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DETECTION OF SUPERLUMINAL MOTION IN THE CORE-DOMINATED QUASAR 0106+013

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ABSTRACT

We have observed the core-dominated quasar 0106+013 with a global VLBI Array at $\lambda = 6$ cm in 1986 and 1988. The radio structure changed dramatically between the two epochs from barely resolved to well-separated double with flux ratio 3:2. Identifying the changes with east-west movement between two components, we find the proper motion $\mu = 0.20 \pm 0.5$ mas yr^{-1} which corresponds to $v/c = (8.2 \pm 2.0)/h$ (for $z = 2.107$; $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$). The speed is typical of superluminal quasars. We note that 0106+013 is a key object in VLBI-based geodetic measurements; knowledge of its structure should improve the accuracy of measurements of crustal dynamics.

Subject headings: quasars — radio sources: galaxies — relativity

I. INTRODUCTION

In 1986, M. H. Cohen and colleagues began a program to study the VLBI morphology of strong, highly variable radio sources. One of the aims of the survey was to study sources at high redshift because observing their internal proper motions can be used to constrain cosmological models (Yahil 1979; Cohen *et al.* 1988) via the proper motion–redshift diagram ("μ-z diagram"). The distribution of speeds can also be used to test relativistic beaming theories. Further, sources at high redshift may behave differently from low-redshift sources, and any detectable evolutionary effects would be of intrinsic interest. We observed the core-dominated quasar 0106+013 because it is strong, it has variable flux, and its high redshift of $z = 2.107$ makes measurement of its internal proper motions particularly useful on the μ-z diagram. The quasar 0106+013, also known as OC 012 and 4C 1.02, has been used for many years as a "point source" calibrator at radio frequencies. Because it has been bright for many years (see, for example, light curves in Aller *et al.* 1985), it has also been used for optical and radio reference frame ties (e.g., Argue *et al.* 1984) and is a key point in VLBI–based crustal dynamics studies (e.g., Robertson, Fallon, and Carter 1986; Sovers *et al.* 1988).

II. OBSERVATIONS

Two observing sessions were conducted with the global VLBI Array in 1986 June and 1988 June. The frequency was 4.991 GHz with a bandwidth of 2 MHz. The antennas used in 1986 were Onsala, Effelsberg, Jodrell Bank, Bologna, Hartebeesthoek (South Africa), Arecibo, Haystack, NRAO[1] Green Bank, NRL Maryland Point, NRAO Very Large Array, Owens Valley, and Hat Creek. The same set of antennas was used in 1988 with the addition of the antennas at Westerbork, Fort Davis, the new VLBA antenna at Pie Town (New Mexico), and the deletion of the antennas at Hartebeesthoek, Arecibo, Maryland Point, and Hat Creek. The full width at half-maximum of the 1986 beam was 0.9 × 4.0 mas with position angle 171°. The flux density measured by the 40 m antenna at Owens Valley was 4.2 Jy and 3.1 Jy during the 1986 and 1988 observing sessions, respectively. The absolute flux density calibration is uncertain by about 10%.

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

We cross-correlated the tapes from the antennas on the JPL/Caltech Block II Correlator. The data were fringe-fitted using the new CALIB software (version 15OCT88) from the NRAO AIPS group, and images were made using the Caltech VLBI software package. Using the global array to observe this nearly equatorial source (with uniform weighting of the data) produced a dirty beam with several peaks over 50% power. We chose a Gaussian CLEAN beam whose envelope encloses the central peaks over 50% in the 1986 observations; the 1988 observations require a slightly larger envelope. To allow a comparison of the two observations, we convolved the 1988 data with the 1986 beam, i.e., images were formed by convolving the CLEAN components with a Gaussian beam of FWHM 0.9 mas × 4.0 mas with position angle 171°.

III. RESULTS

a) Structure

The 1986 and 1988 images, convolved with the full CLEAN beam, are shown in Figures 1 and 2. Figures 3 and 4 show the same CLEAN components convolved with a "superresolving" beam of 0.45 mas × 4.0 mas with position angle 171°. In 1986, the source was barely resolved in the east-west direction and unresolved north-south. The data were well fitted by a model with two circular Gaussian components with separation of 0.75 ± 0.05 mas. By 1988, the source had changed dramatically: it was a strong double with flux ratio 3:2 and east-west separation of about 1.15 ± 0.05 mas. The details of the models are given in Table 1. The components are labeled E (east) and W (west). We are unable at this time to identify the core from lack of spectral index information.

In 1986, components E and W had flux densities of 0.8 and 2.8 Jy, respectively, while the total flux density was 4.2 Jy. By 1988, E and W had flux densities of 1.8 and 1.1 Jy, respectively, while the total flux density had declined to 3.1 Jy. Both maps are missing some of the flux density; because there is no evidence that the "missing flux" is seen on the short baselines, we think that it must be diffuse, i.e., be on scales of 10 mas or larger. The overall flux calibration, of course, is uncertain by about 10%, so there may not be much flux density actually "missing."

b) Superluminal Motion

We interpret the change in the structure between 1986 and 1988 as an increasing separation of E and W from about 0.75

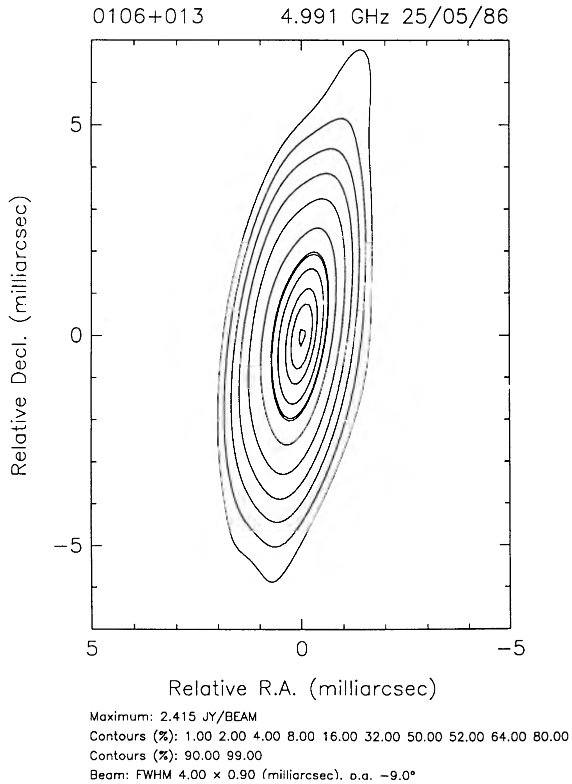

FIG. 1.—Image at 5 GHz from data obtained in 1986 May. The CLEAN components are convolved with a beam of FWHM 0.9 × 4.0 mas with position angle 171°. In all images, north is at the top, and east is to the left.

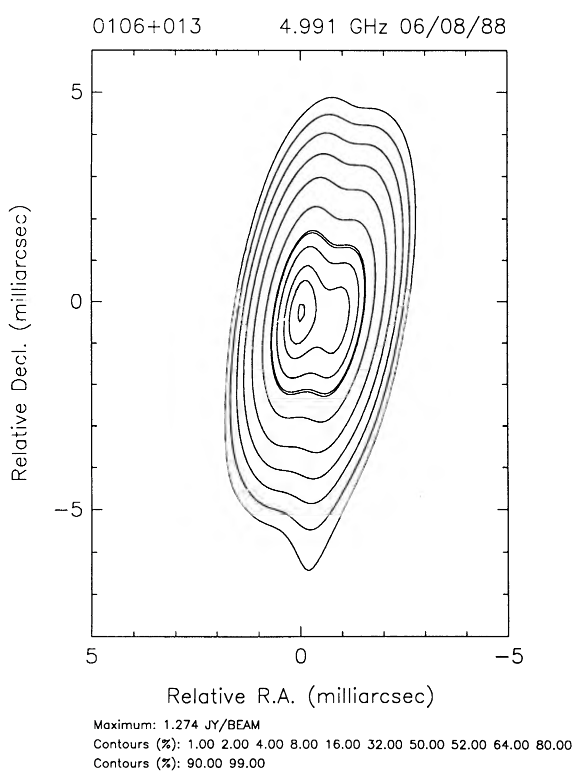

FIG. 2.—Image at 5 GHz from data obtained in 1988 June. The CLEAN components are convolved with a beam of FWHM 0.9 × 4.0 mas with position angle 171°.

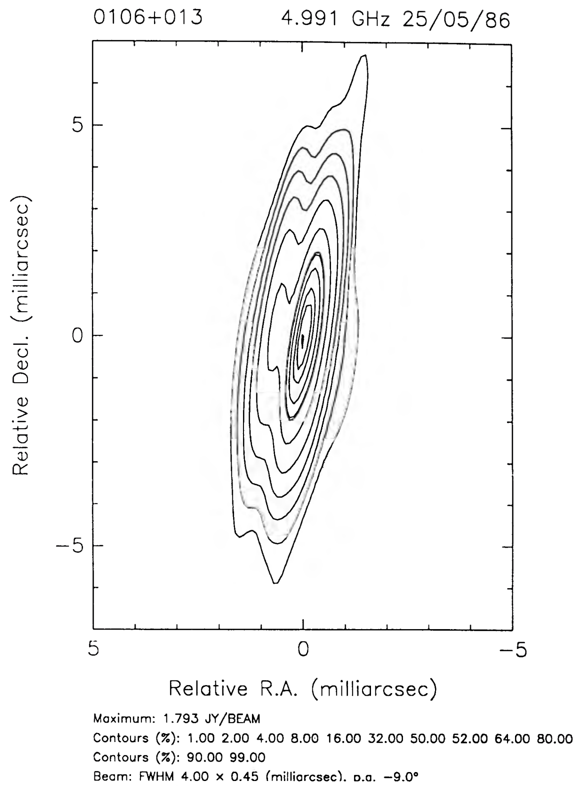

FIG. 3.—Superresolved image of 1986 May with CLEAN components convolved with a beam of FWHM 0.45 × 4.0 mas with position angle 171°.

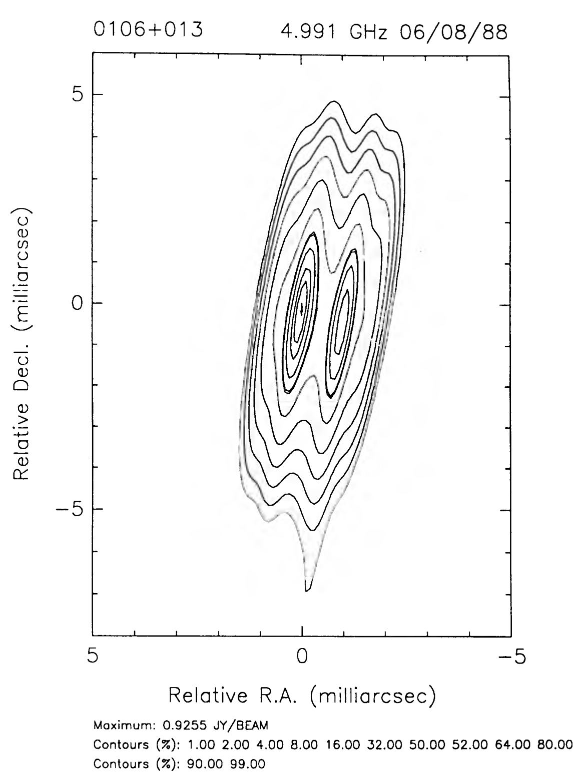

FIG. 4.—Superresolved image of 1988 June with CLEAN components convolved with a beam of FWHM 0.45 × 4.0 mas with position angle 171°.

TABLE 1

CHARACTERISTICS OF THE CIRCULAR GAUSSIAN MODELS

Flux[a] (Jy) (1)	Radius[b] (mas) (2)	Theta[c]	Size[d] (mas) (4)
	1986 Data		
2.8.........	0	0°	0.7
0.8.........	0.75	78	0.7
	1988 Data		
1.8.........	0	0	0.9
1.1.........	1.15	70	0.7

[a] Component flux density.
[b] Distance of center of component from the origin.
[c] Position angle of center of component with respect to the origin, north through east.
[d] Major axis of component.

to 1.15 mas. This motion corresponds to about one-half the beamwidth in the east-west direction. Our estimate of the error in the separation measurement is about one-eighth beam or 0.10 mas; it can be this small because the structures are simple, the components are bright, and the motion is along the direction of maximum resolution. We estimate the position angle along which the components move as $70° \pm 20°$ with the caveat that the high elongation of the beam makes such estimates difficult. These observations give $\mu = 0.2 \pm 0.05$ mas yr^{-1}, corresponding to $v/c = (8.2 \pm 2.0)/h$, where $h = H_0/100$ km s^{-1} Mpc^{-1}; $q_0 = 0.5$. This value is typical of the maximum apparent transverse speed seen in other strong, variable quasars.

IV. DISCUSSION

In compact radio sources, the "core," when it exists, is at one end of the linear structure. It is typically the most compact part of the source at centimeter wavelengths. It has the flattest spectrum and thus represents that portion of the source which persists to the short-wavelength (mm) region. The core cannot be identified in Figures 1 and 2, because there is no spectral information and because neither component is relatively stable. However, we can use the evolution of other sources as a guide in interpreting the structure of 0106+013. We note that 6 cm observations of a $z = 2$ quasar are equivalent to 2 cm observations of nearby quasars. There is little 2 cm information on quasars, but the behavior must be between that for 2.8 cm and 1.3 cm (common observing wavelengths for VLBI). At these short wavelengths, the core brightness tends to be equal to or stronger than any of the moving components, but in 0106+013, the core may be weaker than the moving component. Because of time dilation which is important at high redshifts, we expect the moving component in 0106+013 to fade slowly in our rest frame. Deciding which of the two components is the core will require further monitoring and, probably, observation at another frequency. We see two alternative versions of events in 0106+013 based on which component we identify as the core.

1. Component E is the core.—The core E was weak in 1986 (0.8 Jy) and brightened by 1988 (1.8 Jy), as if the ejection of a new component were imminent. In this version, component W was ejected about 1982 (assuming constant speed of 0.2 mas yr^{-1}): it was very bright in 1986 (2.8 Jy) and faded to 1.1 Jy in 1988. In this scenario, we expect W will dim as it moves further from the core, as moving components do in nearby sources at 2.8 and 1.3 cm. We also expect the emergence of a new component from the core because it is brightening.

2. Component W is the core.—The core W was bright in 1986 (2.8 Jy) and faded by 1988 (1.1 Jy). The traveling component E has moved away from the core toward the east and has brightened from 0.8 Jy to 1.8 Jy as it moved. We know of no other source which has a component brightening to this extent at either 2.8 or 1.3 cm; usually components fade on a time scale of a half-dozen years as they move away from the core.

Regardless of which component is the core, the VLBI morphology has a position angle which is quite different from the arcsecond morphology. VLA observations by Kollgaard, Wardle, and Roberts (1990) show that 0106+013 has a core-jet structure with a very faint jet pointing to the south. The VLBI jet is east-west, and somewhere on the 10–500 mas scale, it must turn south. Barthel and Miley (1988) have suggested that high-redshift objects are more bent than those at low redshift ($z < 1.5$). The quasar 0106+013 has a 90° bend from its milliarcsecond to arcsecond scale structures, fitting smoothly into the picture of more convoluted structure at high redshifts. An intermediate-scale radio image of 0106+013 with high dynamic range is needed to show where the transition from east-west to north-south morphology occurs, but this will be difficult to obtain due to the equatorial location of 0106+013.

The 1986 VLA map of Kollgaard *et al.* shows that the magnetic field in the arcsecond-scale core was oriented perpendicular to the direction of superluminal motion in 0106+013. However, quasars usually have their arcsecond-scale magnetic fields and VLBI structures aligned (Wardle and Roberts 1988; Gabuzda *et al.* 1989). This feature, and the core discussion above, mark 0106+013 as unusual and worthy of further study.

Because 0106+013 has been bright and compact for many years, it has been used as a reference point in crustal dynamics studies. The effects of radio source structure on measurements important to crustal dynamics have recently undergone thorough examination (e.g., Charlot 1989*a*, *b*; Sovers *et al.* 1988), and software now exists to take advantage of knowledge of source structure. Both the astronomical and geodetic communities would benefit from the mapping of bright, compact radio sources such as 0106+013. It is also worth emphasizing that compact objects can change and evolve into complex structures. No "point source" list is permanent: for example, at least three sources on Shaffer's (1984) list are now known to be extended (0106+013, 0234+285, and 2251+158).

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