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1642+690: A SUPERLUMINAL QUASAR

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ABSTRACT

The radio source 1642+690 (4C 69.21) has previously been found to contain a dominant, compact core with a jet extending 5″ to the south. This *Letter* presents two 5 GHz VLBI maps of the core, made in 1980 and 1983, which show that the milliarcsecond structure of the source is similar to that of the well-known superluminal sources 3C 273 and 3C 345. A milliarcsecond jet is closely aligned with the arcsecond jet, and a "knot" in the jet is moving outwards along the jet at 0.34 mas yr^{-1}. We have found that the associated optical object is a quasar with redshift $z = 0.75$. At this redshift, the displacement of the knot implies an apparent transverse velocity of $9.3h^{-1}c$ ($H_0 = 100h$ km s^{-1} Mpc^{-1}, $q_0 = 0.05$).

Subject headings: interferometry — quasars — radio sources: variable

I. INTRODUCTION

Over the last few years a number of compact radio sources have been found to be "superluminal": that is, they show internal motions with an apparent transverse velocity greater than the speed of light, *c*. At least eight such sources are now known (Cohen and Unwin 1984, and references therein); this *Letter* reports the discovery of another, with one of the highest apparent velocities yet seen.

Since 1977 we have been engaged on a project to survey the milliarcsecond structure and internal motions of a complete, unbiased sample of radio sources (Pearson and Readhead 1981, 1984*a*, 1986). The sample contains 65 sources, selected from the NRAO–MPIfR 6 cm Strong Source Surveys S4 and S5 (Pauliny-Toth *et al.* 1978; Kühr *et al.* 1981*a*) as having total flux density at 5 GHz ≥ 1.3 Jy. We have now made first-epoch maps of most of the 45 core-dominated sources in the sample and have completed second-epoch maps of several.

The main purpose of the survey is to investigate the statistics of compact radio sources. Studies of individual sources can be very rewarding, but they may give us a biased view of the radio source population. With a statistically complete sample, we can, in addition to exploring the full range of source morphologies, address a number of specific questions that will cast light on the fundamental cause of galactic nuclear activity. One aim of the survey was to look for correlations between VLBI, optical, and X-ray properties of the sources which may indicate physical connections and constrain theoretical models. Another aim was to discover more superluminal sources and to find out just how common they are. The sample contains three established superluminal sources (3C 179, 3C 345, and BL Lacertae), and we recently discovered another (1928+738; Eckart *et al.* 1985). In this *Letter* we present new optical (§ III) and VLBI (§ IV) observations that suggest that a fifth member of the sample, 1642+690, is also a superluminal source. Thus, at least five out of 65 sources are superluminal, and we can expect to find more as our observations proceed.

II. PREVIOUS OBSERVATIONS OF 1642+690

The radio source 1642+690 (4C 69.21; 1950.0 coordinates: $16^h42^m18\overset{s}{.}08$, $69°02'13\overset{''}{.}2$) has appeared in a number of sky surveys (e.g., Kühr *et al.* 1981*b*). Interferometric observations have shown that it is a compact source, and it is used as a calibration source for the Very Large Array (Perley 1982) and as a reference source for geodetic VLBI measurements (Carter, Robertson, and MacKay 1985). Although 1642+690 has been detected in previous VLBI experiments (Waltman *et al.* 1981; Preston *et al.* 1985), no VLBI maps have been published. A number of VLA observations have been reported (Perley, Fomalont, and Johnston 1980, 1982; Perley 1982), including a 5 GHz map (Perley, Fomalont, and Johnston 1980). The most revealing observations are those made with the Jodrell Bank MERLIN array (Browne and Orr 1981; Browne *et al.* 1982). The MERLIN maps are reproduced in Figure 1: prominent features are the dominant, compact core; a curved jet extending 5″ to the south; and additional low-brightness emission 6″ north of the core. The full extent of the low-brightness emission has probably not been determined, however. The 408 MHz MERLIN map includes only 80% of the flux density of the source; the remaining 20% must have a scale size ≳ 5″ (Browne *et al.* 1982).

A number of measurements of the total flux density of 1642+690 can be found in the literature (e.g., A. M. Cohen *et al.* 1977; Pauliny-Toth *et al.* 1978; Owen *et al.* 1978; Kühr *et al.* 1981*a*; Owen, Spangler, and Cotton 1980; Perley 1982; Seielstad, Pearson, and Readhead 1983). The source has attracted attention owing to its variability and its strong millimeter-wavelength emission. The flux-density history at 10.7 GHz is shown in Figure 2: the flux density has dropped from a maximum of more than 3 Jy in 1978 to a minimum of about 1.2 Jy in 1983. A spectrum compiled from measurements made in about 1978.1 is shown in Figure 3.

Polarimetry has been reported by Perley, Fomalont, and Johnston (1980), Perley (1982), and Rudnick and Jones (1982, 1983). At 5 GHz, the percentage polarization is 2.4%–2.7%

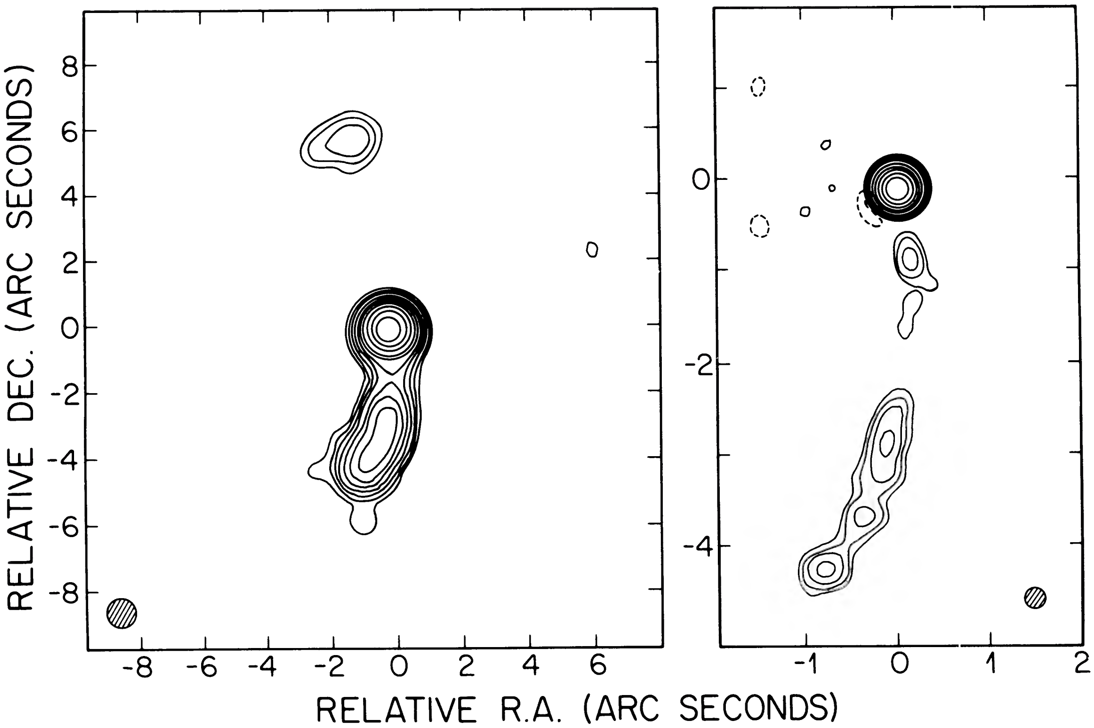

FIG. 1.—MERLIN maps of 1642+690, reproduced from Browne and Orr (1981). The contours have equal logarithmic spacing. (*left*) 408 MHz map: peak brightness = 0.877 Jy per beam, contour levels = 0.50, 0.85, 1.44, ..., 58.9%. (*right*) 1666 MHz map: peak brightness = 1.2 Jy per beam, contour levels = 0.80, 1.30, 2.10, ..., 61.7%.

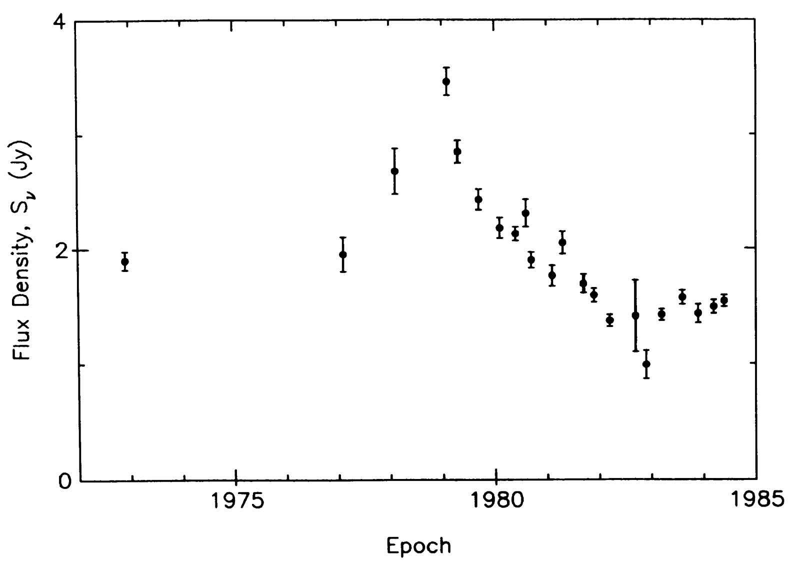

FIG. 2.—Flux-density history of 1642+690 at 10.7 GHz. Data are from Pauliny-Toth *et al.* (1978), Owen *et al.* (1978, 1980; interpolated to 10.7 GHz), and Seielstad *et al.* (1983), supplemented by observations made at the Owens Valley Radio Observatory in a continuation of the program reported by Seielstad *et al.* (1983).

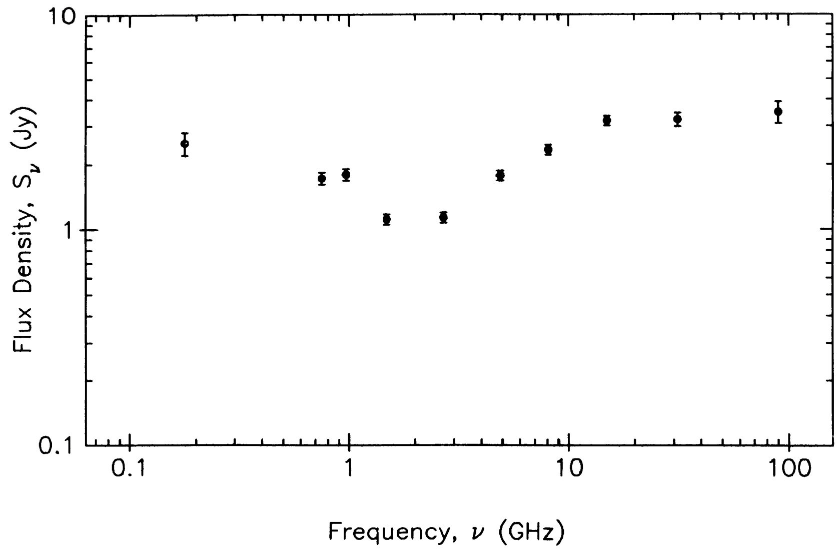

FIG. 3.—Radio spectrum of 1642+690. Data are from Owen *et al.* (1980) and refer to epoch 1978.1, except for the point at 178 MHz which is from the 4C survey (Gower, Scott, and Wills 1967).

with position angle (p.a.) 116°–144°. The rotation measure is unknown, but assuming that Faraday rotation is small at 5 GHz, the polarization position angle shows no simple relationship to the arcsecond or milliarcsecond structure.

III. OPTICAL OBSERVATIONS

The radio source 1642+690 was identified with a 19 mag blue stellar object by A. M. Cohen *et al.* (1977) and by Kühr (1977), and this identification has been confirmed by Argue and Sullivan (1980). No spectrum or redshift of the object has been published. We have obtained a spectrum using the Double Spectrograph on the 5 m Hale telescope of Palomar Observatory (Oke and Gunn 1982) in the course of a program to obtain spectra of all the sources in the sample defined in § I (Lawrence *et al.* 1986). The spectrum confirms that the object is a quasar, with an emission-line redshift of 0.75. At this redshift, 1″ corresponds to $4.8h^{-1}$ kpc (assuming $H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.05$, following Cohen and Unwin 1984).

IV. VLBI OBSERVATIONS

We have made two VLBI maps of 1642+690 at 5 GHz, using antennas of the US VLBI Network in 1980 July (1980.53) and 1983 December (1983.93) (Table 1). Left-circular polarization was recorded with the Mark II system and a bandwidth of 1.8 MHz, and the data were cross correlated using the processor at the California Institute of Technology. Similar u,v-plane coverage was obtained in both experiments, with a maximum baseline of 1.4×10^8 wavelengths. Maps were made using self-calibration procedures based on both Högbom's CLEAN and the Maximum Entropy method (e.g., Pearson and Readhead 1984*b*). The Maximum Entropy maps have higher resolution but are otherwise consistent with the CLEAN maps, which are shown in Figure 4. The noise in the observations would give an rms flux density error on the maps ≈ 1.2 mJy per beam (1980.53) or 0.9 mJy per beam (1983.93), but the errors in the maps are 3–4 times greater than this owing to the limited dynamic range (about 200:1). The following features are notable.

1. Both maps show a strong, unresolved "core." Lower limits on the brightness of the core (measured with a 1 mas beam) are 6×10^{10} K (1980.53) and 4×10^{10} K (1983.93).

2. Both maps show lower brightness extensions to the south of the core in p.a. 195° ± 2°, but not to the north of the core. The position angle of this milliarcsecond "jet" coincides with that of the arcsecond jet (Fig. 1). The arcsecond jet follows a smooth curve that can be represented by a circular arc with a constant curvature (change in p.a. ≈ 5° per arcsec); this curve intersects the core in p.a. 194°. The milliarcsecond jet is curved in the opposite sense to the arcsecond jet.

3. The differences between the two maps are striking (Fig. 5). The core is considerably weaker at the later epoch and is extended in the direction of the jet. The separation between the core and a discrete peak at the southern end of the

TABLE 1

VLBI OBSERVATIONS

Epoch	Frequency (MHz)	Total Observing Time (hr)	Total Flux Density (Jy)[a]	Antennas[b]
1980.53	5011	12	1.93 ± 0.05	B, K, G, F, O
1983.93	4989	12	1.37 ± 0.05	B, K, G, Y, O

[a] Measured at Effelsberg during the observations.

[b] B—MPIfR, Effelsberg, W. Germany (100 m); F—GRAS, Fort Davis, TX (26 m); G—NRAO, Green Bank, WV (43 m); K—Haystack, MA (37 m); O—Owens Valley, CA (40 m); Y—VLA (NRAO), Socorro, NM (one 25 m antenna).

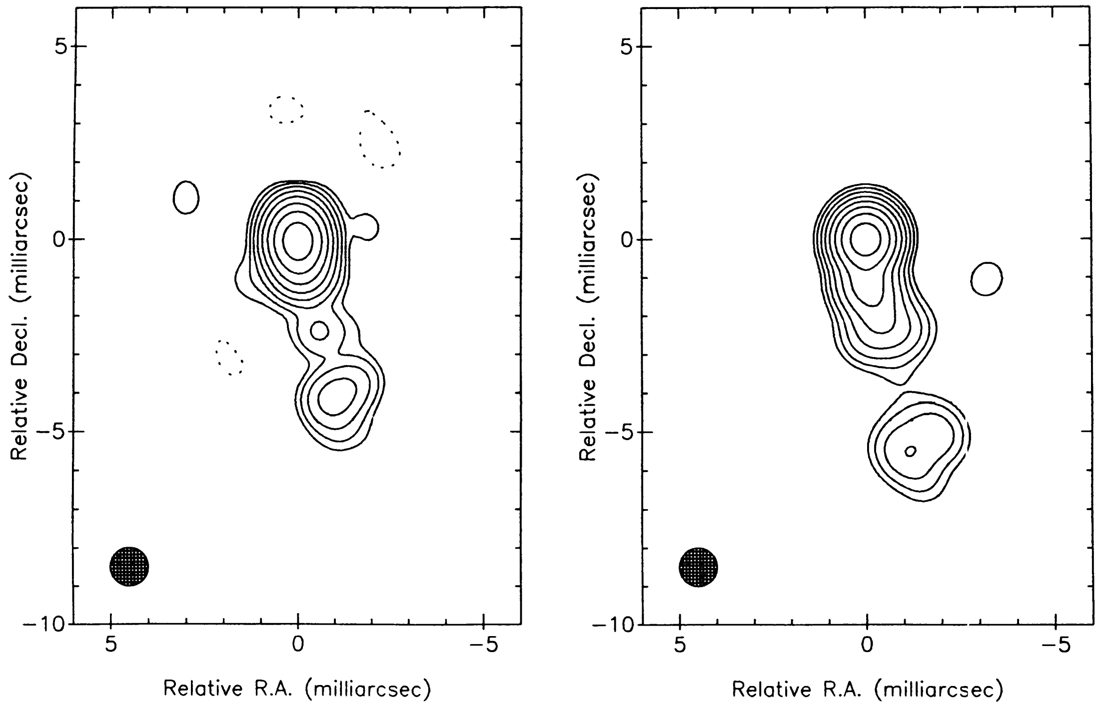

FIG. 4.—VLBI maps of 1642+690 at 5 GHz. Both maps are presented with a circular Gaussian restoring beam with FWHM 1.0 mas (*hatched circle*) and contour levels −0.5 (*dashed*), 0.5, 1, 2, 4, 8, 16, 32, 64% of the peak. (*left*) Epoch 1980.53: peak brightness 1.32 Jy per beam. (*right*) Epoch 1983.93: peak brightness 0.79 Jy per beam.

milliarcsecond jet has increased from 4.2 ± 0.1 to 5.4 ± 0.1 mas in 3.4 yr, an apparent angular expansion speed of 0.34 ± 0.04 mas yr^{-1}. The uncertainty in this measurement is due to the limited resolution of the observations and to the angular size of the southern peak. This southern peak, or "knot," is resolved perpendicular to the jet at both epochs: the deconvolved FWHM from the CLEAN maps is ~ 1.0 mas, and the Maximum Entropy maps indicate an overall size ≈ 1.5 mas.

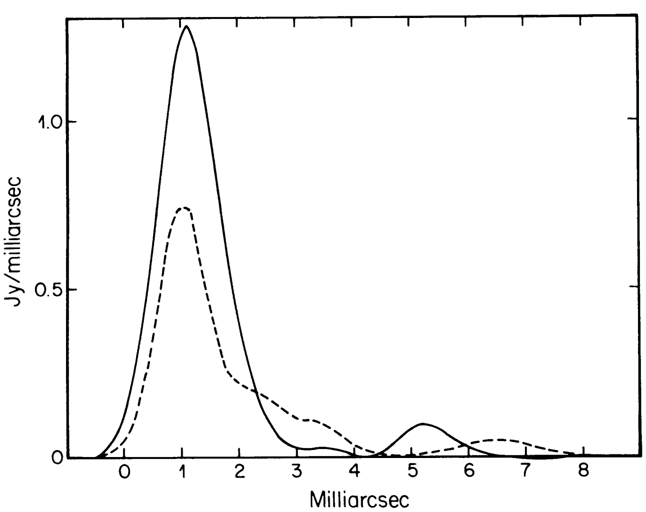

FIG. 5.—Profiles of the maps of Fig. 4 along the position angle of the jet, 194°. *Solid curve*: epoch 1980.53; *dashed curve*: epoch 1983.93. The convolving beam is a Gaussian with FWHM 1.0 mas.

Note that we have measured the change in separation of the core and the knot, not the proper motion of the knot relative to a fixed feature of the source. Astrometric observations may be able to determine whether all the movement should be attributed to the knot while the core remains stationary.

4. The maximum entropy map suggests that the extension of the core at the second epoch should be regarded as a second knot with a peak ~ 1.5 mas south of the core. Future observations should allow us to measure the speed of this knot.

V. 1642+690 AS A SUPERLUMINAL SOURCE

Using the redshift of the quasar and assuming $H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.05$, the apparent angular expansion speed can be converted to an apparent linear transverse speed of $(9.3 \pm 0.1)h^{-1}c$ (M. H. Cohen *et al.* 1977). Thus 1642+690 must be classed as a superluminal source. There remains some uncertainty that must be resolved by future observations: we can only be sure that we have measured the expansion of a real feature of the source after we have followed it through several observations (cf. Pearson *et al.* 1981). But the similarity of this source to the well-studied superluminal sources 3C 273 and 3C 345 leaves us in little doubt. These similarities include the arcsecond jet, the unresolved core, the fact that an expansion rather than a contraction is seen, and the close alignment of the expansion vector with the axis of both the milliarcsecond and the arcsecond structure.

If the apparent superluminal motion is caused by bulk motion of the radiating plasma at a speed βc close to the line of sight to the observer, then the angle between the motion and the line of sight, θ, must be less than 12°3, and β is minimized if $\theta = 6°$ (taking $h = 1$), giving a Lorentz factor $\gamma_{min} = 9.4$ (e.g., Cohen and Unwin 1984). If the entire source is inclined at < 12°3 to the line of sight, its total linear size exceeds 250 kpc. Schilizzi and de Bruyn (1983) have shown that when this argument is applied to the other superluminal sources, the derived linear sizes are much greater than those of other sources of comparable luminosity. This does not appear to be a problem with 1642+690, but the high-dynamic-range observations necessary to determine the maximum extent of the source have not yet been made.

VI. CONCLUSION

The quasar 1642+690 is almost certainly a superluminal source. Further VLBI maps at 5 GHz and other frequencies are required to confirm this conclusion and to determine the physical conditions within the source.

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