THE ASTROPHYSICAL JOURNAL, 334:560–572, 1988 November 15

VLBI AND MERLIN OBSERVATIONS OF 3C 120 AT 1.7 GHz: SUPERLUMINAL MOTIONS BEYOND 0".05

J. M. BENSON
National Radio Astronomy Observatory,[1] Charlottesville, Virginia
R. C. WALKER
National Radio Astronomy Observatory,[1] Socorro, New Mexico
S. C. UNWIN
Owens Valley Radio Observatory, California Institute of Technology, Pasadena, California
T. W. B. MUXLOW AND P. N. WILKINSON
Nuffield Radio Astronomy Laboratories, Jodrell Bank, United Kingdom
R. S. BOOTH AND G. PILBRATT
Onsala Space Observatory, Onsala, Sweden
AND
R. S. SIMON
E. O. Hulburt Center for Space Research, US Naval Research Laboratory, Washington, DC
Received 1988 February 11; accepted 1988 April 3

ABSTRACT

The radio galaxy 3C 120 was observed at 1.7 GHz in 1982 and 1984 with VLBI arrays consisting of 14 and 18 stations. Near the time of the second VLBI observations, 1.7 GHz data were also obtained with MERLIN.

The VLBI results show that substantial changes in structure occurred between the observations. The changes provide evidence for superluminal motions at 0".05 and, perhaps, at 0".1 from the core. This is a significantly larger angular scale than that at which superluminal motions have been observed before. The velocity is not well established but is consistent with that seen at 5 GHz on scales of a few milliarcseconds. This result, if confirmed by further observations, shows that the jet does not slow down quickly just outside the core region.

The lower resolution results from the combined MERLIN–VLBI observations show that the continuity and simple evolution with distance of the 3C 120 jet that were found by Walker, Benson, and Unwin are maintained on scales of tens to hundreds of parsecs where the coverage of previous observations was poor. This strengthens the conclusion that the conditions within the jet are established on subparsec scales and are not altered significantly, other than by expansion, over many orders of magnitude in core distance.

There are no direct measurements or convincing arguments that give the velocity of the large-scale, one-sided jets often seen in powerful radio sources. The superluminal motions often observed on parsec scales in such sources are usually considered to be good evidence that the velocity on those scales is relativistic. The extension of the range of observed superluminal motions, along with the continuity over all scales of the jet in 3C 120, adds to the indirect evidence that the large-scale jets are relativistic.

Subject headings: galaxies: individual (3C 120) — galaxies: jets — galaxies: structure — interferometry — radio sources: galaxies

I. INTRODUCTION

The nuclear region of the galaxy associated with the radio source 3C 120 is a powerful and variable emitter of radiation at all wavelengths (Halpern 1984; Lyutyi 1979; Wlerick, Westerlund, and Garnier 1979; Pollock *et al.* 1979; Oke, Readhead, and Sargent 1970; Rieke and Lebofsky 1979; Epstein *et al.* 1982; and Aller, Olsen, and Aller 1976). In most respects, 3C 120 resembles quasars, except that the central source is not so bright optically that it overwhelms the rest of the galaxy, and it is relatively nearby, so that the galaxy has an angular size sufficiently large for morphological studies (Baldwin *et al.* 1980; also Arp 1987 for good images and an alternative distance estimate).

The 3C 120 radio source consists of a bright core that is resolved by Very Long Baseline Interferometry (VLBI), a one-sided jet that extends from parsec scales to about $100h^{-1}$ kpc (for $z = 0.033$ and $H_0 = 100h$ km s^{-1} Mpc^{-1}), and diffuse structure up to 14′, or $400h^{-1}$ kpc across (Balick, Heckman, and Crane 1982; Walker, Benson, and Unwin 1987*a*, hereafter Paper I). The jet brightness follows a simple power-law decay with width, suggesting that the physical parameters are established on subparsec scales and decay in a simple way from there to well outside the galaxy. On the smallest scales observed, superluminal motions are seen (Seielstad *et al.* 1979; Walker *et al.* 1982; Walker, Benson, and Unwin 1987*b*, hereafter Paper II) with angular velocities of up to 2.5 milliarcseconds (mas) per year, or about $4h^{-1}$ times the speed of light.

The presence of the superluminal motions implies, by the standard model (Blandford and Königl 1979), that the jet is

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

TABLE I

PARTICIPATING OBSERVATORIES

Observatory	Location	1982 October	1984 April	Diameter (m)	T_{sys} (K)
Arecibo	Puerto Rico	x	x	300	30
Cambridge	UK	...	x	18	90
Crimea	USSR	...	x	22	110
Defford	UK	...	x	25	40
Effelsberg	FRG	x	x	100	36
Fort Davis	Texas	x	x	25	73
Green Bank	West Virginia	x	x	43	23
Haystack	Massachusetts	x	x	37	92
Hat Creek	California	x	x	25	62
Jodrell Bank Mark II	UK	x	x	38 × 25	43
Maryland Point	Maryland	x	x	25	70
North Liberty	Iowa	x	x	18	75
Penticton	British Columbia	x	x	25	100
Onsala	Sweden	x	x	25	30
Owens Valley	California	x	x	40	50
Torun	Poland	...	x	18	18
VLA	New Mexico	x	x	[a]	50
Westerbork	Holland	x	x	[b]	68

[a] Phased array of 27 antennas, each 25 m in diameter.
[b] Phased array of 3 antennas, each 25 m in diameter.

close to the line of sight (within about 24° for $v/c = 4$) and that the features causing the bright knots are moving relativistically. In this model, the one-sidedness of the jet is easily explained by relativistic beaming that enhances the approaching jet and diminishes the receding jet. Also, large apparent bends can be explained as small bends seen in projection. However, if the source is near the line of sight on all scales, its deprojected size is considerably larger than the $400h^{-1}$ kpc observed, placing it among the larger sources known. Similar large deprojected sizes are seen in other superluminal sources (e.g., Schilizzi and de Bruyn 1983) and are a problem for the standard model.

So far, there has been no direct measurement of the velocity of a jet outside of the region a few mas from the core where superluminal motions are seen. Observations within those few mas provide no evidence that jets slow down with distance. The one-sidedness on larger scales, if due to beaming, suggests that the relativistic motions continue to kpc scales and beyond. This suggestion could be strengthened considerably if the range of scales over which the superluminal motions are observed were extended.

The observation of superluminal motions on large scales is made difficult by the large size and low brightness of components far from the core (see the unsuccessful attempts by Pilbratt, Booth, and Porcas 1987). The source 3C 120 provides one of the best opportunities to look for such motions. It has the highest angular rates of motion of any known superluminal source, so the large size of components is less of a problem. Also, it has structure on all scales providing a variety of observational options.

In order to look for superluminal motions beyond the region where they have been seen before, and in order to study the structure of the 3C 120 jet on scales between those usually seen with VLBI and those seen with the VLA, we made VLBI observations of the source at 1.7 GHz in 1982 October and in 1984 April. The structures of interest were expected to be weak relative to the core (Pilbratt, Booth, and Porcas 1987), so a large number of stations were used each time in an effort to obtain high dynamic range and good image fidelity. With 14 stations in 1982, and 18 stations in 1984, these were the largest VLB arrays assembled up to the time of the observations. At close to the time of the second observation, MERLIN data at 1.7 GHz were obtained to provide coverage of short baselines. The 1984 VLBI observations were done as part of what has become known as the "World Radio Array," during which four sources were observed and special efforts were made to enlist several stations that were not normally used for VLBI, including two separate MERLIN antennas. This paper reports the results of these 3C 120 observations.

II. OBSERVATIONS

The VLBI observations were made on 1982 October 10 and 1984 April 6. The observatories used are listed in Table 1. For each observatory, the table gives the name, location, participation in each experiment, antenna diameter, and zenith system temperature. Most of the observatories were participating as members or associate members of either the US VLBI Network or the European VLBI Network. The observations occurred during regularly scheduled network observing sessions. The Mark II VLBI system (Clark 1973) was used with an effective bandwidth of 1.8 MHz. The observing frequency was 1661 MHz in 1982 and 1664 MHz in 1984. Special efforts were made to equip a few observatories that are not normally used for VLBI. For the Dominion Radio Astronomy Observatory at Penticton, the National Radio Astronomy Observatory (NRAO) provided a low-noise FET amplifier, while the Smithsonian Astrophysical Observatory provided a Mark II formatter and recorder. For Cambridge, the Onsala Space Observatory provided Mark II equipment and personnel. For Defford, one of the MERLIN antennas, the radio astronomy information was sent over a microwave link and recorded on Mark II equipment at Jodrell Bank. Phase coherence was maintained via the L-band link (Davies, Anderson, and Morison 1980).

The data for the 1982 observations were processed on the five-station VLBI correlator at Caltech. In order to take advantage of the global fringe fitting method of Schwab and Cotton (1983), the 1984 observations were processed on the three-station correlator at NRAO in Charlottesville, Virginia, despite the very large amount of processor time required. (Global fringe fitting became available for the Caltech processor later.)

The initial calibration was done following the methods of Cohen *et al.* (1975), using system temperatures measured at the time of the observations and known gain curves. For the Very Large Array (VLA) and Westerbork, where the signals from many antennas were phased and added to form the VLBI signal, the calibration was based on correlation coefficients produced by the local instrument's correlator. As for most VLBI observations, the raw phases were not calibrated, but care was taken to maintain the integrity of the closure phases. Several very compact sources (DA 193, OQ 208, 0235+164) were observed to aid in finding a consistent calibration for all antennas. While all of these sources are slightly resolved on the longest baselines, they are sufficiently simple and compact that they could be used for calibration with the aid of simple structure models. After the normal calibration, the 1984 VLBI and MERLIN data were scaled by factors of 0.94 and 1.03, respectively, in order to match the amplitudes on the Jodrell to Defford baseline that is common to both instruments. The MERLIN data were scaled by a smaller factor than the VLBI data because the absolute calibration of MERLIN is thought to be better than that of VLBI. In any case, the absolute amplitude calibration should not be trusted to better than about 10%.

The mapping was done by the normal iterative method in which the source structure and the antenna gains are determined simultaneously (Readhead and Wilkinson 1978; Schwab 1980; Cornwell and Wilkinson 1981). Most of the processing was done within the Astronomical Image Processing System (AIPS) written at NRAO, although occasional tasks were done with the Caltech VLBI processing programs or with specially written software. The final maps were produced from the self-calibrated data using the CLEAN algorithm (Högbom 1974). The contour plots in this paper show the CLEAN map including the residuals and are contoured with seven levels per factor of 10 in brightness.

VLBI *u-v* data contain points with a very wide range of sensitivities. Because of this, the best scheme for weighting the data in the mapping process is not obvious. Uniform weighting will produce the lowest sidelobes but can cause the map noise to be dominated by the weakest baselines. Weighting based on sensitivity (natural weighting) will provide the greatest sensitivity in the map but will cause the *u-v* plane to be dominated by the few strong baselines. This leads to higher sidelobes and probably slows convergence of the mapping process. Several weighting options were tried. It was found that uniform weighting with compressed visibility weights is clearly better in the early iterations of the self-calibration process. However, for the final iterations and for the maps produced for publication, natural weighting was found to give the best results. For the natural weighting, Arecibo was given about the same weight as Bonn and the VLA, despite about an order of magnitude greater sensitivity, in order to reflect the likely presence of residual calibration errors and to avoid extremely high sidelobes.

Despite the large number of antennas, the dynamic range of the VLBI maps seems to be limited to somewhat under 2000:1, measured as peak to off-source rms. The noise limit is several times higher. MERLIN has been able to do significantly better with only 6 antennas. The reason for the limited dynamic range of the VLBI maps is likely to be uncalibrated, time-dependent errors in the closure parameters. Attempts to remove constant closure errors determined from calibrator data have proved very successful at MERLIN and the VLA (see Walker 1985). However, similar efforts did not significantly help our VLBI data. While we are not entirely satisfied with the dynamic range that we have achieved, it is instructive to recall that only a few years ago a dynamic range of 100:1 for a VLBI map was considered exceptionally good. The subject of VLBI map errors is discussed more extensively by Wilkinson, Conway, and Biretta (1988).

The *u-v* coverages obtained by the two VLBI experiments are shown in Figure 1. Despite the large number of stations, the quality of the coverage is limited by the small north-south distribution of the antennas and by the low declination (about 5°) of the source. Also the lack of a station in the mid-Atlantic produces some large gaps.

The MERLIN data were taken on 1984 May 10 at 1668 MHz. The bandwidth was 10 MHz. At the times of both the VLBI and the MERLIN observations, the 76 m Mark I antenna at Jodrell was not available, so the 25 × 38 m Mark II antenna was used. The data were calibrated using standard MERLIN software.

The 1984 VLBI and MERLIN data have been combined to make maps sensitive to intermediate-scale structures. In order to obtain sensible results from the combined data set, it was necessary to adjust the phase center and the weights, in addition to the amplitudes mentioned earlier, of one data set to match the other. This was facilitated by the fact that the Jodrell Mark II to Defford baseline was present in both data sets—one of the reasons why Defford was included in the VLBI observations. The phase center adjustment was necessary because the self-calibration procedures used for both data sets do not preserve absolute position information. The relative weights had to be adjusted because the different instruments used different weight scales.

No attempt was made to self-calibrate the combined data set. There is very little overlap in the baselines from the two sets, and the longest MERLIN baseline is over 100 times shorter than the shortest baselines connecting some parts of the VLB array. It was felt that no one model would apply to a wide enough range of spacings to allow a successful joint calibration that would not seriously degrade the internal calibration of each data set.

The inner 5×10^6 wavelengths of the *u-v* coverage for the combined data set are shown in Figure 2. The hourglass-shaped region of dense coverage at less than 0.7×10^6 wavelengths is the contribution of MERLIN. Note that the density of coverage falls off sharply outside of that provided by MERLIN. This made high-quality maps with just a few times the MERLIN resolution difficult to make.

III. RESULTS

Figure 3 shows the VLBI maps at nearly full resolution from both 1982 and 1984. The convolving beam and the contour levels are identical in the two maps. In both maps, the brightest feature is close to, but not quite at, the eastern end of the source. The jet extends toward the west, expanding and decaying with distance until it falls below the noise level beyond 220 mas. Note that the contours are logarithmic, so the weaker features are much weaker than the bright components near the core.

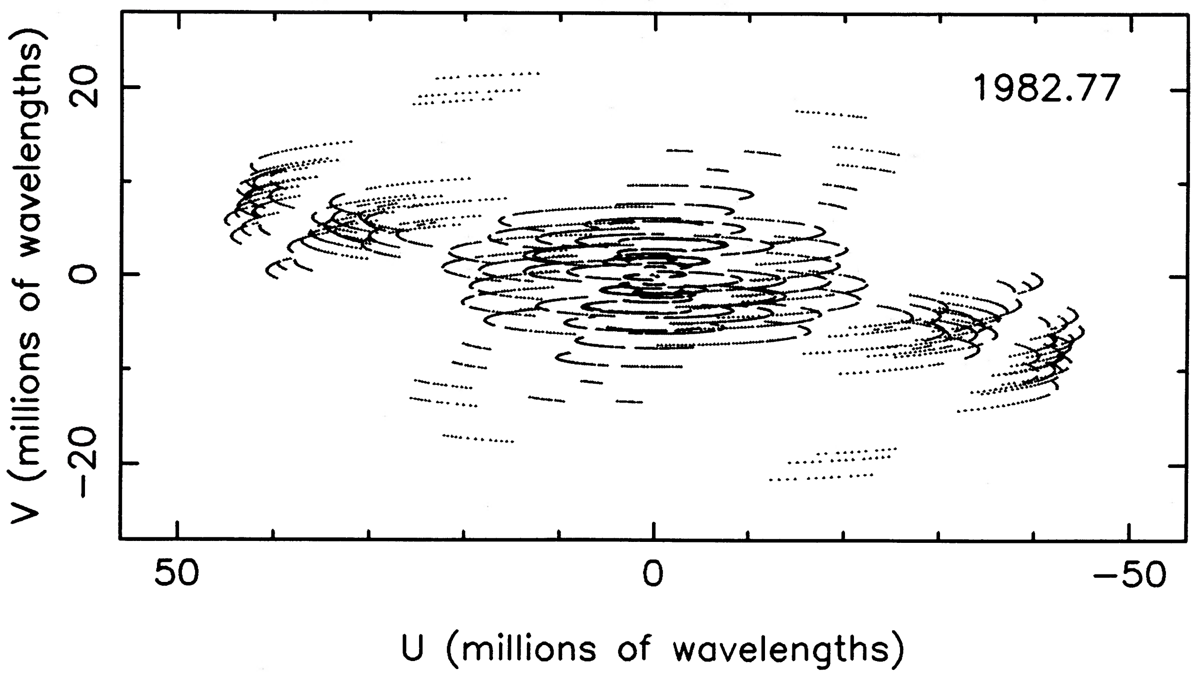

FIG. 1*a*

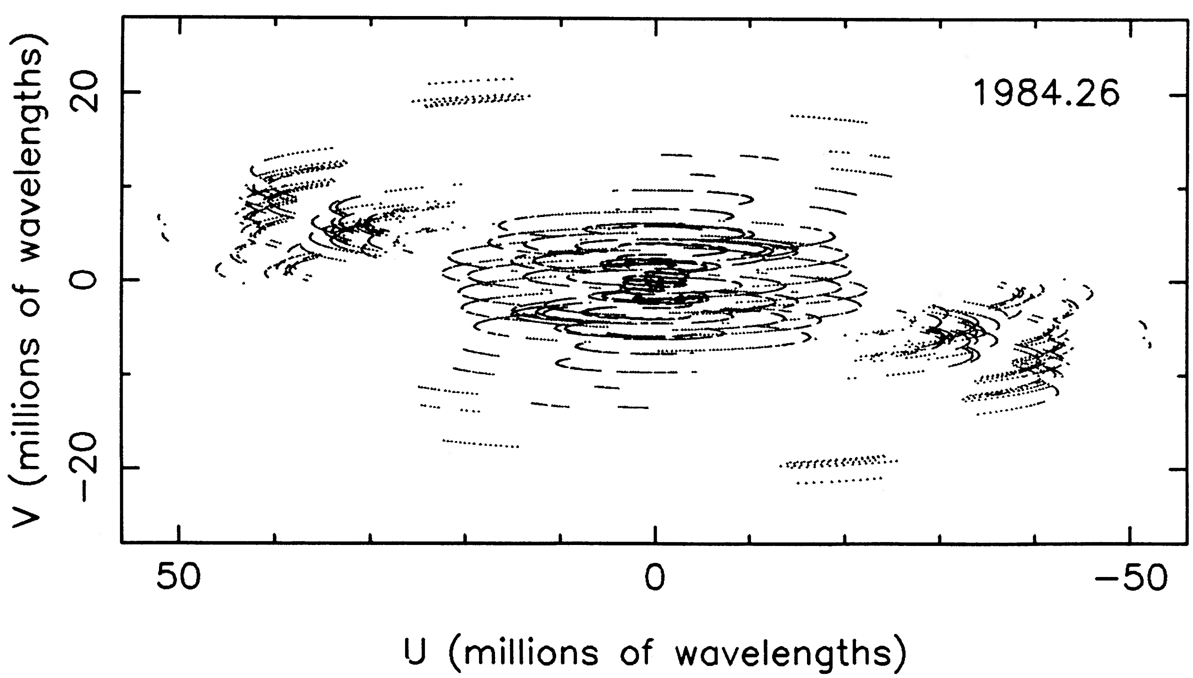

FIG. 1*b*

FIG. 1.—*Top*: Coverage of the *u-v* plane provided by the 1982.77 VLBI observations. *Bottom*: The same, for 1984.26.

The errors in maps such as these are hard to determine. The off-source noise level is determined by a combination of the noise in the observations and errors in calibration, including closure errors. For a low-declination source such as 3C 120, calibration errors, and the nearly east-west *u-v* tracks, lead to enhanced noise north and south of the brightest features. On source, the errors are increased significantly because the deconvolution algorithms (e.g., CLEAN) cannot find a unique interpolation across the gaps in the *u-v* coverage. The differences between the maps, especially in the regions of low-level emission, give some indication of the errors. However, the source structure is expected to change with time, so some differences are real. Changes in the stronger components are especially likely to be real. After working extensively with the data, we believe the changes along the center of the jet between the core and about 40 mas, the shifts in the positions of the groups of components at 50 and 90 mas, and the presence of an expanding jet out to at least 220 mas. The protuberances along the

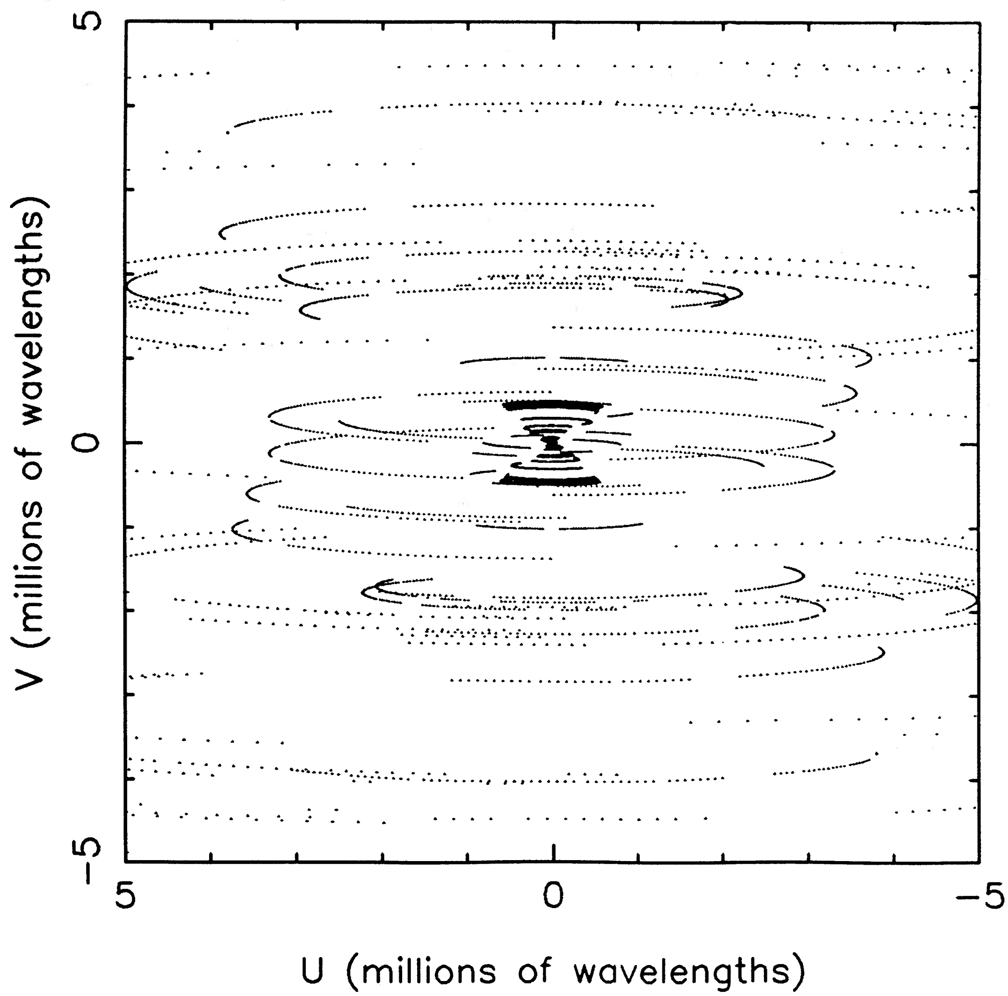

FIG. 2.—The *u-v* coverage for baselines shorter than 5×10^6 wavelengths in the combined MERLIN–VLBI data set. The "hourglass" of relatively dense coverage at less than 10^6 wavelengths is the coverage of MERLIN.

side of the jet in the bright regions in 1982 and all negative holes are not real. The details of structures in the low-level emission regions, including everything more than about 100 mas from the core, are poorly determined.

The proper alignment of the maps is also hard to determine because absolute position information is lost in the self-calibration process. It is only possible to determine changes in the relative positions of features. Superluminal motions are typically seen as changes in the separation between a flat or inverted spectrum "core," located at one end of the observed structures, and steeper spectrum "jet" components. The core is usually assumed to be the stationary component and is used to align maps from different epochs. That the core is the more stationary component has been verified astrometrically in one case (3C 345; Bartel *et al.* 1984).

The VLBI observations presented in Paper II show that, at 5 GHz, the radio emission from 3C 120 is dominated by a core and a few moving components of similar strength, all confined to a region of about 5 mas or less in length (varies somewhat with epoch). The resolution of the 1.7 GHz maps is 4 mas along the direction of the jet, so the 5 GHz components are blended together into a single bright, and slightly resolved, component. At 1.7 GHz, the core is expected to be weaker, while the jet components are expected to be stronger than at 5 GHz. Therefore we estimate that the centroid of the bright component at 1.7 GHz will be near the centroid of the moving components at a location about 1.7 ± 1 mas west of the 5 GHz core. The apparent resolution of the bright component to the east is an effect of the weakness of the core relative to the jet components at 1.7 GHz. As new moving components are born and old, more distant, ones fade, the position of the bright 1.7 GHz component will jitter, but will not follow the moving components away from the core. We estimate that the jitter is about ± 1 mas about the mean position. For want of a better reference, we have aligned the 1.7 GHz maps on the brightest feature, understanding that the jitter in the position of this feature introduces an uncertainty of about ± 1 mas in the measured motions of any other features.

Figure 4 is a closer view of the brighter features of the source. The maps are the same as those in Figure 3—only the plot window is different. In this figure the coordinate grid has been superposed over the contours to aid in comparing the locations of features. The coordinate origin in both cases is aligned with the brightest feature.

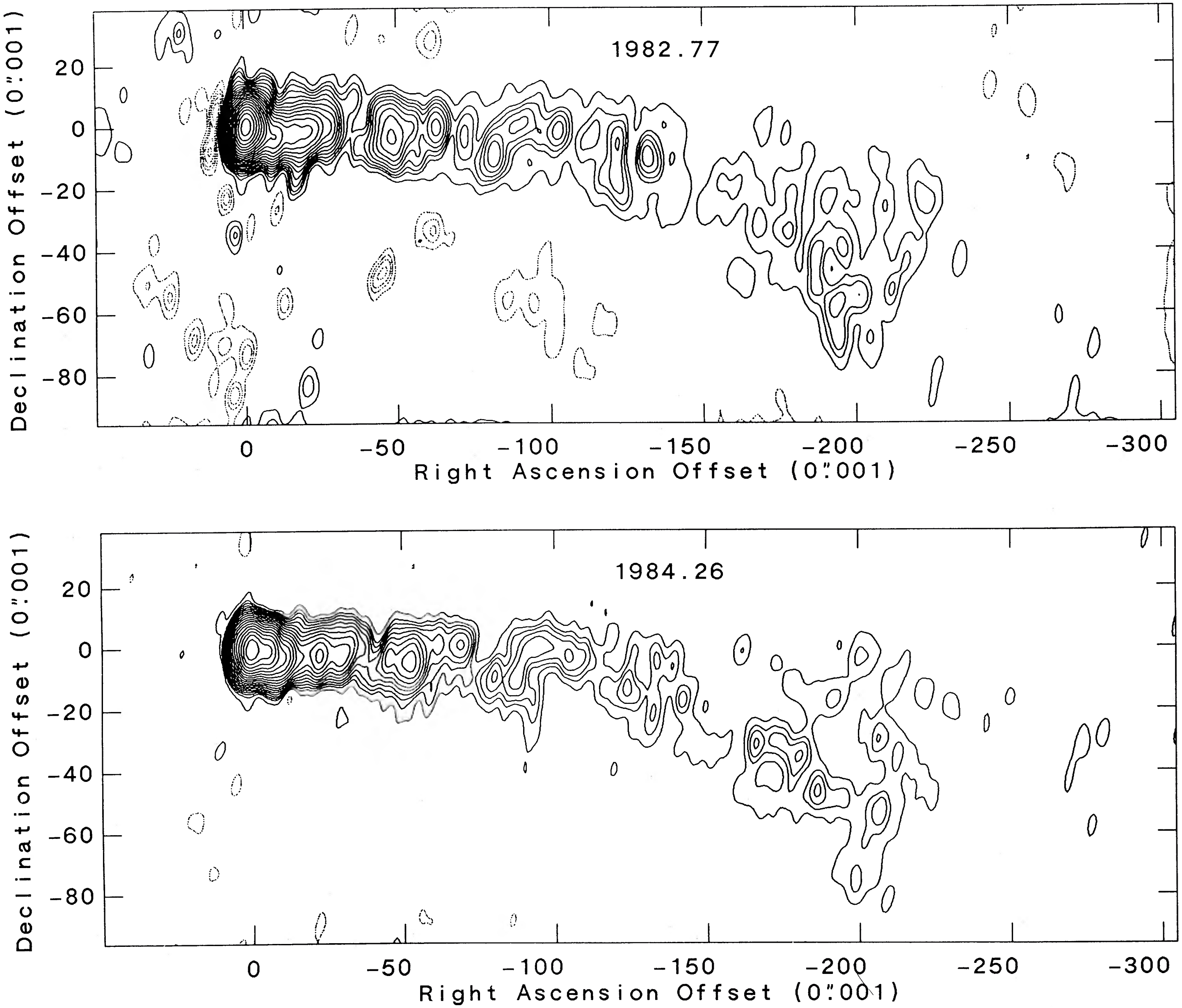

FIG. 3.—VLBI maps of 3C 120 at 1.7 GHz made from data taken in 1982.77 and 1984.26. For both epochs, the convolving beam is 4 × 10 mas (FWHM) elongated along position angle −10°. The logarithmic contour levels are −4.48, −3.22, −2.32, −1.2, 1.2, 2.32, 3.22, 4.48, 6.22, 8.64, 12.0, 16.7, 23.2, 32.2, 44.8, 62.2, 86.4, 120, 167, 232, 322, 448, 622, 864, 1200, and 1670 mJy beam^{-1}. The peak flux density was 1.49 Jy beam^{-1} in 1982.77 and 0.61 Jy beam^{-1} in 1984.26.

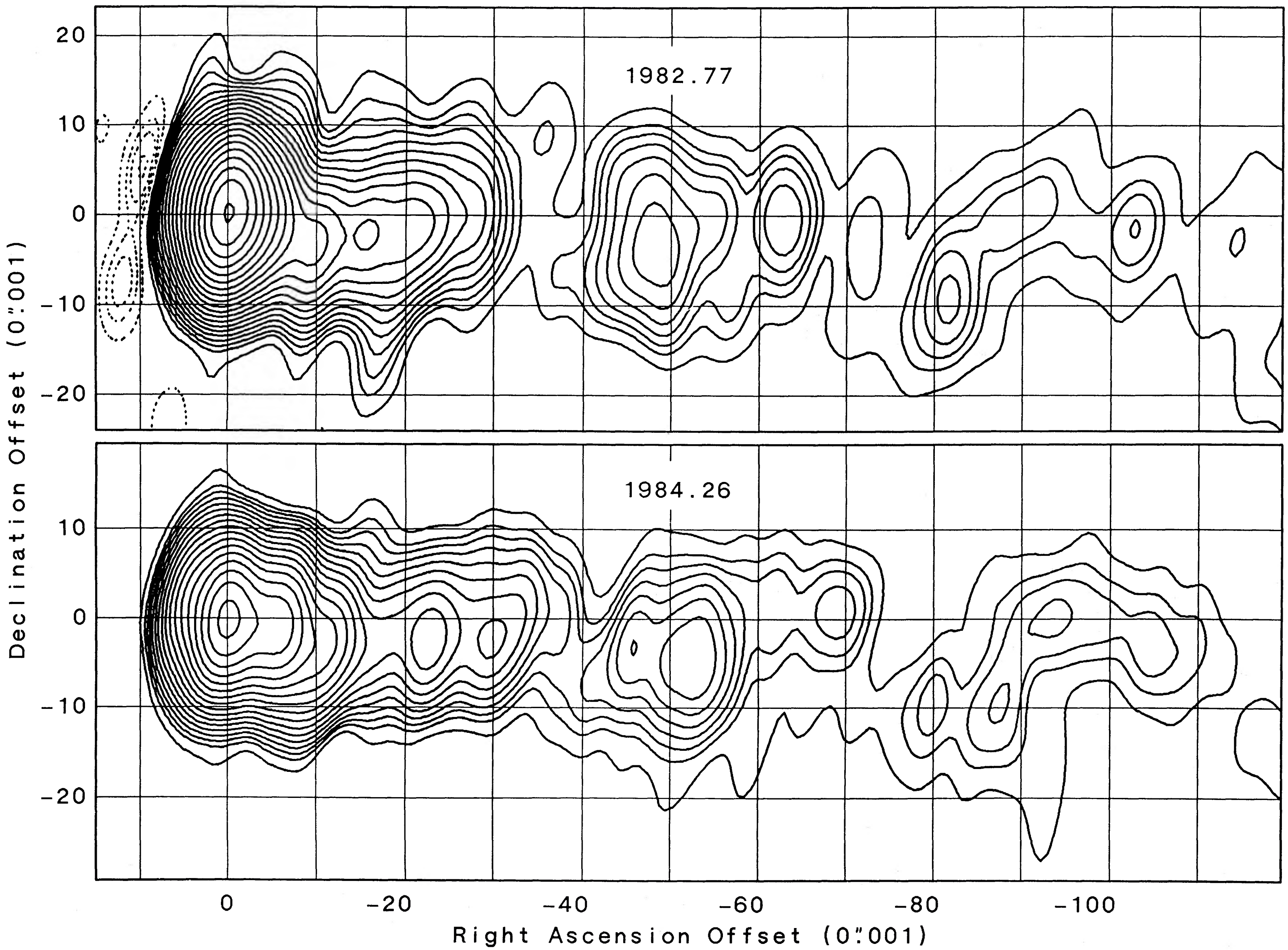

FIG. 4.—Blowup of the central portions of the maps in Fig. 3. The coordinates have been aligned so that (0, 0) is centered on the brightest point in each map. The coordinate grid is plotted to guide the eye in comparing the locations of features. Note that the alignment of the maps is arbitrary, since the data do not constrain the absolute position. See the text for a discussion of the alignment used. Contour levels are logarithmic, with seven per decade. The levels are −5.36, −3.86, −2.00, 2.00, 3.86, 5.36, 7.46, 14.4, 20.0, 27.8, 38.6, 53.6, 74.6, 114, 200, 278, 386, 536, 746, and 1440 mJy beam^{-1}.

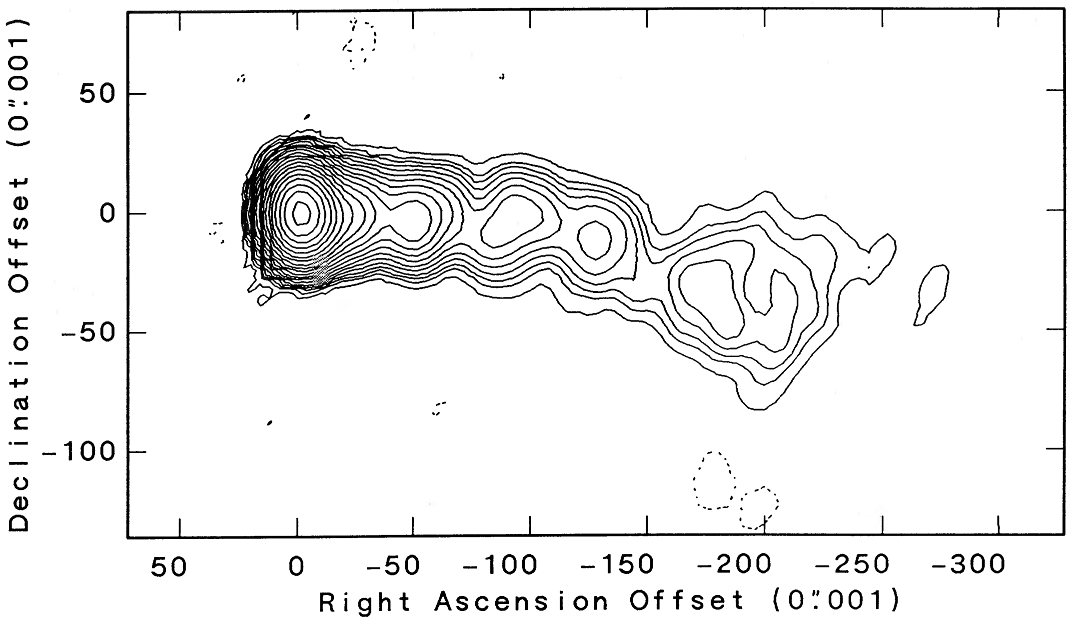

FIG. 5.—Map of 3C 120 made from combined MERLIN and VLBI data taken in 1984. Uniform weighting was used along with a taper of 10×10^6 wavelengths in the east-west direction and 30×10^6 wavelengths in the north-south direction. The resulting beam has a FWHM of 22×14 mas elongated along position angle $-2°$. Contour levels are the same as those in Fig. 4.

Regions of clear changes occur along the ridge of the jet at about 12, 32, and 50 mas. In the first two cases, the length of the bright portion of the jet seems to have been extended. In the latter case, the centroid of the feature extending between about 40 and 70 mas has moved farther from the core. There is also a strong suggestion of motion of the overall group of components between 75 and 110 mas from the core. While the reliability of the details of these components is not great, the overall shape (arc extending north, then west) is consistent between the epochs. If the maps are overlaid, the best alignment is obtained with a shift slightly greater than that needed for the 50 mas feature.

In order to provide an objective measure of the motion, a program was written to cross-correlate specific regions as a function of offset. For the region along the jet between 40 and 70 mas, the cross-correlation peaks at an offset of about 3.1 mas. Farther out, between 75 and 110 mas, the peak occurs at about 5.8 mas. The errors in these measurements are dominated by a combination of errors in the maps and uncertainty in the position of the brightest feature relative to the high-frequency core, both of which are uncertain as discussed above. Based on the variations in structure seen in the many maps made during the efforts to improve the dynamic range, we estimate the error for the 50 mas feature to be about ± 1.5 mas and that for the 90 mas features to be roughly ± 5 mas. These numbers show that we consider the motion of the 50 mas feature to be convincing, while the motion of the 90 mas features seems real but is in need of confirmation with third epoch observations.

Figures 5–8 show the results obtained from the combined VLBI–MERLIN data set. In all cases, refer to the figure captions for exact beam sizes and contour levels. Figure 5 was made with uniform weighting and a taper than gave a beam of about 14×22 mas. It shows the same region as is shown in Figure 3, but with lower resolution so the jet in the regions far from the core is brighter (in janskys per beam) and therefore more reliable. It clearly shows the wiggling of the jet in the vicinity of 100 mas and the brightening along the southern side beyond about 170 mas.

The structure of the jet at about 0".05 resolution is shown in Figure 6. Again this map was made with uniform weighting. Now the jet is seen to extend to about 0".5 in a somewhat southwesterly direction from the regions seen at higher resolution.

Figure 7 shows the jet with 0".1 resolution. The map was made with natural weighting. The features about 0".5 north and south of the core are calibration artifacts, probably at least partly due to closure errors. This map shows that, beyond 0".5, the brightest portion of the jet is almost due west of the core rather than in the somewhat more southerly direction that might have been expected based on the higher resolution maps. This might be the result of a bend to the north near 0".5. However, it is also possible the jet is broad (on the order of 0".3 at 1" from the core) and edge-brightened in this region. The low-level features south of the main ridge near 1" do not appear much different from noise here but were seen in a number of maps of similar resolution that were made with a variety of mapping parameters. The persistence of these features suggests that there actually is emission south of the main ridge of the jet, but it did not prove possible to obtain sufficient dynamic range to be sure. The bright knot at about 4" is clearly seen in this map. Comparison with 15 GHz data from the VLA with similar resolution, some of which are shown in Paper I, shows good agreement, although the jet is so weak at 15 GHz that the extra dynamic range of the VLA does not help define its structure.

The final map, shown in Figure 8, has a resolution of 0".3. The taper used for this map is such that it is based primarily on MERLIN data. Now the jet is seen almost connecting to the 4" knot, and emission up to 10" from the core is seen. This map is

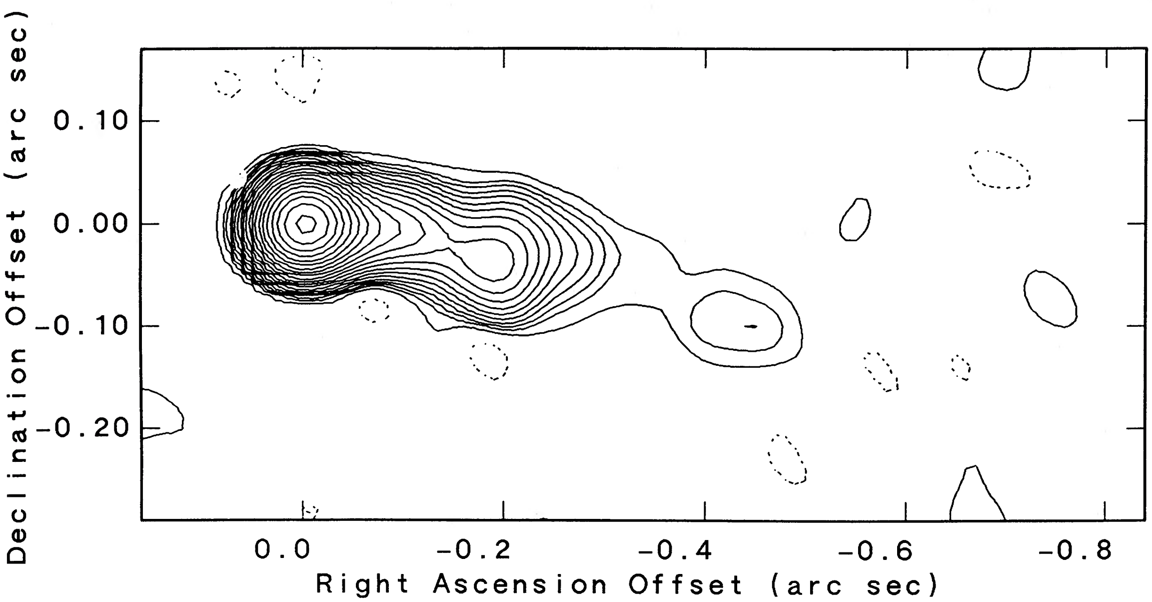

FIG. 6.—Combined MERLIN–VLBI map of 3C 120 made using a 3×10^6 wavelength taper and uniform weighting. A circular convolving beam with a FWHM of 50 mas was used. Contour levels are the same as in Fig. 4.

rather similar to others made with the VLA and presented in Paper I. Note that the "ears" just north and south of the core are calibration artifacts similar to those seen in Figure 7.

IV. DISCUSSION

The 5 GHz monitoring observations of superluminal motions in 3C 120 have found features moving at about 1.4 mas yr^{-1} in the early 1970s and in 1979 (Walker *et al.* 1982). During the early 1980s, four features with rates of about 2.5 mas yr^{-1} were observed (Paper II). Over the 1.5 yr between the two epochs of the 1.7 GHz maps reported here, displacements of 2.1 and 3.7 mas would be expected for the 1.4 and 2.5 mas yr^{-1} rates measured at 5 GHz. The motion of 3.1 ± 1.5 mas observed at 50 mas is within this range, indicating that the velocity at 50 mas is similar to that near the core. At 90 mas, the motion of 5.8 ± 5 mas is too uncertain to make a strong statement about the velocity, but is consistent with the velocity near the core and with higher velocities. Note that, at 3.1 mas in 1.5 yr, or 2.1 mas yr^{-1}, the components observed would have left the core well before VLBI was invented.

These observations extend the angular range over which superluminal motions have been observed in any source by at least a factor of 2 (probable motions beyond 20 mas have been seen in 3C 273 by Cohen *et al.* 1983) and in 3C 120 by at least a factor of 5. In 3C 120, the 5 GHz monitoring observations have shown good evidence for motions to about 6 mas and possibly to about 10 mas. The 1.7 GHz observations do not, however, extend the range of superluminal motions to larger physical scales. With a redshift of only 0.033, an angular scale of 50 mas corresponds to about $25h^{-1}$ pc. In other superluminal sources with redshifts of order 0.5 (e.g., 3C 345), the same physical scale corresponds to an angular scale of order 3 mas, or well within the range of the observed motions.

The extension of the angular scale of superluminal motions is important because it shows that the motions are maintained over a relatively large range of scales. Our data indicate that the jet does not slow down over an order of magnitude in core distance. This is consistent with the concept that the large-scale jets are also relativistic and that the one-sidedness is due to relativistic beaming (see Bridle and Perley 1984). Future observations of 3C 120 should extend the range even farther, perhaps even to the 4″ knot that is about $2h^{-1}$ kpc from the core.

Paper I contained extensive observations of the 3C 120 radio jet on a very wide range of scales. The simple evolution of the jet brightness, and hence of the physical parameters, was emphasized. The VLBI–MERLIN data presented in this paper contribute to this discussion in two ways: they fill in a range of scales where the coverage by the maps presented in Paper I was poor, and they show a region in which the transverse extent of the jet, relative to the core distance, is relatively large. Also note that some of the high-resolution data used in the discussion in Paper I was from the 1982 October observations at 1.7 GHz, the experimental details of which are presented in this paper.

The contribution of the current data to the discussion of the evolution of jet parameters is seen by comparison of Figures 9 and 10 with the corresponding figures (Figs. 15 and 17) in Paper I. Figure 9 shows the emission per unit length of jet as a function of core distance for data from all along the jet. These are the data from Figure 15 of Paper I plus results from the four VLBI–MERLIN maps presented here. As with the earlier data, the numbers were derived by an automated procedure that makes slices across the jet and fits a single Gaussian to the resulting profile. The results of these fits are then edited by hand to eliminate the ones with poor signal-to-noise ratio. Similarly, Figure 10 is the same as Figure 17 of Paper I with the current data added. In both cases it is seen that the new points fill in a sparsely covered regime in the earlier data. In both figures, a newly fitted power law is shown and the parameters are given in the figure captions. These power laws are essentially the same as those found in Paper I. Figures 9 and 10 reinforce the results presented in Paper I on the overall evolution of the jet, and the reader is referred to that paper for an extensive discussion of the implications.

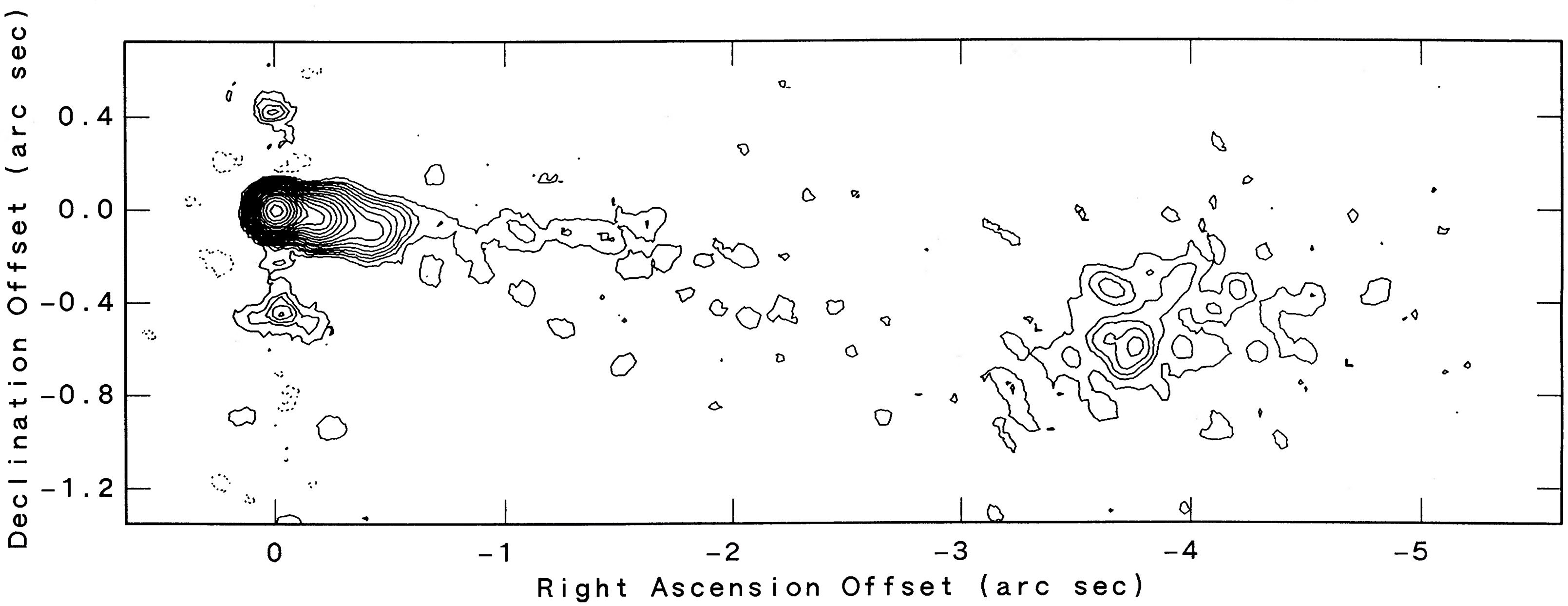

FIG. 7.—MERLIN–VLBI map of 3C 120 made with a 2.5 × 10^6 wavelength taper and natural weighting. A 0″.1 circular convolving beam was used. Contour levels are the same as in Fig. 4. Note that the features about 0″.5 north and south of the core are artifacts of imperfect calibration of nonclosing gain offsets in the data. They are not real.

1988ApJ...334..560B

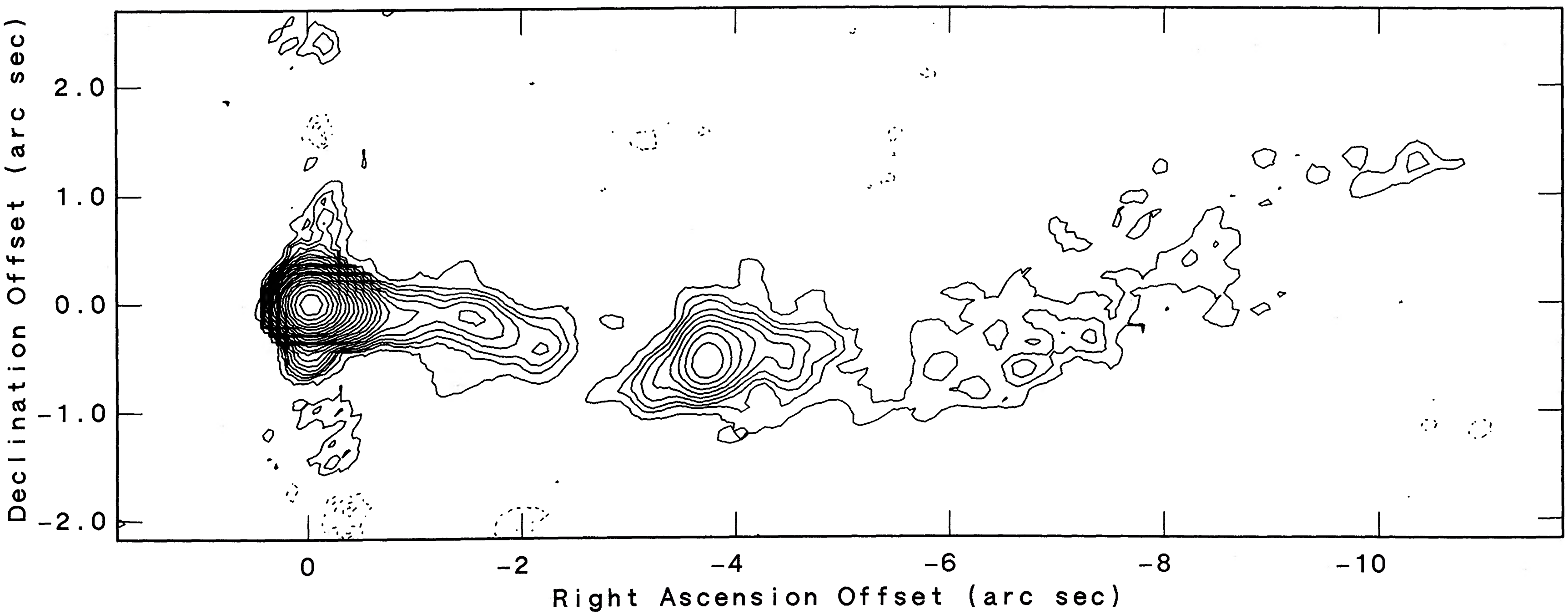

FIG. 8.—MERLIN–VLBI map of 3C 120 made with a 0.7×10^6 wavelength taper and natural weighting. With this taper, the map is dominated by the MERLIN data. A 0″.3 circular convolving beam was used. Contour levels are 0.75 times those used in Fig. 4. Again, the "ears" north and south of the core are calibration artifacts.

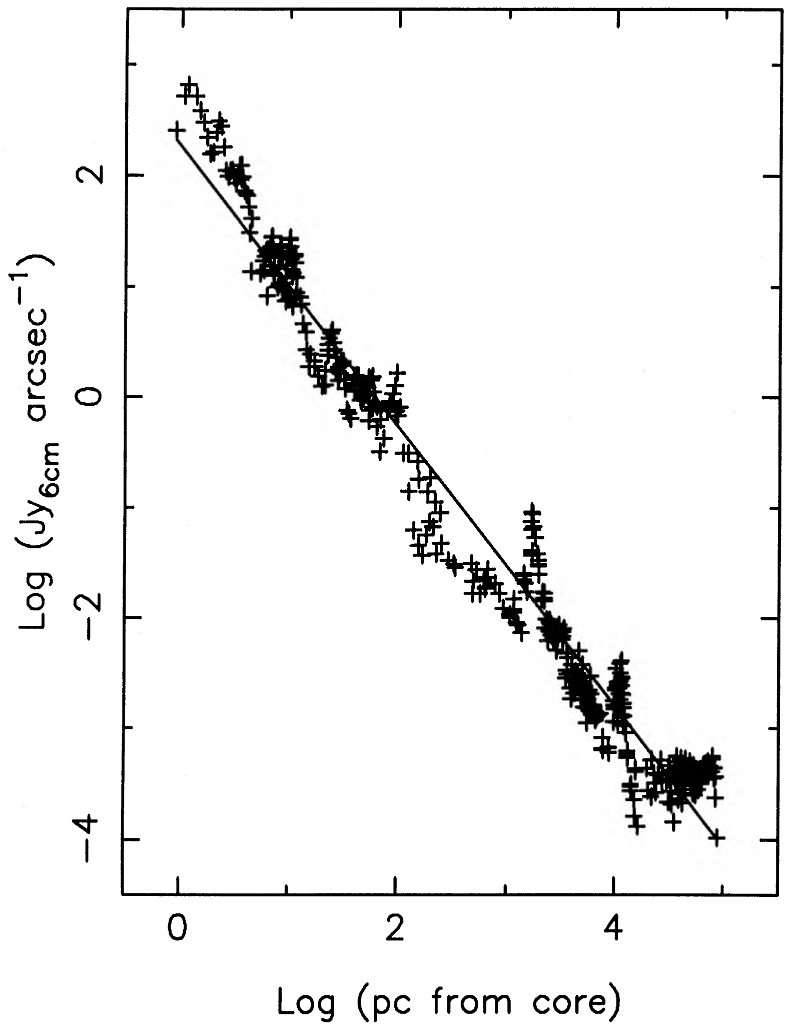

FIG. 9

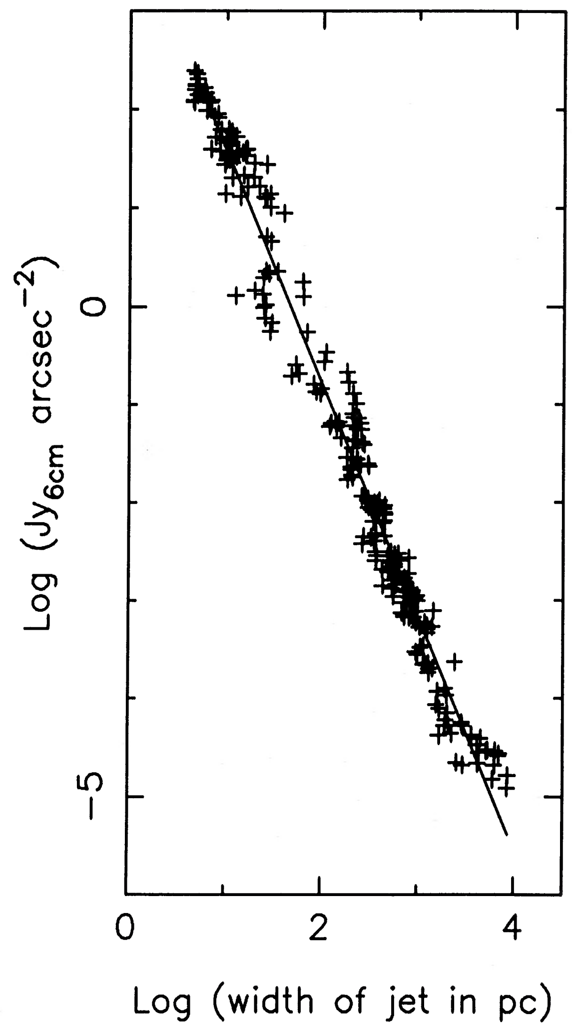

FIG. 10

FIG. 9.—Plot of the emission per unit length of the 3C 120 jet as a function of distance from the core. This is essentially Fig. 15 of Paper I with the data from the MERLIN–VLBI maps presented in this paper added. The data are derived from Gaussian fits to slices across the jet. The emission has been adjusted to the emission at 5 GHz using a spectral index of 0.65. The line is the result of a least-squares fit to a power law with index -1.27 ± 0.03

FIG. 10.—Central intensity of the 3C 120 jet as a function of jet width. This is Fig. 17 of Paper I with the MERLIN–VLBI results added. Points for which the width measurement is not reliable are excluded. The parameters plotted are those needed to derive physical conditions in the jet under the equipartition assumption. The line represents the result of a least-squares fit to a power law of index -2.37 ± 0.07.

The region of the 3C 120 jet observed with the experiments discussed here is one in which there is significant transverse resolution. It is apparent that there is much internal structure in the jet. In particular, there seem to be knots and wiggles, somewhat reminiscent of the structures seen in the M87 jet that suggest, for M87, that much of the radio emission may come from surface phenomena (F. Owen 1988, private communication). The apparent opening angle of the 3C 120 jet in this region is relatively large compared to that seen on larger scales. Either the mechanism responsible for collimating the jet is more effective on the larger scales, or the large opening angle on small scales is a projection effect. A jet with a constant actual opening angle will have a larger apparent opening angle where it lies close to the line of sight. Since the superluminal motions suggest a line-of-sight geometry on small scales and since there is considerable bending in the plane of the sky on large scales, it would not be surprising if projection effects are significant.

V. CONCLUSIONS

The major results of the study presented here are the following:

1. Significant changes in the radio structure of 3C 120 are seen on scales out to 100 mas between two observations separated by 1.5 yr. The changes indicate the presence of superluminal motions at 50 mas and probably at 90 mas from the core. These are the largest angular scales on which superluminal motions have been observed.

2. The continuity of the 3C 120 jet on scales of a fraction of an arcsecond is established. The 1982 data presented here formed part of the discussion of continuity in Paper I. The more recent work reinforces the conclusions therein. The jet on these scales is wider, relative to core distance, than on other scales and has complex internal structure.

3. The observation that the jet does not slow down over an order of magnitude in core distance, combined with the continuity of the physical parameters deduced from observations over many orders of magnitude in core distance, suggests that the jet remains relativistic on even larger scales. This supports the concept that the powerful, one-sided jets are relativistic on all scales and that the one-sidedness is the result of relativistic beaming.

The authors would like to express their appreciation to the staffs of all of the observatories involved in these observations and to the US and European VLBI networks, without whose support these observations would not have been possible. We are also grateful to the other astronomers involved in the World Radio Array observations who helped organize and execute the 1984 session. We heartily thank Bob Vernon and the staff of the NRAO Correlator for diligently processing the World Radio Array experiment for over three months! Special thanks go to Dr. Guy Pooley and Professor A. Hewish of the Mullard Radio Astronomy Observatory for allowing us to use the Cambridge antenna for VLBI for the first time and for help in running the observations; to Biörn Nilsson of Onsala, who made special efforts to equip and run the Cambridge antenna; and to Dr. John Galt and the staff of the Dominion Radio Astronomy Observatory for special efforts to support a new receiver and VLBI system. The VLBI program at the Owens Valley Radio Observatory is supported by the National Science Foundation. The Onsala Space Observatory is operated by Chalmers University of Technology, Göteborg, with financial support from the Swedish Natural Science Research Council (NFR).

REFERENCES

Aller, H. D., Olsen, E. T., and Aller, M. F. 1976, *A.J.*, **81**, 738.
Arp, H. 1987, *J. Ap. Astr.*, **8**, 231.
Baldwin, J. A., Carswell, R. F., Wampler, E. J., Smith, H. E., Burbidge, E. M., and Boksenberg, A. 1980, *Ap. J.*, **236**, 388.
Balick, B., Heckman, T. M., and Crane, P. C. 1982, *Ap. J.*, **254**, 483.
Bartel, N., Ratner, M. I., Shapiro, I. I., Herring, T. A., and Corey, B. E. 1984, in *IAU Symposium 110, VLBI and Compact Radio Sources*, ed. R. Fanti, K. I. Kellermann, and G. Setti (Dordrecht: Reidel), p. 113.
Blandford, R. D., and Königl, A. 1979, *Ap. J.*, **232**, 34.
Bridle, A. H., and Perley, R. A. 1984, *Ann. Rev. Astr. Ap.*, **22**, 319.
Clark, B. G. 1973, *Proc. IEEE*, **61**, 1242.
Cohen, M. H., *et al.* 1975, *Ap. J.*, **201**, 249.
———. 1983, *Ap. J.*, **272**, 383.
Cornwell, T. J., and Wilkinson, P. N. 1981, *M.N.R.A.S.*, **196**, 1067.
Davies, J. G., Anderson, B., and Morison, I. 1980, *Nature*, **288**, 64.
Epstein, E. E., Fogarty, W. G., Mottmann, J., and Schneider, E. 1982, *A.J.*, **87**, 449.
Halpern, J. P. 1984, *Ap. J.*, **290**, 130.
Högbom, J. A. 1974, *Astr. Ap. Suppl.*, **15**, 417.
Lyutyi, V. M. 1979, *Soviet Astr.*, **23**, 518.
Oke, J. B., Readhead, A. C. S., and Sargent, W. L. W. 1980, *Pub. A.S.P.*, **92**, 758.
Pilbratt, G., Booth, R. S., and Porcas, R. W. 1987, *Astr. Ap.*, **173**, 12.
Pollock, J. T., Pica, A. J., Smith, A. G., Leacock, R. J., Edwards, P. L., and Scott, R. L. 1979, *Ap. J.*, **290**, 130.
Readhead, A. C. S., and Wilkinson, P. N. 1978, *Ap. J.*, **223**, 25.
Rieke, G. G., and Lebofsky, M. J. 1979, *Ap. J.*, **227**, 710.
Schilizzi, R. T., and de Bruyn, A. G. 1983, *Nature*, **303**, 26.
Schwab, F. R. 1980, *Proc. SPIE*, **231**, 18.
Schwab, F. R., and Cotton, W. D. 1983, *A.J.*, **88**, 688.
Seielstad, G. A., Cohen, M. H., Linfield, R. P., Moffet, A. T., Romney, J. D., Schilizzi, R. T., and Shaffer, D. B. 1979, *Ap. J.*, **229**, 53.
Walker, R. C. 1985, VLA Scientif Memo, No. 152.
Walker, R. C., Benson, J. M., and Unwin, S. C. 1987*a*, *Ap. J.*, **316**, 546 (Paper I).
———. 1987*b*, in *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge University Press), p. 48 (Paper II).
Walker, R. C., Seielstad, G. A., Simon, R. S., Unwin, S. C., Pearson, T. J., and Linfield, R. P. 1982, *Ap. J.*, **257**, 56.
Wilkinson, P. N., Conway, J., and Biretta, J. 1988, in *IAU Symposium 129, The Impact of VLBI on Astrophysics and Geophysics*, ed. M. J. Reid and J. M. Moran (Dordrecht: Reidel), p. 509.
Wlerick, G., Westerlund, B., and Garnier, R. 1979, *Astr. Ap.*, **72**, 277.

J. M. BENSON: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

R. S. BOOTH: Onsala Space Observatory, S-43900 Onsala, Sweden

T. W. B. MUXLOW and P. N. WILKINSON: Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK119DL, UK

G. PILBRATT: Astrophysics Division, ESA/ESTEC, Postbus 299, NL-2200 AG Nordwijk ZH, The Netherlands

R. S. SIMON: Code 4134S, US Naval Research Laboratory, Washington, DC 24944

S. C. UNWIN: Caltech 105-24, Pasadena CA 91125

R. C. WALKER; National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801