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APPARENT SUPERLUMINAL MOTION IN THE QUASAR NRAO 140

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ABSTRACT

Very long baseline interferometer (VLBI) measurements of the compact radio structure in the quasar NRAO 140 ($z = 1.258$) have been obtained at three epochs at a wavelength of 2.8 cm. These observations indicate that the two most compact radio components are separating at an angular rate of 0.10–0.14 milli-arcsec per year. For cosmological distances and $H_0 = 50$ and $q_0 = 0$, this corresponds to a velocity of separation (in the quasar's rest frame) of 10 ± 2 times the speed of light, c; for $H_0 = 100$ and $q_0 = 1$, the value is $(3.1 \pm 0.6)c$. Other interpretations of the temporal changes in correlated flux density and closure phase are discussed and are considered unlikely. The derived velocities are consistent with an earlier prediction by us that the separation velocity should be greater than about $4c$.

Extrapolation back to the epoch of zero separation indicates that the expansion originated between late 1963 and late 1968 (under the assumption of constant velocity). This range includes the beginning of an isolated outburst in flux density at 2.8 cm.

These results *cannot* be used to make any statements concerning the validity of cosmological interpretations of QSO redshifts.

Subject headings: interferometry — quasars — relativity — X-rays: sources

I. INTRODUCTION

NRAO 140 (0333+321) is a quasar ($z = 1.258$) which is among only three or four such objects (and the one with the highest z) which were detected at X-ray energies prior to the operation of the *Einstein Observatory* (Marscher *et al.* 1979). We obtained contemporaneous X-ray and radio VLBI observations of the source in early 1980 to determine whether Compton scattering within the radio source is the primary X-ray emission mechanism (Marscher and Broderick 1981*b*, hereafter Paper II). Instead, we found that the radio parameters predicted more than 10^3 times more X-ray flux than was observed. Since the Compton calculation is independent of distance, and since the troublesome component was partially resolved (and hence not a high brightness-temperature emitter), we concluded that relativistic motion aimed almost directly toward the observer, with the Lorentz factor exceeding 4, needed to be invoked in order to bring the predicted Compton flux down to the observed level (Marscher and Broderick 1981*a*, hereafter Paper I; also Paper II). Since relativistic motion is also the preferred explanation for the apparent superluminal expansion seen in some compact extragalactic radio sources (e.g., Cohen 1981; Kellermann and Pauliny-Toth 1981; Marscher and Scott 1980), we predicted that the compact components in NRAO 140 should appear to separate at a speed exceeding about $4c$. (Note: this prediction was based upon an analogy with similar objects; it serves as neither a necessary nor a sufficient condition for the existence of relativistic motion in NRAO 140.)

We report in this *Letter* subsequent VLBI observations which indicate that the compact components in NRAO 140 are indeed separating at a superluminal rate, if one assumes (as we shall) standard cosmological distances with $H_0 \lesssim 100$ and $q_0 \lesssim 1$.

II. OBSERVATIONS

We observed NRAO 140 at 2.8 cm using an intercontinental VLB array for 6 hr on 1981 February 2–3 and for 11 hr on 1981 June 8. The stations used were the 100 m telescope at Effelsburg, West Germany (referred to as BONN); the 37 m antenna at Haystack, Massachusetts (HSTK); the 43 m dish at the National Radio Astronomy Observatory[1] in Green Bank, West Virginia

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

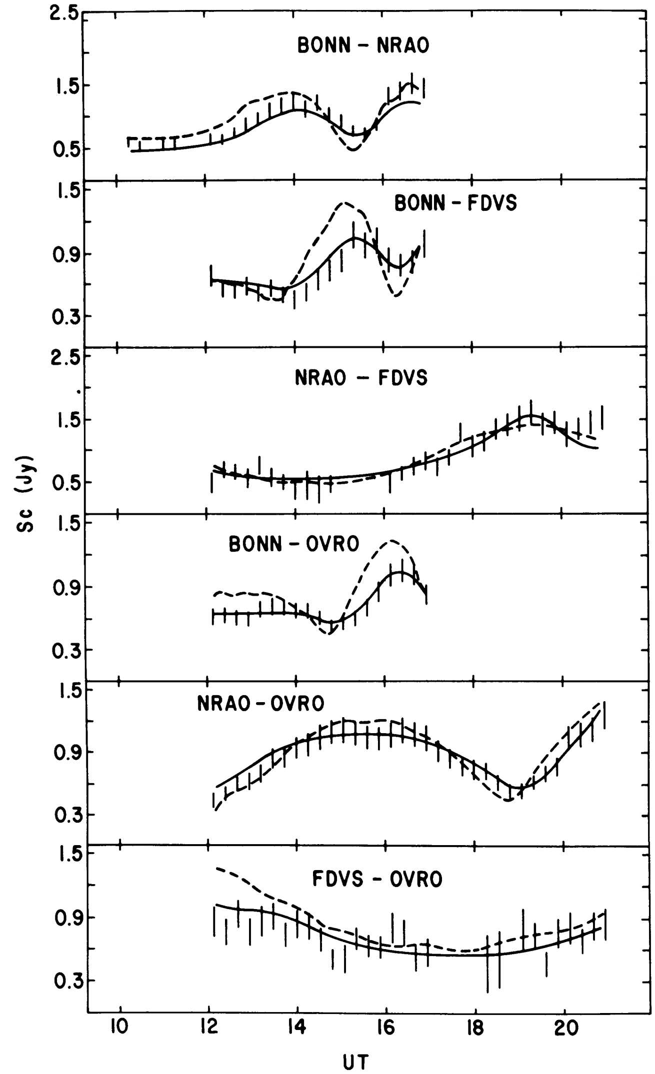

FIG. 1.—Correlated flux density vs. universal time for NRAO 140 on 1981 June 8 at 2.8 cm. *Dashed curve*: hybrid map model for 1980 April observations. *Solid curve*: best-fit model for 1981 June, as discussed in text.

(NRAO); the 26 m dish at Harvard Radio Astronomy Station in Fort Davis, Texas (FDVS); and the 40 m antenna at the Owens Valley Radio Observatory near Big Pine, California (OVRO). FDVS was not used in February, and a pointing problem at HSTK caused us to lose that station in June. Total flux density measurements were taken at BONN just prior to our observations. System temperature calibrations were made at least once every hour, while standard gain curves were used to derive antenna temperatures.

Processing of the video tapes and all post-processing data reduction were performed at Caltech using the Jet Propulsion Laboratory, California Institute of Technology (JPL-CIT) VLBI processor and VAX computer.

III. RESULTS

The correlated flux densities and closure phases are plotted in Figures 1 and 2, respectively, as a function of universal time on 1981 June 8. Since the 1981 February 2–3 $u - v$ tracks were relatively short (6 hr), the data taken on this date were not sufficient to construct a map of the source. These data are not illustrated here, and we merely note that they follow the temporal trends discussed for the more complete observations.

Receiver problems at FDVS, combined with the relative weakness of NRAO 140 at 2.8 cm ($S_\nu = 2.15$ Jy on 1981 June 8), caused the source to be only marginally detected on the NRAO-FDVS and FDVS-OVRO baselines whenever the correlated flux density S_c fell below

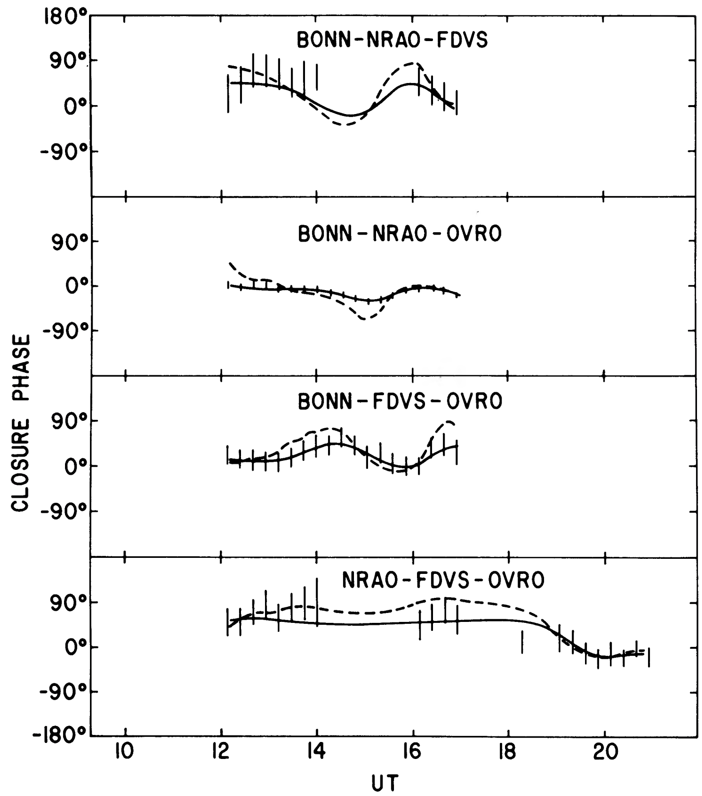

FIG. 2.—Closure phase vs. universal time for NRAO 140 on 1981 June 8 at 2.8 cm. Curves have same meaning as in Fig. 1.

about 0.6 Jy. When a source is only marginally detected, the closure phases determined by the correlator become much less reliable than normal. Hence, the following sets of closure phases are poorly determined: BONN-NRAO-FDVS from 1200 to 1400 hr UT; BONN-FDVS-OVRO from 1400 to 1900 hr UT; and NRAO-FDVS-OVRO from 1200 to 1900 hr UT. We have attempted to partially compensate for this problem by adopting error bars which reflect the uncertainties in the affected data points.

The dashed curves in Figures 1 and 2 represent the fit of the 1980 April hybrid map model (the model curves pass through the middle of the 1980 April data points) to the 1981 June data. (The 1980 April observations and model are discussed thoroughly in Papers I and II.) This illustrates the changes which have occurred in the visibility function between the two epochs. In particular, the maxima and minima in the correlated flux densities have shifted in the sense that the angular separation of the compact components has increased. This trend is also apparent in the 1981 February data, which are not shown. In addition, the BONN-NRAO-OVRO closure phases have changed substantially, indicating that the flux densities or sizes of the components have changed.

To quantify these trends, we have obtained source models which are capable of reproducing the observed correlated flux densities and closure phases. As in Paper I, we adopt a three-component model: a strong, compact, elliptical Gaussian component (A); a weaker, compact component (B), and a more diffuse, elongated component (Jet). For 1981 June 8, we find for a best-fit model: S_ν (A) = 0.95 Jy, FWHM (A) = 0.40 milliarcsec (mas), axial ratio (ratio of minor to major axis) AR (A) = 0 (unresolved minor axis) elongated along P.A. 134°; S_ν (B) = 0.42 Jy, separation from A $\theta_{\rm sep}$ = 1.77 ± 0.02 mas along P.A. 127°, FWHM (B) = 0.57 mas, AR (B) = 0.67, elongated along P.A. 151°; S_ν (Jet) = 0.78 Jy (other parameters not well determined by the 1981 June data). Because of the substantial uncertainties in much of the closure phase data, only the following information is considered reliable: component A is long and thin; component B has expanded somewhat since 1980 April; component B has decreased in flux density; and the separation of components A and B has increased by nearly 10% while maintaining a constant position angle ($\theta_{\rm sep}$ = 1.64 ± 0.02 mas in 1980 April). The fit of this model to the data is given by the solid curves in Figures 1 and 2.

The long, thin structure of component A leads to the suspicion that it is really composed of two subcomponents. For this reason, we have also obtained best-fit models which adopt this as an assumption, for both

1980 April and 1981 June. We shall use the designation "A1" for the subcomponent which is further from component B and "A2" for the other one. For 1980 April we obtain θ_{sep} (A1 to B) = 1.73 ± 0.02 mas and θ_{sep} (brightness centroid of A1, A2 to B) = 1.62 ± 0.02 mas. For 1981 June we find θ_{sep} (A1 to B) = 1.87 ± 0.02 mas and θ_{sep} (centroid of A1, A2 to B) = 1.76 ± 0.02 mas. These models yield fits to the data which are nearly identical to that of the simpler model described above.

By comparing the increase in component separation from 1980 April to 1981 June obtained for each model, we obtain consistently the value $\Delta\theta_{sep}$ (1980 April to 1981 June) = 0.14 ± 0.02 mas. This corresponds to an angular separation rate $\dot{\theta}_{sep} = 0.12 \pm 0.02$ mas yr^{-1} for NRAO 140. In the rest frame of the quasar, we then obtain an apparent velocity of separation which ranges from $V_{sep} = (10 \pm 2)c$ for $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, to $V_{sep} = (3.1 \pm 0.5)c$ for $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 1$. These values for V_{sep} are entirely consistent with our previous assertion (Papers I and II) that at least component B is undergoing bulk relativistic motion with the Lorentz factor exceeding ~ 4.

IV. DISCUSSION

a) *Possibilities Other Than Superluminal Motion*

Since the fractional increase in component separation which we have observed in NRAO 140 amounts to less than 10%, we wish to stress that our conclusion, that apparent superluminal motion is occurring in this source, is certainly not unequivocal. Here we consider other possible interpretations of our observational results.

One potential problem is that any particular model based on data from four stations is not unique. One must therefore make certain that there does not exist a model in which the components are not separating superluminally. In general, such a model source would be composed of three distinct compact components which change in brightness so as to simulate expansion of the source. We have searched for such a model using latest model-fitting procedures in the JPL-CIT VLBI software package and have found none which gives a reasonable fit to the data.

Another problem is that the increase in component separation from 1980 April to 1981 June is less than 50% of the FWHM major axis of component B. This, together with the apparent decrease in brightness of component B, would suggest that if the part of component B which is closest to component A had disappeared between the two dates of observation, the centroid of B could have shifted enough to simulate the observed component motion. Indeed, we can model component B in 1980 April as being composed of two unresolved subcomponents, although this exacerbates the Compton problem discussed in Papers I and II. If the subcomponent of B closest to A had nearly disappeared by 1981 June, the brightness centroid of B could have shifted enough to create the illusion of component motion. However, we have already established that component B appeared quite large in 1981 June, such that, if it appeared as an unresolved subcomponent in 1980 April, it has expanded at a highly superluminal rate.

Hence, the two possibilities by which apparent superluminal motion could be avoided do not appear to be likely alternatives. Nevertheless, it is important to continue monitoring NRAO 140 to confirm and establish the rate of the apparent superluminal motion.

b) *Relationship between Structural Variations and Outbursts in Flux Density*

Using the observed rate of increase of component separation and assuming that this rate is constant, we can establish the extrapolated epoch of zero separation. We find that the source expansion was initiated (if the extrapolation is valid) sometime between late 1963 and late 1968. The flux density history of NRAO 140 is interesting in that, unlike the other known superluminal sources (e.g., Cohen *et al.* 1977), it is not extremely variable in the radio. If we piece together the radio "light curve" of NRAO 140 from the data of Medd *et al.* (1972), Altschuler and Wardle (1976), Marscher *et al.* (1979), and W. A. Dent and T. J. Balonek (private communication), we find that the flux density at centimetric wavelengths has been nearly constant since 1966.5 except for two distinct outbursts. One began in early 1968 at 2.8 cm, while the other started in early 1977 at 3.8 cm. We can therefore match the creation of component B with the isolated flux density outburst of 1968. However, it is not as straightforward to form a connection between the outburst of 1977 and a structural feature at 2.8 cm. In the VLBI model wherein component A is made up of two subcomponents, A1 and A2, we could identify A2 as a product of the 1977 event. The separation rate of A1 from A2 would then be less than half of that of A1, A2 from B. Further monitoring of NRAO 140 with a VLB array should determine whether the creation of component A2 was in fact the cause of the 1977 radio flare.

c) *Relationship to Cosmological Parameters and the Nature of QSO Redshifts*

As we have proposed in a previous paper (Marscher and Broderick 1981*c*), X-ray and VLBI observations of a large sample of sources similar to NRAO 140 would allow one to place upper limits on the cosmological parameters H_0 and q_0, provided that QSO redshifts are cosmological in origin. This is done by determining a distance-independent lower limit for the Lorentz factor of relativistic motion in the manner of Papers I and II. This can then be compared with the distance-dependent determination of the Lorentz factor needed to produce the observed superluminal motion in order to derive a lower limit on the distance.

Despite the self-consistency of this procedure, it is not possible to exclude noncosmological distances in this way. The difficulty occurs because the connection between apparent superluminal motion and relativistic motion is a *theoretical* one, and it is *not* backed up by direct observational evidence (such as blueshifting of a spectral feature).

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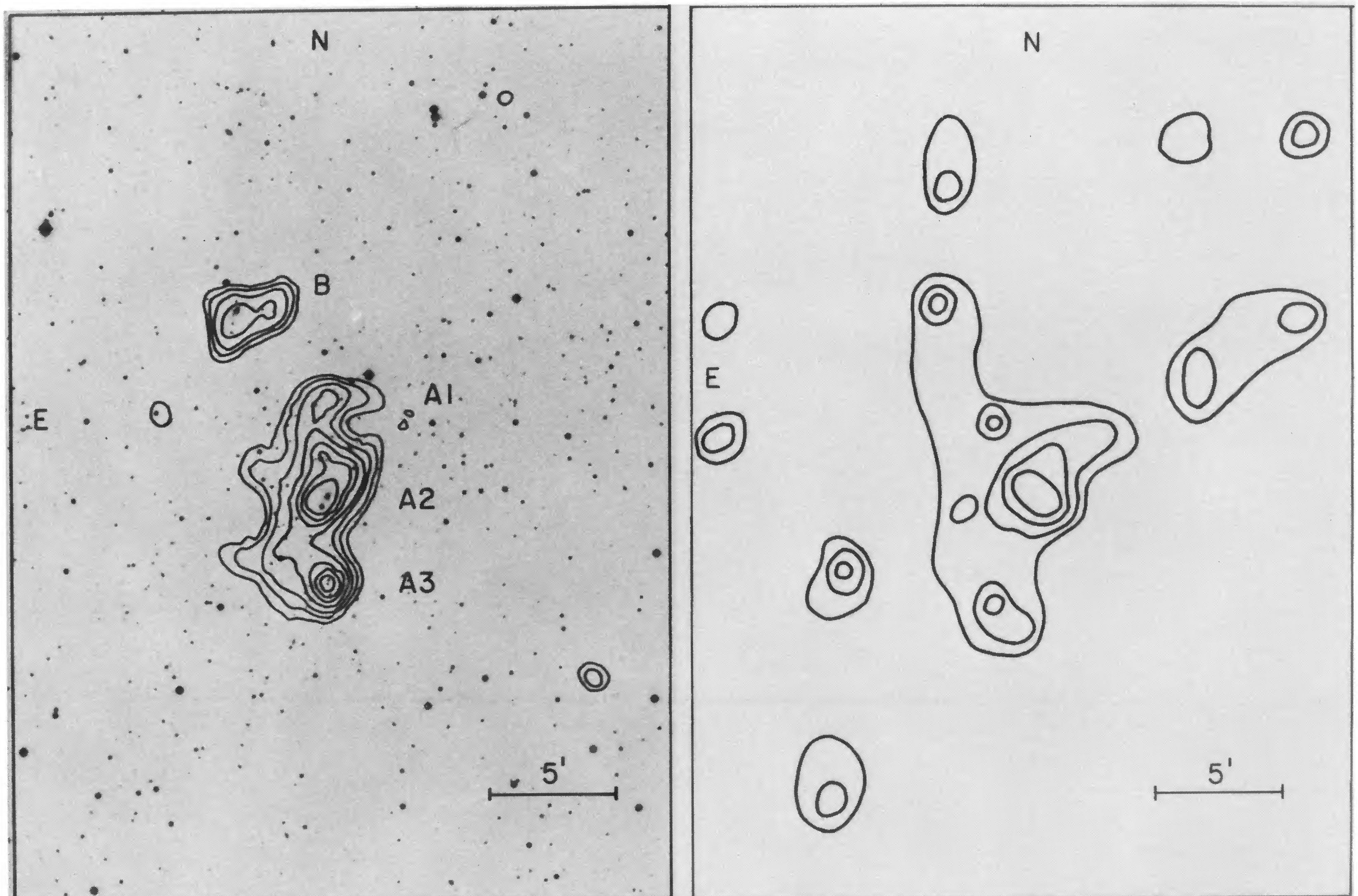

FIG. 1.—(*left*) X-ray contours of A2069 superposed on POSS E print. The background level is 0.24 counts per cell (16″ × 16″). Contours correspond to: 0.18, 0.26, 0.38, 0.55, 0.74, 0.86, and 1.01 counts above the background. (*right*) Galaxy surface number density contours of A2069. Outer optical contour is 3 σ above the background density, and each step is 1 σ.

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