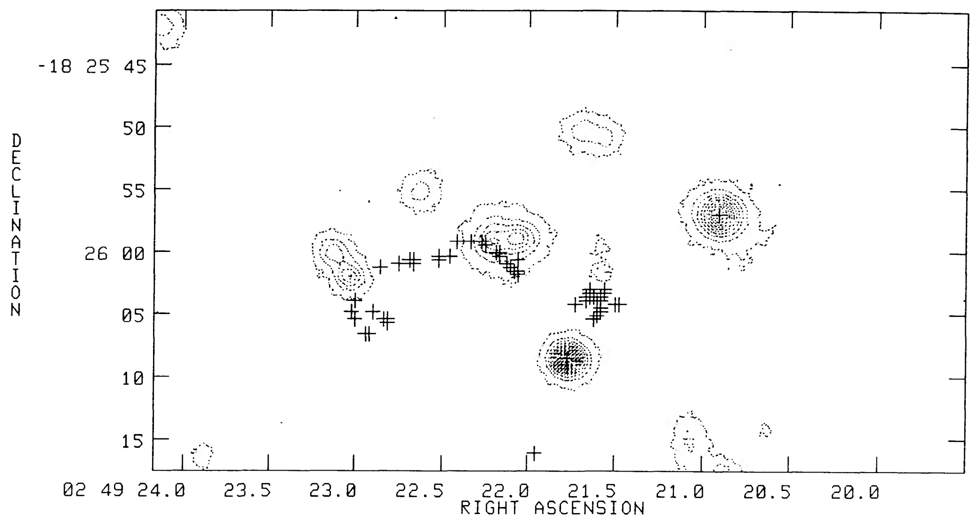

FIG. 1*b*

FIG. 1.—(*a*) Contour plot of $\lambda = 20$ cm radio map (*solid contours*) of 0249−184 superposed on an optical *I* band image (*dotted contours*) of the field. The radio contours are 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the peak brightness of 370 μJy beam. No attempt has been made to calibrate the optical image; the contours are linear in the CCD data numbers. (*b*) Plot of the CLEAN components associated with radio peaks greater than 4 σ, superimposed on the optical image (*dotted contours*). The size of the crosses ($\pm 1\ \sigma$) represents the uncertainty in the registration of the radio and optical images. The crosses at the locations of the two bright stellar objects are the positions of the stellar objects calculated in the radio image used in the image registration.

and an overlap between the two pieces (Fig. 2); the separation between the two pieces is $\Delta\theta \cos \eta$ and the overlap is $\Delta\theta(\cos^2 \eta/\sin \eta)$, where $\Delta\theta$ is the image splitting for a point source, and η is the angle between the string and the unlensed jet. There is a break in the CLEAN component model of the radio jet, $\sim 4''$ east of galaxy A2, with separation of $\sim 1\overset{''}{.}6$. The (perhaps overly) simple model of a stationary string predicts that the break should be accompanied by a $1\overset{''}{.}3$ overlap, which is not observed.

There are perhaps three ways in which lensing by a cosmic string might still be consistent with the data: if the radio properties of the galaxy change radically during the time delay of the lens, if the radio-emitting regions of the galaxies fail to lie in a part of the sky that is multiply imaged, or if the source of radio emission is in front of the lens. The first possibility is extremely unlikely, given the short (of order 1 yr) time delay and the long lifetime of radio lobes. Since both the radio and optical sources of emission are extended and their registration is uncertain, the second possibility must be seriously considered. In the case of lensing by a straight string, the images are not magnified. A difference in the magnitudes of the two galaxies images must then be due to partial imaging of the galaxy; part of the galaxy falls outside of the region of the sky that is multiply imaged by the string. For the radio emission to be associated with the fainter of the two galaxy images only, it must also fall outside the region of the sky that is multiply imaged, but on the other side of the string. This sort of lensing geometry may be consistent with the data, but seems rather

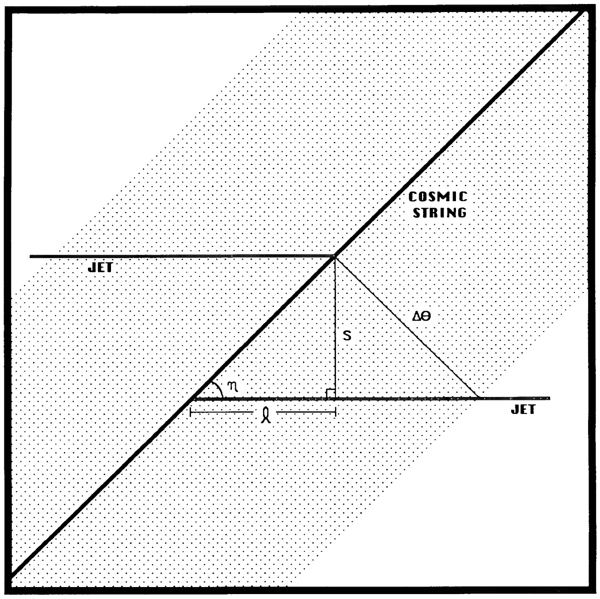

FIG. 2.—Schematic diagram of lensing of a linear structure, such as a radio jet, by a cosmic string. The angle between the string and the jet is η, and the part of the sky that is imaged twice is represented by the shaded region. A point source in the shaded region has two images with angular separation $\Delta\theta$. The cosmic string causes an apparent break in the jet with separation s and overlap l.

contrived. A less contrived configuration may be possible if one can arrange for the magnification of the partial image of the galaxy to cause it to be brighter than the full image of the galaxy. This might be possible with a curved string. The third possibility implies that the redshift of the radio source is smaller than 0.2 (the smallest redshift among the galaxy pairs), and that the intrinsic power and linear size of the radio source are correspondingly reduced by factors of at least 6 and 1.6, respectively. The large range of these values normally seen in FRI radio sources precludes an interesting lower limit on the radio source redshift, but it would be surprising not to detect a low redshift galaxy in the CCD image. The detection of a core radio component, perhaps possible with observations at higher frequencies, would help to determine whether the radio emission and galaxy are indeed physically associated.

Some of the above discussion has been based on the lensing properties expected for a straight string. We note in passing that the values of the angular separation $\Delta\theta$ observed are *not* distributed as one would expect on the hypothesis of lensing by a convoluted cosmic string loop. The widely varying position angles of the galaxy pairs indicate that the putative lensing cosmic string must be quite irregular and convoluted on the scale of the galaxy group. This in itself is consistent with the complicated string configurations calculated in string evolution simulations (Bennett and Bouchet 1988). However, it implies that α, the angle between the string and the line of sight, should vary widely from pair to pair, and that different pieces of the string may move with very different velocities. Although Cowie and Hu have taken the near constancy of the splittings to be evidence for the presence of a string, it might also be interpreted as contrary evidence. If the observed $\Delta\theta$ value for pair C at $z = 0.200$ is corrected to the value it would have if it were at the redshift (0.43) of the other galaxies, all four values lie in the narrow range of 2".45–2".57 having a mean of 2".52 and dispersion of only 0".05 (probably consistent with measuring errors). The angular splitting produced by a cosmic string lens varies as sin α. For randomly distributed values of α, the probability of observing a splitting greater than $\Delta\theta$ is just

$$P(\geq \Delta\theta) = \sqrt{1 - \left(\frac{\Delta\theta}{\Delta\theta_0}\right)^2}\,,$$

where $\Delta\theta_0$ is the angular splitting which would result if the string were perpendicular to the line of sight. It is then easy to show that $\langle\Delta\theta\rangle = (\pi/4)\Delta\theta_0$, $\sigma_{\Delta\theta} = \Delta\theta_0(\frac{2}{3} - \pi^2/16)^{1/2}$, and thus $\sigma_{\Delta\theta}/\langle\Delta\theta\rangle = 0.284$. This constrasts strongly with the observed value of the latter ratio which is 0.019, nearly 15 times smaller. Although this anomaly might be explained by a selection effect that eliminates small $\Delta\theta$ pairs from detection, it should be recognized that this explanation implies the existence of large numbers of undetected, small separation pairs created by cosmic string lenses. Similarly, varying velocities along the string would tend to introduce a dispersion in the image splittings measured; the possible splittings range from $[(1 - v/c)/(1 + v/c)]^{1/2}\Delta\theta$ to $[(1 + v/c)/(1 - v/c)]^{1/2}\Delta\theta$ (Vilenkin 1986). Since the velocity is likely to be of order the speed of light along at least some sections of the string, the effect on the dispersion could be quite large.

In summary, these VLA observations of the twin galaxies field make the lensing interpretation appear unlikely, yet in the absence of higher resolution optical data and more precise registration of the radio and optical images, cannot rule out all possible string lens models.

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