THE ASTROPHYSICAL JOURNAL, 182:L57–L60, 1973 June 1

VARIATIONS IN THE RADIO STRUCTURE OF BL LACERTAE

B. G. CLARK,* K. I. KELLERMANN,* M. H. COHEN,† D. B. SHAFFER,†
J. J. BRODERICK,‡§ D. L. JAUNCEY,‡|| L. I. MATVEYENKO,#
AND I. G. MOISEEV**

Received 1973 January 22; revised 1973 March 12

ABSTRACT

We have observed the structure of the rapid variable radio source BL Lac (VRO 42.22.01) using long baseline interferometer systems with baselines up to 266 million wavelengths. Despite large variations in the total flux and in the overall size of this source, it has maintained an elongated brightness distribution, and the direction of elongation has not changed during the 1.3 years of observation. No simple model of stationary variable components or of separating, evolving components appears to fit all the data for this source. In particular, it apparently cannot be explained in terms of a stationary brightness distribution with a single variable component of very small angular size.

The peak brightness temperature of VRO 42.22.01 is in excess of 5×10^{12} ° K at 11 cm wavelength, a value close to the limit set by inverse Compton scattering.

Subject headings: quasi-stellar sources or objects — radio sources — variable stars

The radio source BL Lacertae (VRO 42.22.01) is distinctive because of its very high variability in total flux (e.g., MacLeod *et al.* 1971). Information about the variation in angular structure accompanying the flux variation can be provided by long baseline interferometry. The source was observed at 7840 MHz with the Goldstack interferometer, consisting of the 36-m Haystack telescope near Tyngsboro, Massachusetts, and the 64-m telescope near Goldstone, California, by Cohen *et al.* (1971), who established that the source is small and elongated. These authors noted that observations on this 3800-km (102 million wavelengths) baseline were consistent with a simple double model. The data are shown in figure 1*a* as a function of baseline projected on the elongation of the source, P.A. 175°.

This source was later observed at a frequency of 8430 MHz on a 9000-km baseline (Clark *et al.* 1972; Matveyenko *et al.* 1973). These observations were made with the 64-m Goldstone telescope, the 43-m telescope at Green Bank, West Virginia, and the 22-m telescope near Simeis, the Crimea, USSR. The maximum effective baseline was about 266 million wavelengths.

At this time BL Lac had a maximum fringe visibility near unity. Allowing for the calibration uncertainty of about 15 percent, the size of the radio source in P.A. 95° was no greater than 0".0003 (1.5 nanoradians). The radio source was therefore, at that time, essentially a line source in P.A. 5°. We may therefore project the data from the

* National Radio Astronomy Observatory, operated by Associated Universities, Inc., under contract with the National Science Foundation.

† Owens Valley Radio Observatory, California Institute of Technology. Supported by NFS grant GP 19400 and ONR contract N00014-67-A-0094-0019.

‡ National Astronomy and Ionosphere Center, operated by Cornell University under contract with the National Science Foundation.

§ Arecibo Observatory, Arecibo, Puerto Rico.

|| Cornell-Sydney University Astronomy Center, Cornell University, Ithaca, New York. Supported in part by NFS grant GP 28942.

Institute of Space Sciences, Academy of Sciences of the USSR, Moscow.

** Crimean Astrophysical Observatory, Academy of Sciences of the USSR.

Green Bank–Crimea and Goldstone-Crimea baselines onto that position angle. This is done in figure 1*b*.

Because of the uncertainties in the data, only the curvature of this plot is significant, and therefore only the second moment of the source brightness distribution is well determined. The data are, for instance, well represented by a line source of length 0″001 or by a point double of separation 0″00056.

These determinations agree well in position angle, but poorly in size, with the 1971 February model proposed by Cohen *et al.* (1971) from the observations with the Goldstack interferometer, which operates at a similar frequency (7840 or 7850 MHz) but on a much shorter baseline than the U.S.–Crimea interferometers. However, it can still be definitely concluded that the visibility on 1971 February 18 was lower (and hence the size greater) than on 1971 June 25.

Observations with the Goldstack interferometer, begun by Cohen *et al.* (1971), have been repeated and extended since that time. The data from these observations are shown in figures 1*c*, 1*d*, and 1*e* as a function of baseline projected on P.A. 175°. For each date of observation the source was assumed to lie along a line, and its position angle and the second moment of the brightness distribution along it were determined. The position angle and the separation of a point double with the same second moment as that observed are tabulated in columns (4) and (3), respectively, of table 1. Because observations were made at only positive hour angles in 1971 November, the position angle of the source is poorly determined, though the size is well determined. The observations of 1972 June 7 display a higher uncertainty because of difficulties with the recording apparatus during this experiment.

Table 1 shows two interesting trends: the position angle of the elongated source has not significantly changed in the course of observations over 1.3 years, and the source is smaller when it is strongest.

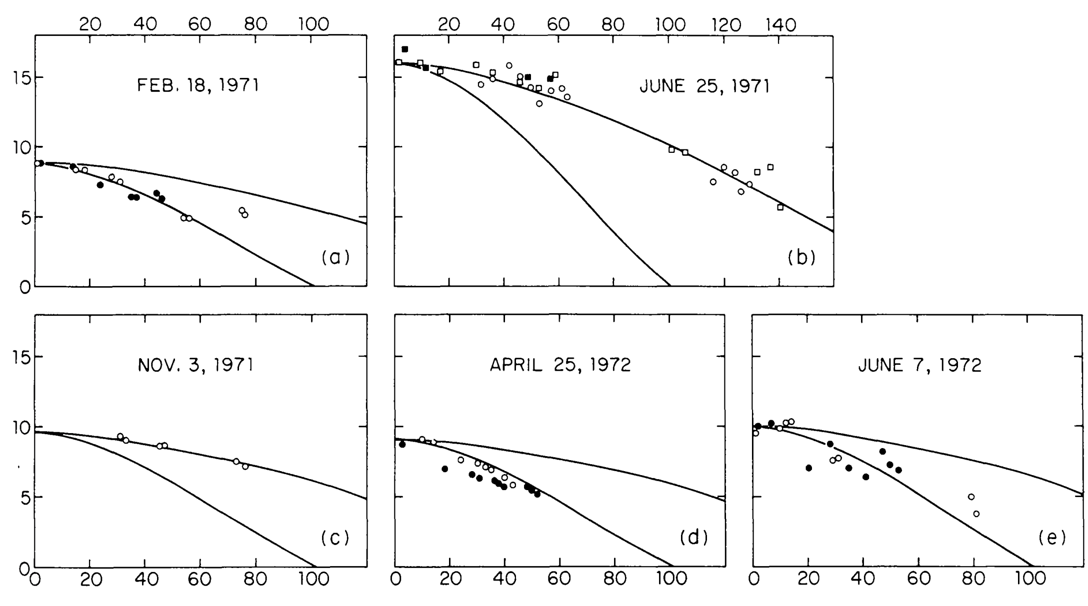

FIG. 1.—Observations of the fringe visibility of BL Lac. Ordinate is flux units, abscissa is baseline in millions of wavelengths. All baselines projected onto position angle 175°, except fig. 1*b*, which is projected onto P.A. 185°. *Filled symbols*, observations made east of meridian; *open symbols*, observations made west of meridian. All observations made with Goldstack interferometer, except fig. 1*b*, where circles are observations with the Goldstone-Crimea interferometer and squares are made with the Green Bank–Crimea baseline. In each case, the lines shown are the visibility function of a 0″001 and a 0″0005 point double radio source, with the same zero spacing intercept (total flux density) as the observed data.

TABLE 1

OBSERVATIONS

Date	Flux (f.u.)	Size (milliarcsec)	P.A.
1971 February 18	9.3	0.90 ± 0.2	174° ± 7°
1971 June 25	15.0	0.56 ± 0.07	185 ± 3
1971 November 3	9.2	0.67 ± 0.2	...
1972 April 25	8.3	1.06 ± 0.2	175 ± 7
1972 June 7	8.2	0.98 ± 0.2	161 ± 10

Two interpretations have been proposed for the apparent variation of radio structure. The hypothesis favored by Whitney *et al.* (1971) is that the fringe visibility changes which they observed in the radio source 3C 279 are caused by the apparent or actual recession of two (or more) radio emitting regions from each other. At the same time the receding components are evolving. If the evolution includes expansion of the components, and the components are optically thick, the flux should increase with time; thus, even if we are randomly sampling independent events, the size should increase with increasing flux. This case can be excluded by the data of table 1. If, on the other hand, the components are optically thin, their flux decreases with time, and the apparent size should increase with decreasing flux.

Measurements of the spectrum and its variations with time are somewhat ambiguous on this point. The spectrum is flat or slightly inverted between 7850 and 10,700 MHz (Medd *et al.* 1973; Dent and Kajoian 1973; McLeod *et al.* 1971). This may be explained either by optical-depth effects or by a flat or cutoff electron energy spectrum below about 40 GHz critical frequency. The major variations seem to occur with no time differential, a fact most easily explained by supposing that they are due to electron energy (or number) variations within an optically thin source. The source clearly has components which become optically thick below 3 GHz.

Dent (1972) favors the hypothesis that the observed visibility changes are caused by the variation in flux of a compact bright spot within the source. Under this hypothesis as well, the apparent size of the source should decrease with increasing flux as the source is more and more dominated by the compact component. Compared in detail, however, the data do not appear to fit any simple model. For instance, a point triple source with a variable central component cannot reproduce figure 1*b* and the data of table 1. Not only are the anomalous data of 1971 November (when the source was weak and small) not reproduced, but also it appears impossible to get such a steep dependence of apparent size on flux. Apparent size, being the square root of the second moment, tends to go as $(\text{flux})^{-0.5}$ in this model, whereas table 1 suggests apparent size $\sim (\text{flux})^{-1}$.

A model involving bright flares at random locations within an extended overall brightness distribution is unlikely to give rise to the observed constancy of position angles of elongation.

The model with the lowest peak brightness temperature which is consistent with the observations of June 25, when the source was strong and bright, is a uniform elliptical disk $0''.0012 \times 0''.0003$ in size. The brightness temperature of the disk in this model is 9×10^{11} ° K, and is a firm lower limit to the peak brightness temperature in the source. Physically reasonable models have peak brightness temperatures appreciably higher.

The bright flare of late June, 1971, was also observed at 11 cm. The source flux density was measured to be 8.8 flux units on the NRAO interferometer on 1971 July 12 at 2695 MHz, contrasted with a level of 6.1 and 5.9 flux units measured in May and October. The strongly inverted spectrum indicates that parts of the source were optically thick at 11 cm wavelength, but we believe that basically the same physical objects are seen at both wavelengths. We may apply the same angular size limits to most if not all of the 8.8 flux units of observed flux at 2695 MHz, yielding a minimum peak brightness temperature at this frequency of 5×10^{12} ° K, an interesting lower limit in terms of the upper limit to brightness imposed by inverse Compton scattering (Kellermann and Pauliny-Toth 1969).

This ratio source shares many characteristics with the radio source OJ 287, including extremely violent variations in radio flux, with their concomitant implied high brightness temperatures, and featureless optical spectra. It is usually assumed that these radio sources lie at the extreme end of a continuum of properties exhibited by quasi-stellar sources. Our observations show that the structure and variations of structure in BL Lac are at least superficially similar to those of the quasi-stellar radio source 3C 279 and indeed, to those of the radio galaxy 3C 120 (Schaffer *et al.* 1972). In none of these sources, however, do simple, physically reasonable models fit the data well. More probably, in all of the sources, there are moving components each of which may have a time-variable intensity due to expansion or to acceleration of relativistic electrons. Models invoking relativistic collective motions are probably necessary, and have been briefly considered by Ozernoy and Sazinov (1969), van der Laan (1971), and De Young (1972). These models have so many free parameters that to relate them in detail to the actual sources requires a great deal more observational work.

The operation of the Goldstack interferometer depends heavily upon assistance from the staffs of the Goldstone and Haystack Observatories, whose special efforts we wish to acknowledge. Some of the Goldstack observations reported here were made under the aegis of the JPL "Quasar Patrol" program of long baseline interferometry.

REFERENCES

Clark, B. G., Broderick, J. J., Ephanov, V. A., Kellermann, K. I., Cohen, M. H., Kogan, L. R., Kostenko, V. I., Matveyenko, L. I., Moiseev, I. G., Mukhina, M. M., Steinshleiger, V. B., and Jauncey, D. L. 1972, *Astr. Zh.* **49**, 700.
Cohen, M. H., Cannon, W., Purcell, G. H., Shaffer, D. B., Broderick, J. J., Kellermann, K. I., and Jauncey, D. L. 1971, *Ap. J.*, **170**, 207.
Dent, W. A. 1972, *Science*, **175**, 1105.
Dent, W. A., and Kajoian, G. 1973, *A.J.*, **77**, 819.
De Young, D. S. 1972, *Ap. J.*, **177**, 573.
Kellermann, K. I., and Pauliny-Toth, I. I. K. 1969, *Ap. J.*, **155**, L71.
Laan, H. van der. 1971, *Semain d'Etude, The Nuclei of Galaxies* (Pontificae Academie Scientiorum), p. 245.
MacLeod, J. M., Andrew, B. H., Medd, W. J., and Olson, E. T. 1971, *Ap. Letters*, **9**, 19.
Matveyenko, L., *et al.* 1973, *Astr. Zh.* (in press)
Medd, W. J., Andrew, B. H., Harvey, G. A., and Locke, J. L. 1973, in press.
Ozernoy, L. M., and Sazonov, V. N. 1969, *Ap. and Space Sci.*, **3**, 395.
Shaffer, D. B., Cohen, M. H., Jauncey, D. L., and Kellermann, K. I. 1972, *Ap. J.* (*Letters*), **173**, L147.
Whitney, A. R., Shapiro, I. I., Rogers, A. E. E., Robertson, D. S., Knight, C. A., Clark, T. A., Goldstein, R. M., Marandino, G. E., and Vandenberg, N. R. 1971, *Science*, **173**, 225.