

## VLBI MONITORING OF THE SUPERLUMINAL QUASAR 3C 273, 1977–1982

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### ABSTRACT

The compact radio structure of the quasar 3C 273 has been monitored with a VLBI array at 5.0 and 10.7 GHz, at 6 month intervals during 1977–1982. On each hybrid map there is a bright “core” at the east end of the source, and several compact “knots” extending to the west. Superluminal motion of at least two knots is visible at both frequencies, with apparent speeds  $v \approx 6c$  (for  $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). These knots decay with half-lives of 1–2 years as they move out from the core; their positions are frequency-independent. The knots lie along a curved jet whose position angle is  $-115^\circ$  near the core, while further out the jet curves toward the position angle of the outer ( $20''$ ) optical and radio jet ( $-137^\circ$ ). More than 90% of the bend occurs within a projected distance of 70 pc from the core (less than 0.1% of the total jet length). No counterjet is seen on milli-arcsecond scales above a level  $\sim 10\%$  of the jet brightness. We deduce lower limits to the Doppler factors  $\delta$  of the knots, by comparing the predicted inverse Compton X-ray emission from a simple homogeneous sphere model with the observed flux; at least one knot must be moving relativistically with  $\delta_{\min} \gtrsim 2.5$ . Applying the inhomogeneous relativistic-jet model of Königl (1981) to the VLBI core, we find that very little of the observed X-ray flux can be inverse Compton emission from the core.

*Subject headings:* interferometry — quasars — radiation mechanisms — radio sources: variable

### I. INTRODUCTION

The quasar 3C 273 is very bright both optically ( $m_v = 13.0$ ,  $z = 0.158$  [Schmidt 1963]) and in the radio range ( $\sim 30 \text{ Jy}$  at 5.0 GHz), so that a large amount of observational data has been accumulated over the years. Its structure is unusual because of the well-known optical jet extending about  $20''$  from the nucleus in position angle (P.A.)  $-137^\circ$  (Greenstein and Schmidt 1964). Recent high-resolution observations on the VLA (Perley 1984) and MERLIN (Conway *et al.* 1981) show a radio jet (3C 273 A) coincident with the optical jet.

The compact radio source (3C 273 B) is centered on the nucleus of the quasar, and is unresolved by connected-element interferometers. It has been a principal object of study by very long baseline interferometry (VLBI) since the first development of that technique (Brotten *et al.* 1967; Clark, Cohen, and Jauncey 1967), and studies of its compact structure quickly showed that there were rapid changes in the visibility amplitudes, indicative of internal proper motions. The apparent expansion speed was found to be  $v/c \approx 5$ , making it a “superluminal” radio source (the early work is summarized by Seielstad *et al.* 1979). Pearson *et al.* (1981, hereafter P81) presented a series of five hybrid maps at 10.7 GHz from 1977 to 1980, showing superluminal motion of a compact component, or “knot,” in the VLBI “jet,” relative to the unresolved core.

In this paper we present the results of observations which continue and extend the monitoring program described in P81.

Our new results are more extensive because (1) they include transatlantic baselines to Effelsberg, FRG, which double the angular resolution and thereby reveal more complicated structure; (2) the monitoring covered two frequencies, 5.0 and 10.7 GHz, enabling us to derive the spectra of individual components, and to study how these spectra change.

In § II we describe the VLBI monitoring observations, data reduction, calibration, and mapping techniques. Section III presents hybrid maps from the monitoring program, with a brief discussion of the main features. Results on the source kinematics (superluminal motion of the knots, and their time evolution) are given in § IV. In § V we present synchro-Compton models of the knots and derive limits to their Doppler factors ( $\delta$ ) from X-ray measurements. We also consider the constraints on jet geometry provided by the combined measurements of  $\delta$  and  $v/c$ . For the core, we compare the inhomogeneous-jet model of Königl (1981) with the available data. Section VI discusses the relation between 3C 273 and the similar superluminal source 3C 345. We summarize the main results of the paper in § VII.

Throughout this paper we use  $h = H_0/100$ , where  $H_0$  is the Hubble constant in  $\text{km s}^{-1} \text{ Mpc}^{-1}$ , and  $q_0 = 0.05$ . For  $z = 0.158$ , the comoving coordinate distance to 3C 273 is  $R = 440 h^{-1} \text{ Mpc}$ , and the linear scale is 1 milli-arcsecond (mas) =  $1.84 h^{-1} \text{ pc}$ . Spectral index  $\alpha$  is defined by  $S \propto \nu^\alpha$ .

### II. VLBI MONITORING PROGRAM AND DATA ANALYSIS

The compact radio structure of 3C 273 has been monitored with VLBI experiments at the epochs and frequencies shown in

<sup>1</sup> NRC–NRL Cooperative Research Associate.

TABLE 1  
VLBI OBSERVATIONS OF 3C 273

| Epoch        | Frequency<br>(GHz) | Polarization  | Stations <sup>a</sup> | Flux Density <sup>b</sup><br>(Jy) |
|--------------|--------------------|---------------|-----------------------|-----------------------------------|
| 1979.25..... | 5.00               | linear E-W    | BGOH                  | 40.0                              |
| 1979.44..... | 10.65              | left-circular | BKGFO                 | 30.7                              |
| 1979.92..... | 5.01               | linear E-W    | BKGFO                 | 36.0                              |
| 1980.27..... | 10.65              | left-circular | BKGO                  | 27.0                              |
| 1980.52..... | 10.65              | left-circular | BKGFO                 | 27.8                              |
| 1981.10..... | 10.65              | left-circular | BKGFO                 | 30.4                              |
| 1981.26..... | 4.99               | left-circular | BKGFOH                | 34.8                              |
| 1981.63..... | 4.99               | left-circular | BKFO                  | 33.8                              |

<sup>a</sup> B = Max-Planck-Institut für Radioastronomie, Effelsberg, FRG (100 m); K = Haystack Observatory, Westford, MA (37 m); G = National Radio Astronomy Observatory, Green Bank, WV (43 m); F = George R. Agassiz Station, Fort Davis, TX (26 m); O = Owens Valley Radio Observatory, California Institute of Technology, Big Pine, CA (40 m); H = Radio Astronomy Laboratory, University of California, Hat Creek, CA (26 m).

<sup>b</sup> Measured during the observations at one or more stations.

Table 1. All experiments were coordinated and performed during observing sessions of the US VLBI Network. In this paper we concentrate on high-resolution maps made since 1979, but we also present the previously unpublished low-resolution 5.0 GHz maps from 1977 onward. At least five telescopes were scheduled at all epochs, to provide the  $(u, v)$  coverage needed to map this low-declination source (decl. =  $2^{\circ}3$ ). However, there were a number of partial and complete failures at some telescopes, especially during the 5.0 GHz runs; Table 1 only lists stations which produced some usable data. The  $(u, v)$  coverage was insufficient in the 1980.27 and 1981.63 observations to map the source.

We recorded the telescope data using the NRAO<sup>2</sup> Mk II system and performed the correlations on the CIT/JPL processor. The effective bandwidth of the system was 1.8 MHz. We selected coherent integration times between 30 and 120 s, which gave a signal-to-noise ratio  $\geq 3$  at all times and on all baselines, and kept unknown baseline-dependent errors due to coherence losses to a minimum. The visibility amplitudes were calibrated using antenna temperature measurements made during the observations when possible, and curves of antenna gain versus elevation or hour-angle at other times. For observations involving four stations, intersections of tracks in the  $(u, v)$ -plane were used to check the consistency of the amplitude calibration, and thus to make small adjustments. For the larger experiments (five or more stations), there are so many crossing points that an automated procedure is required to make the necessary antenna-based corrections. We therefore relied on self-calibration, as described below. In the limiting case of a large number of stations, self-calibration with a good model is equivalent to making the intersections consistent in a least squares sense.

The maps were made using the iterative self-calibration algorithm of Cornwell and Wilkinson (1981), which adjusts the antenna gains. Practical details of this method are discussed by Unwin *et al.* (1983, hereafter U83), who reduced similar observations of 3C 345 in this way. Normally, we used a large "window" in the CLEAN step, but for some of the maps we had to reduce the window size to improve the convergence on each iteration. Once a good map was found, further iterations

with a larger window produced little change. 3C 345 was usually observed in the same sessions (U83), but for 3C 273 it proved harder to make a map which fitted the observed visibilities, because (1) 3C 273 is at a much lower declination, so its  $(u, v)$  coverage is poor in the N-S direction; (2) the  $(u, v)$  tracks are shorter, especially on the longest baselines, which introduces gaps in the coverage and thus makes self-calibration harder; (3) complicated structure requires better  $(u, v)$  coverage for reliable mapping than does simple structure (Pearson and Readhead 1984), and 3C 273 appears to be intrinsically more complicated than 3C 345 (see § III below), especially at 5.0 GHz and below. In particular, 3C 273 does not contain a dominant unresolved feature, so that internal phase referencing is harder.

Finally, we noted that 3C 273 contains structure which is too extended to be mapped in our observations, but is still much smaller than the resolution of MERLIN or the VLA. Our shortest baseline was Owens Valley Radio Observatory–Hat Creek at 5.0 GHz (fringe spacing = 40 mas), and the peak correlated flux density on this baseline was typically less than the total flux density by  $\geq 5$  Jy. This difference cannot be accounted for by calibration or correlator errors. In the  $(u, v)$ -plane the peak flux lies in P.A.  $\approx -40^{\circ}$ , roughly perpendicular to that of the most extended structure seen at the lower frequency of 2.3 GHz by Cohen *et al.* (1983). We therefore conclude that there must be several janskys of structure on a scale  $\geq 15$  mas in P.A.  $\approx -130^{\circ}$ , i.e., roughly along the jet.

### III. MAPS

Figure 1 shows the complete sequence of hybrid maps made at 5.0 GHz, convolved to the resolution of the 1978 observations. The map from 1977.92 has been published previously by Readhead *et al.* (1979). By making maps with slightly different calibration and with different starting models, we estimate that they are reliable to approximately the first contour in Figure 1, or roughly 5% of the peak. Since 1979 the data (both at 5.0 and at 10.7 GHz) have been more complete and better calibrated, and the maps are reliable to a lower level than the earlier observations. None of the following discussion depends on the reality of the weakest features in the maps we show. Higher resolution maps from the last three epochs are shown in Figure 2. They were made from 4-, 5-, and 6-station observations, respectively, so that the final map has a higher dynamic range than the first.

Since all VLBI maps are made using closure phases rather than true visibility phases, a reference point is needed in order to align maps made at different times. The maps in Figures 1 and 2 have been aligned on the half-power point of the eastern edge of the core; this is the most plausible alignment, and has been used previously by P81, and for 3C 345 by U83. We define the core position to be one-half beamwidth west of the eastern half-power point; this is usually very close to the brightest peak on each map. In only the final map (1981.26) is the core weaker than the first jet component (but only slightly), and there is little doubt that the alignment in Figure 1 is correct; the weakening of the core also fits a smooth trend (see § IV below).

These maps show that the basic structure always consists of a bright core at the eastern end and one or more jet components extending out to  $\sim 20$  mas in P.A.  $\approx -115^{\circ}$ . The changes between epochs are small enough that we can trace the evolution of individual features. We adopt the convention of Cohen *et al.* (1983), labeling the core as D and the knots in the jet as  $C_1, C_2$ , etc.,  $C_1$  being the most distant from the core and

<sup>2</sup> The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

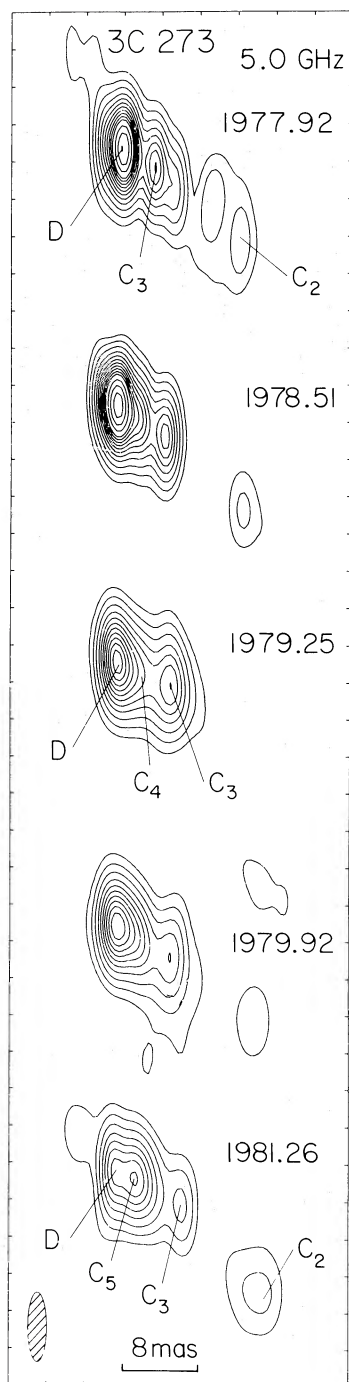


FIG. 1.—Hybrid maps of the compact radio structure in 3C 273 at 5.0 GHz, made with a beam size of  $7.5 \times 2.0$  mas in P.A.  $0^\circ$ . Contours are drawn at 0.6, 1.2, 2, 3, 4, . . . , 10, 12, 14, and 16 Jy per beam area. There are no negative areas below  $-0.6$  Jy per beam area. Map quality varies with the number of stations used (see Table 1). The maps are aligned on the core (see text for details).

seen only at 2.3 GHz (Cohen *et al.* 1983). The resolved outer component  $C_2$  is detected reliably only on the 1981.26 map, because shorter baselines were used in that observation (Table 1). Apparent superluminal motion between D and  $C_3$  was seen at 10.7 GHz by P81, and Figure 1 shows that the same relative motion also occurred at 5.0 GHz. In the high-resolution maps of Figure 2, two additional components ( $C_4$  and  $C_5$ ) are

marked. If we assume that all the jet components have similar proper motions to that of  $C_3$  seen by P81 ( $0.76 \text{ mas yr}^{-1}$ ), then the shoulder between D and  $C_3$  in 1979.92 (Fig. 2) is  $C_4$ , and the shoulder between  $C_5$  and  $C_3$  in 1981.26 is  $C_4$ . This assumption is reasonable because 3C 345 shows a similar evolution, and has two knots which move at roughly the same speed (U83). In 3C 120 the evolution is more complicated, but again the changes are most easily interpreted as outward motion of several knots (Walker *et al.* 1982).

Figure 3 shows the high-resolution 10.7 GHz maps for 1979–1981. Low-resolution maps from 1977 through 1980 are shown by P81, and are not reproduced here. Except for the core D, many of the components on these maps are not resolved as discrete knots, so the task of identifying and labeling individual features is difficult. The figure shows the identifications, based on comparisons with the other maps, and using the labeling convention described above. In the 1981.10 map there appears to be a new knot ( $C_6$ ) at  $R \approx 1.1$  mas. This separation is below the resolution limit of the 5.0 GHz map from almost the same epoch (1981.26; see Fig. 2), but  $C_6$  may contribute to the 5.0 GHz brightness of the core D.

#### IV. SOURCE KINEMATICS

##### a) Superluminal Motion

The maps in Figures 1, 2, and 3 show that the proper motion seen by P81 between components  $C_3$  and D continues at least

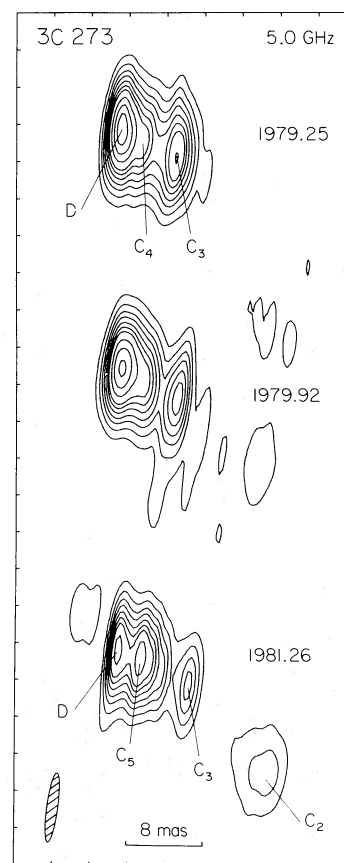


FIG. 2.—Hybrid maps of the compact radio structure in 3C 273 at 5.0 GHz, made with a beam size of  $7.5 \times 1.15$  mas in P.A.  $-8^\circ$ . Contours are drawn at 0.3, 0.6, 1.2, 1.5, 2.0, 2.5, 3, 4, 5, and 6 Jy per beam area. There are no negative areas below  $-0.3$  Jy per beam area. Other details as in Fig. 1.

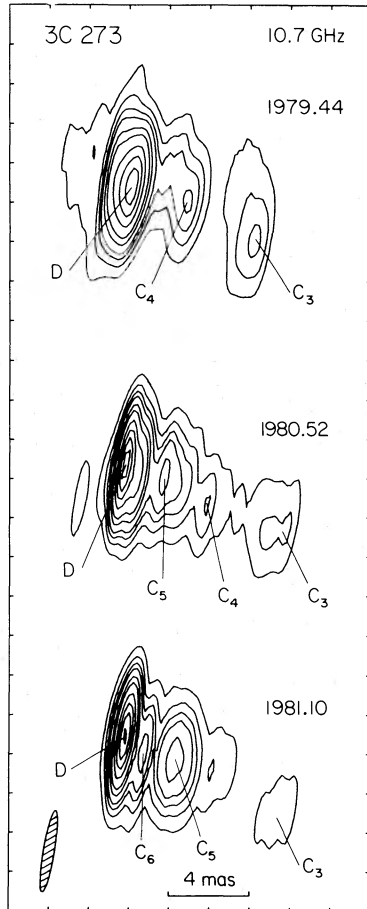


FIG. 3

FIG. 3.—Hybrid maps of the compact radio structure in 3C 273 at 10.7 GHz, made with a beam size of  $4.2 \times 0.55$  mas in P.A.  $-10^\circ$ . Contours are drawn at 0.2, 0.4, 0.7, 1.0, 1.5, 2, 3, 4, 6, 8, ..., 18 Jy per beam area. There are no negative areas below  $-0.2$  Jy per beam area. Other details as in Fig. 1.

FIG. 4.—Separation of components in the 3C 273 jet from the core at 5.0 and 10.7 GHz, as a function of observing epoch. Measurements of  $C_3$  from P81 are also shown. The straight lines represent linear least squares fits to the observed points, shown with  $\pm 1\sigma$  error bars estimated from the map measurements.

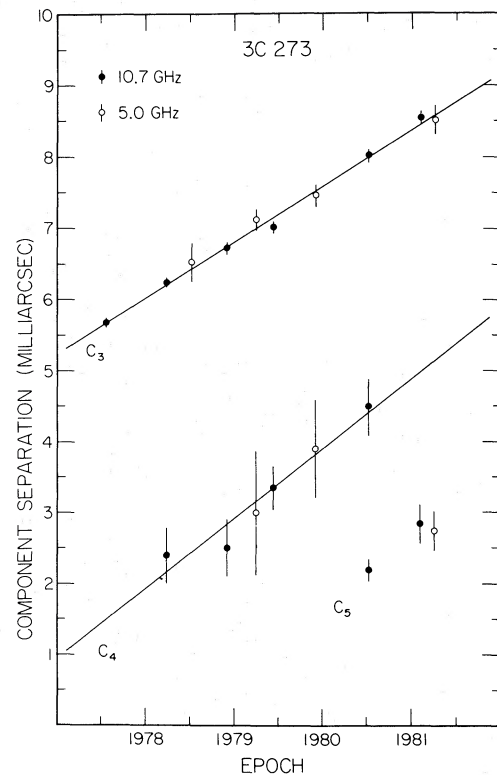


FIG. 4

until 1981.26. Following P81, we aligned the maps as described in § III above, and measured the radial distances of the various components from the core. The results are plotted on the time sequence shown in Figure 4. They are most extensive for knot  $C_3$ , which continues to show a steady proper motion, with no evidence of acceleration. Furthermore, its position is independent of frequency (between 5.0 and 10.7 GHz), so there are no significant spectral gradients across it. (We believe that there is no significant frequency dependence in the position of the reference point; see § Vc.)

Table 2 gives the results of a linear least squares fit to the motion of components  $C_3$  and  $C_4$ , both of which are superluminal relative to the core D. When we discuss superluminal motion, we assume that the core D is stationary, from argu-

ments in P81 and U83, and by analogy with 3C 345, for which an absolute measurement has been made by Bartel *et al.* (1984). There is considerable scatter in the measurements of  $C_4$ , due to blending with adjacent features, but the speed is consistent with that of  $C_3$ . Only three measurements of the position of  $C_5$  are available, but they are again consistent with superluminal motion at  $v/c \approx 6 h^{-1}$ . The uncertainty is large because  $C_5$  is resolved, and appears to change shape, so it has no single well-defined velocity.

#### b) Evolution of Component Brightness

The maps in Figures 1–3 show evolution of the component flux densities, as well as proper motion. To study these changes quantitatively, we estimated the flux densities of each com-

TABLE 2  
SUPERLUMINAL MOTION IN THE 3C 273 JET

| Component                                          | $C_3$                   | $C_4$                   |
|----------------------------------------------------|-------------------------|-------------------------|
| Proper motion <sup>a</sup> (mas yr <sup>-1</sup> ) | $0.79 \pm 0.03$         | $0.99 \pm 0.24$         |
| Apparent transverse velocity <sup>b</sup>          | $(5.5 \pm 0.2) h^{-1}c$ | $(6.9 \pm 1.7) h^{-1}c$ |
| Epoch of zero separation <sup>a</sup> (yr)         | $1970.3 \pm 0.2$        | $1976.0 \pm 0.6$        |

<sup>a</sup> Assuming constant velocity.

<sup>b</sup> Relative to the core D (Hubble constant  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ ).

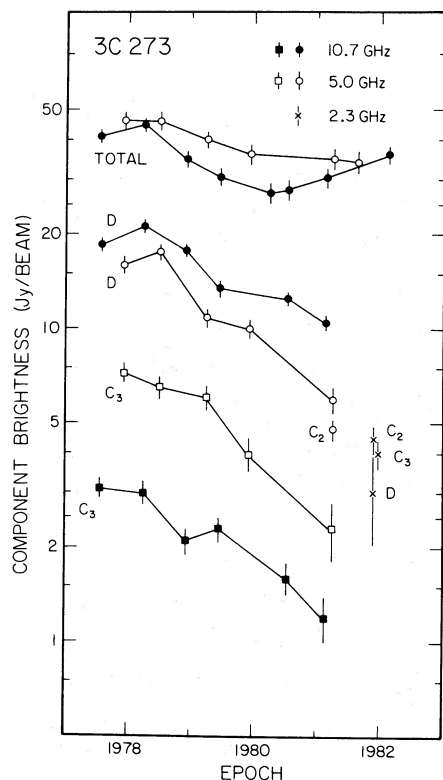


FIG. 5.—Variation in peak brightness of components D and  $C_3$ , at 5.0 and 10.7 GHz, as a function of observing epoch, derived from maps made with a restoring beam with FWHM  $7.5 \times 2.0$  mas, in P.A.  $0^\circ$ . Bars represent estimated  $\pm 1 \sigma$  errors. The variation in total flux density at 5.0 and 10.7 GHz is also shown.

ponent at each epoch directly from the maps, by taking the peak brightness. The results, plotted on a logarithmic scale against epoch, are shown in Figures 5 and 6. If the source structure were simpler, more reliable estimates could perhaps have been made by model fitting. Complicated models (four or more Gaussians) would be required, however, perhaps introducing unknown systematic effects. The hybrid maps are free of this kind of bias, and we allow for the limited dynamic range in the error estimates. By using the peak flux density only, we minimize the effects of blending. For resolved components (e.g., on the 10.7 GHz maps of Fig. 3), we used lower resolution maps to give more reliable estimates of peak brightness.

Figure 5 shows the results from maps made with a  $7.5 \times 2.0$  mas beam. Measurements were possible only for  $C_3$  and the core D; also shown is the variation in total flux density. In all cases the thermal (system) noise is small, and the errors are based on the degree of confusion between adjacent features and the dynamic range on the map. Any systematic errors are likely to be correlated between epochs, since most of the structure changes are moderate. This means that the general trend of roughly exponential decay of D and  $C_3$  at both 5.0 and 10.7 GHz (Fig. 5) is significant. For  $C_3$  the half-lives are  $\sim 2.5$  yr at 10.7 GHz and  $\sim 1.9$  yr at 5.0 GHz, not a significant difference. This contrasts with 3C 345 (U83), which showed some evidence for steepening of its knot spectra with time. For D the half-life is  $\sim 3.4$  yr at 10.7 GHz and  $\sim 2.1$  yr at 5.0 GHz. If this difference is real, it corresponds to an increase in  $\alpha$ , and an upward shift of the spectral peak between 1978 and 1981. This is in the opposite sense from the usual expansion models and instead

probably results from blending of D with  $C_6$  (Figs. 2 and 3), which was strong in 1981.10 at 10.7 GHz but weaker at 5.0 GHz.

At high resolution (beam size =  $7.5 \times 1.15$  mas) we are able to resolve knot  $C_4$  from adjacent features and follow its evolution (Fig. 6). This component also decays exponentially, but at a much faster rate (half-life  $\approx 1.1$  years) than D and  $C_3$ , so it may be fortuitous that D and  $C_3$  have about the same decay rate. Component D is probably stationary (as noted above) and may correspond to a permanent feature with different physics from that of the knots  $C_1$ – $C_6$ . In § Vd below, we discuss D in terms of steady radiation from a relativistic flow along a fixed jet; in this model the decay could result from a reduction in the flux of relativistic fluid.

The total flux density does not show the same rapid decay, but actually begins to increase after 1980.0 (Fig. 5). As the sequence of hybrid maps in Figure 3 indicates, this is because a new component  $C_6$  emerged from the core to enhance the total flux density, at least at 10.7 GHz; it is not seen on the 5.0 GHz maps. In this picture of components being ejected from the core, and decaying as they move out, the total flux density varies much less than the individual knots, since no single component dominates at any time. The variability of individual components is much greater than monitoring of the total flux density would suggest.

Since the decay of components  $C_3$  and  $C_4$  has been followed over only a range of about a factor of 3 in brightness, it is hard to distinguish between various decay mechanisms. The data are consistent with a power-law decay of the form  $S = S_0(t - t_0)^\eta$ . With a suitable choice of epoch  $t_0$ , the decay rate can match the observed rate. For simple adiabatic expansion,  $\eta = 4\alpha - 2$  (Kardashev 1962). Component  $C_3$  has  $\alpha = -1.0$

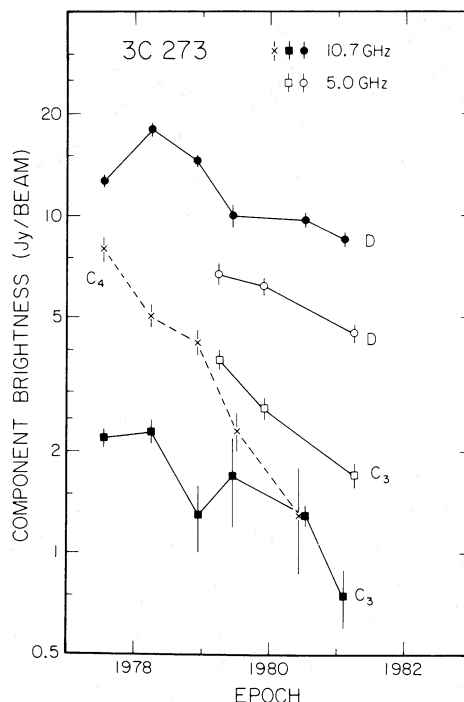


FIG. 6.—Variation of peak brightness of components D,  $C_3$ , and  $C_4$ , as a function of observing epoch, derived from maps made with a restoring beam with FWHM  $7.5 \times 1.15$  mas, in P.A.  $-8^\circ$ . Other details as in Fig. 5.

(§ Vb below),  $\eta = -6$ , and  $t_0 = 1960.0 \pm 2.0$ ; for  $C_4$  we find  $\alpha = -0.9$ ,  $\eta = -5.6$ , and  $t_0 = 1971.0 \pm 2.0$ . In both knots epoch  $t_0$  is earlier than the extrapolated epoch of zero separation from the core (Table 2), perhaps implying that the knots emerge with a finite size from the core; more likely, a power-law decay is not appropriate initially, since the flux density obviously cannot be infinite at epoch  $t_0$ . In this model  $C_3$  and  $C_4$  expand by  $\sim 20\%$  between 1979 and 1981, which is consistent with the maps in Figures 2 and 3.

Adiabatic expansion with continuous reacceleration with energy index  $(2\alpha - 1)$  gives  $\eta = 2\alpha - 1$ , and moves  $t_0$  to later times:  $t_0 = 1970.0 \pm 3.0$  and  $t_0 = 1976.0 \pm 1.0$  for  $C_3$  and  $C_4$ , respectively; these are remarkably close to the zero-separation epochs in Table 2 for both components. Since the components probably originated deep inside the optically thick core, it is perhaps not surprising that no outburst in total flux density occurred at those times. For  $C_3$  the predicted expansion is consistent with the maps, but for  $C_4$  the predicted transverse expansion [ $\omega \propto (t - 1976.0)$ ] is probably too rapid.

Other, more complicated decay mechanisms generally lead to power laws with different values of the index  $\eta$ . The data are probably consistent with a wide range of models. Continued monitoring of the knot fluxes would enable some models to be eliminated, because of the strong dependence of the decay rate on  $\eta$ .

#### c) Nonlinear Structure

Some of the early VLBI observations of 3C 273 showed nonlinear structure (Niell *et al.* 1975), and this is evident in Figures 1 and 2, especially the 1981.26 map. To show this more clearly, we plot in Figure 7 the positions of all the components from the high-resolution maps of Figures 2 and 3, and include the 2.3 GHz position of  $C_2$  from Cohen *et al.* (1983). Near the core, the P.A. is  $-117^\circ$ , while a line joining  $C_3$  and  $C_2$  lies in P.A.  $-138^\circ$ , giving a total bending of at least  $21^\circ$ . Since the optical and large-scale ( $20''$ ) radio jets lie in P.A.  $-137^\circ$  (Conway *et al.* 1981), the source may be straight to within  $1^\circ$  from a projected distance  $R \approx 20$  mas ( $36 h^{-1}$  pc) from the core, out to  $R \approx 20''$  ( $36 h^{-1}$  kpc), a range of 1000 in radius.

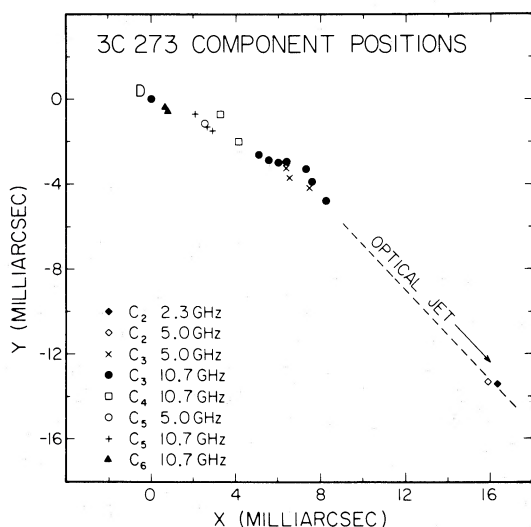


FIG. 7.—Positions on the sky of knots in the jet of 3C 273, relative to the compact core, measured from the high-resolution maps of Figs. 2 and 3. Also shown is the position of knot  $C_2$ , from Cohen *et al.* (1983).

Some “wiggling” on intermediate scales is possible, however, as suggested by the MERLIN map. The 2.3 GHz map of Cohen *et al.* (1983) shows structure extending to at least 35 mas in the direction of the optical jet.

Do the moving components travel independently, or do they follow a single fixed path? Figure 7 shows that the data are consistent with motion along a single curved path, although we have not yet followed the motion of more than one component past any given radius from the core. Unfortunately, the present measurements are limited by the poor resolution in the N-S direction, perpendicular to the jet, and there are too few data to tell whether or not the P.A. of a given component rotates with time to trace out the mean curve in Figure 7. Notice that the curvature is not noticeably stronger near the core. This contrasts with 3C 345, for which similar (but much better) data show strong curvature close to its core, while the arcsec-scale jet is relatively straight (Biretta *et al.* 1983; Moore, Readhead, and Bååth 1983).

### V. MODELS OF THE RADIO AND X-RAY EMISSION

#### a) Overall Electromagnetic Spectrum

The source 3C 273 has the best studied spectrum of all quasars, since it has been observed in every accessible wave band from 22 MHz to 500 MeV. Several authors (e.g., Worrall *et al.* 1980; Königl 1981) have invented models to explain the shape of the spectrum over this huge frequency range (15 orders of magnitude). Our interest in the overall spectrum is in seeing how these models fit the variable VLBI structure of the nucleus. In particular, our observations of apparent superluminal motion strongly suggest that relativistic beaming is important. The very high brightness temperatures of the nuclear components suggest the possibility of inverse Compton scattering of synchrotron photons as a source of high-frequency radiation, especially X-rays.

Although the flux density of 3C 273 is variable, results of many observations made at different epochs give a reasonably accurate picture of the overall spectrum (Ulrich *et al.* 1980; Worrall *et al.* 1980). In the radio range, the spectrum is smooth and flat ( $\alpha \approx 0$ ); above  $\sim 50$  GHz it steepens to  $\alpha \approx -0.8$ , and steepens again to  $\alpha \approx -1$  in the infrared ( $\sim 3 \times 10^{13}$  Hz). The optical-ultraviolet continuum has a flat spectrum ( $\alpha \approx 0$ ) and lies above the extrapolation of the infrared slope. Since the optical continuum is also less polarized and less variable than the radio (Neugebauer *et al.* 1979), it probably arises from a different region than the radio-infrared radiation. The X-ray emission lies roughly on the  $\alpha \sim -1$  extrapolation from the infrared but has a flatter spectral index: Halpern (1982) finds  $\alpha_x = -0.44 \pm 0.05$  in the 1–10 keV range.

#### b) Spectra of Compact Radio Components

Our VLBI maps at 2.3, 5.0, and 10.7 GHz enable us to determine the spectra of certain individual components in the nucleus fairly accurately, within limits due to changes between observations. Figure 8 shows the results of measurements from the maps, referred to 1981.10, the epoch of one of the 10.7 GHz observations. Values for 5.0 GHz were interpolated from adjacent observations, and values from the single 2.3 GHz map of 1981.89 were extrapolated back to 1981.10 by assuming a power-law decay with half-life 3 years. This half-life is consistent with the 2.3 GHz data of Cohen *et al.* (1983), which show a 50% decay in  $C_2$  and a 25% decay in the combined flux density of D,  $C_4$ , and  $C_3$  in 3.6 years. The uncertainty in this

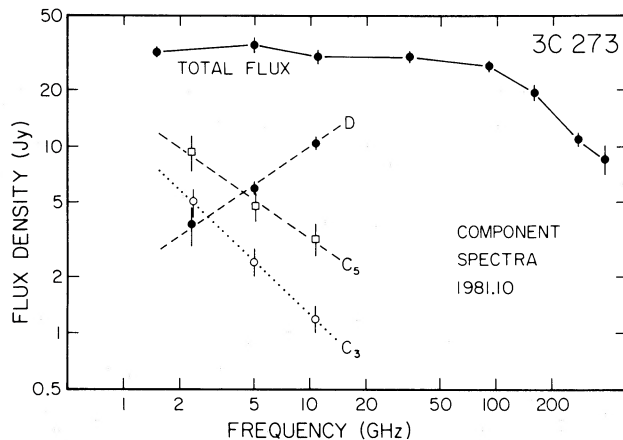


FIG. 8.—Radio spectra of the core, D, and knots  $C_3$  and  $C_5$ , measured from the maps in Figs. 2 and 3, and interpolated to epoch 1981.10. Also shown is the approximate total flux-density spectrum, interpolated to the same epoch, from Table 1 and from Clegg *et al.* 1983 and Landau *et al.* (1983).

extrapolation is not significant in determining the shape of the spectrum. The component brightness curves in Figure 5 include the single 2.3 GHz epoch, and demonstrate that this small extrapolation is reasonable.

There are several points to note in Figure 8: (1) Individual components have spectra different both from one another and from the total flux density, whose spectrum is flat and smooth. (2) The jet components  $C_3$  and  $C_5$  have straight spectra with  $\alpha \approx -1.0$  and  $-0.7$ , respectively, indicative of optically thin synchrotron radiation. Because no lower frequency VLBI observations separate the components reliably, only upper limits to their synchrotron “turnover” frequencies  $\nu_m$  can be deduced. (3) The core D is optically thick with  $\alpha \approx 0.65 \pm 0.15$ ; clearly, it cannot be approximated at all well by a homogeneous self-absorbed synchrotron source, for which  $\alpha = 2.5$ . More likely, it is a blend of components with a range of turnover frequencies, and a simple fit to the data points could be made with (say) a pair of homogeneous spheres with different  $\nu_m$ . (4) The sum of component fluxes in Figure 8 falls short of the total flux density, because (a) not all the knots have their spectra plotted and (b) the maps are missing structure on large scales (§ II).

The trends in spectral indices of the core and knots indicate that the core dominates the total flux density above  $\sim 10$  GHz. This is borne out by the recent 22 GHz observations of Biretta *et al.* (1984), which show the knots to be very weak. The millimeter spectrum of the components is unknown, but by extrapolation we estimate that the turnover frequency of the core lies between 40 and 70 GHz, and the corresponding peak flux density lies between 20 and 25 Jy.

### c) Synchrotron Self-Compton Models

As a model of the VLBI structure we assume that the jet components  $C_3$ ,  $C_4$ , and  $C_5$  are homogeneous spheres containing tangled magnetic fields  $B$  and high-energy electrons which are isotropic in a comoving frame. The electrons produce radio emission by synchrotron radiation, and the X-ray flux (at least in part) by inverse Compton scattering of their own synchrotron photons (e.g., Jones, O’Dell, and Stein 1974). As we noted in § Vb above, the core cannot be homogeneous, and as an example of possible inhomogeneous models we use the Königl (1981) model of an expanding relativistic jet.

A constraint on these models is that the inverse Compton X-radiation should not exceed the observed X-ray flux. For the sphere model this gives a lower limit to the Doppler factor  $\delta$  (the ratio of observed to emitted frequency), where  $\delta = \gamma^{-1}(1 - \beta \cos \theta)^{-1}$  (the bulk speed is  $\beta c$ , at an angle  $\theta$  to the line of sight, and  $\gamma^{-2} = 1 - \beta^2$ ). We also estimate the magnetic fields and minimum internal pressures.

The observational parameters we use for the jet components, and the results of the calculations, are given in Table 3. We omit  $C_4$  because its spectrum is too poorly known, but include a homogeneous sphere calculation for the core D (although it is certainly inhomogeneous), for comparison with the jet components and with the core component in 3C 345 (§ VI). In all cases we have been conservative, in the sense of minimizing the allowed value of  $\delta_{\min}$ , the minimum Doppler factor. To estimate the sphere diameter  $\omega$  we used the 10.7 GHz maps, which have a smoothing beam of  $0.55 \times 4.2$  mas. The jet components are all resolved along the jet but not in the long direction of the beam. To be conservative, we assumed that the source was circular, and used the deconvolved Gaussian E-W diameter multiplied by 1.15, to convert to the optically thin sphere diameter. Component D was measured in the optically thick regime, and since it appeared slightly resolved (E-W) on the 10.7 GHz map, we simply took  $\omega$  equal to the measured FWHM on the map. We assumed  $\alpha = -0.8$  for the (unknown) optically thin spectral index, but in fact  $\delta_{\min}$  is very insensitive to  $\alpha$ . For the synchrotron turnover of D we took the largest values of  $\nu_m$  and  $S_m$  consistent with the total flux-density spectrum and extrapolating the optically thick spectrum of D; this minimizes the limit  $\delta_{\min}$ .

We calculated the self-Compton X-radiation using formulae given by Marscher (1983) or in the Appendix to U83, except that we used the frequency and flux density at the maximum of the spectrum rather than at the intersection of the extrapolations from the optically thick and thin regimes (Cohen 1983). Marscher (1983) used a slightly different definition of the spectral turnover in his formulae. This calculation yields both the intensity of the X-rays and their spectral index, which is the same as the optically thin radio index.

We do not have simultaneous radio and X-ray measurements, so we have taken the closest available observation, in 1981.02 by Halpern (1982), who measured  $S_{\text{obs}} = 1.97 \times 10^{-10}$  ergs  $\text{s}^{-1} \text{cm}^{-2}$  over a 2–10 keV (observed) energy band, and  $\alpha_x = -0.44 \pm 0.04$ . This is more than twice the previous flux measurement of  $S_{\text{obs}} = 8.14 \times 10^{-11}$  ergs  $\text{s}^{-1} \text{cm}^{-2}$  in 1980.48, a value more typical of the period 1978–1980, for which a constant radio to X-ray ratio is consistent with the observations (Halpern 1982). While the flux densities of the core D and

TABLE 3  
HOMOGENEOUS SPHERE MODELS OF COMPONENTS IN 3C 273

| COMPONENT                            | KNOTS                |                      |                        |
|--------------------------------------|----------------------|----------------------|------------------------|
|                                      | $C_3$                | $C_5$                | CORE D                 |
| $\nu_m$ (GHz) .....                  | $\leq 2$             | $\leq 2$             | 70                     |
| $S_m$ (Jy) .....                     | $\geq 6$             | $\geq 10$            | 25                     |
| $\omega_s$ (mas) .....               | 2.1                  | 2.1                  | 0.8                    |
| $\alpha$ .....                       | -1.0                 | -0.7                 | -0.8                   |
| $S_{\text{obs}}$ (Jy at 2 keV) ..... | $1.6 \times 10^{-5}$ | $1.6 \times 10^{-5}$ | $1.6 \times 10^{-5}$   |
| $S_{x1}$ (Jy at 2 keV) .....         | $6.8 \times 10^{-5}$ | $2.3 \times 10^{-3}$ | $7.6 \times 10^{-9}$   |
| $\delta_{\min}$ .....                | 1.3                  | 2.5                  | 0.3                    |
| $(B/\delta)_{\max}$ (gauss) .....    | $3 \times 10^{-4}$   | $1 \times 10^{-4}$   | 22                     |
| $(p_e \delta^2)_{\min}$ (cgs) .....  | 1.1 $h$              | 1.3 $h$              | $7.4 \times 10^{-6} h$ |

knots  $C_3$  and  $C_4$  all decayed until at least 1981.10, the 10.7 GHz brightness of the core more than doubled sometime between 1981.10 and the next VLBI observation in 1982.10 (Biretta *et al.* 1984). It is possible that the radio and X-ray outbursts are correlated, in which case there would have to be a time delay  $> 30$  days, since the X-ray measurement was made 30 days before the 1981.10 map. A time delay might be expected in an inhomogeneous jet model, such as the one discussed in § IVd below, since the inverse Compton X-rays would originate at smaller radii than the radio emission.

The observed radio spectral indices are much steeper than that of the X-rays, so it seems unlikely that the X-rays are due to inverse Compton scattering in  $C_3$  or  $C_5$ . Furthermore, the calculated X-ray flux cannot be larger than the observed value, so equating the calculated and measured flux densities at 2 keV yields  $\delta_{\min}$ , a lower limit to  $\delta$ . The entry  $S_{x1}$  in Table 3 is the calculated inverse Compton X-ray flux density using  $\delta = 1$ . Since other X-ray mechanisms could also be operating, the limits to  $\delta$  apply to each component separately. Component  $C_3$  has  $\delta_{\min} = 1.3$ , which is not significantly different from unity and gives no constraint on the kinematics of the jet. For component  $C_5$ ,  $S_{x1}$  is more than two orders of magnitude larger than  $S_{\text{obs}}$ . This gives  $\delta_{\min} = 2.4$ , which shows that  $C_5$  is at least mildly relativistic, with  $\gamma > 1.4$  and  $\theta < 25^\circ$ . This conclusion is independent of  $H_0$ , and is also independent of the superluminal motion.

The magnetic field calculated for  $C_3$  and  $C_5$  depends on the synchrotron turnover, and the entries in Table 3 are upper limits. In these components,  $B \lesssim 10^{-3}$  gauss, and the corresponding 10.7 GHz electron lifetime is  $\sim 10^4$  yr, which is much longer than the observed lifetimes. As discussed above, expansion losses rather than synchrotron losses are probably responsible for the decay in flux density of the knots.

The energy density in the relativistic electrons can be calculated using equation (5) of Burbidge, Jones, and O'Dell (1974), with a minor modification for spherical geometry. The results depend strongly on  $\delta$  and  $\omega$  ( $p_e \propto \delta^{-5} \omega^{-9}$ ) and weakly on the lower cutoff of the electron energy spectrum. Lower limits to the electron pressure,  $p_e$ , are given in Table 3. Unless  $\delta$  is as large as 20 or 30, the pressure in the particles is much greater than the magnetic pressure; however, the ratio depends strongly on angular size ( $p_m/p_e \propto \omega^{1.7}$ ) and thus cannot be evaluated accurately.

#### d) Relativistic-Jet Model Applied to the Core

The core (component D) is  $\lesssim 1$  mas ( $1.8 h^{-1}$  pc) in size, and represents a region close to, and perhaps surrounding, the "central engine" which powers both the VLBI jet and the 20" optical and radio jet. However, it is obvious from the optically thick slope of  $\alpha = 0.65$  (Fig. 8) that a homogeneous synchrotron model is inadequate, and that a more elaborate model is required. One possibility is to retain spherical symmetry but allow the magnetic field  $B$  and the particle density  $K$  to vary with radius (Marscher 1977; Gould 1979). However, all our maps show a strongly one-sided structure, so the core is more likely to be asymmetric, and a more plausible model is that of a conical jet with a narrow semiangle  $\phi$ . Such a model also has the virtue of providing at least a qualitative explanation of the superluminal motion of the knots.

Königl (1981) has worked out one such model in detail, in which the magnetic field varies as  $B \propto r^{-m}$  and the particle density distribution as  $K \propto r^{-n}$ , where  $r$  is the distance along the axis of the cone from the apex. In this model, the synchro-

tron turnover frequency  $\nu_m(r)$  and "break" frequency  $\nu_b(r)$  vary with radius, giving rise to an integrated spectrum with a different spectral shape from that at any one point in the jet. Two important parameters are  $r_M$ , the smallest radius from which optically thin radiation can be observed, and the corresponding peak frequency  $\nu_M$ . The spectral indices of the model jet, just below and above  $\nu_M$ , are  $\alpha_{s1}$  and  $\alpha_{s2}$  (in the notation of Königl), which are functions of the local spectral index  $\alpha_0$  and the indices  $m$  and  $n$ . With a suitable choice of parameters, we can make  $\alpha_{s1} > 0$  and  $\alpha_{s2} < 0$ . Since we do not resolve the core,  $\alpha_0$  is not directly observable and must be chosen for consistency with the observed  $\alpha_{s1}$  and  $\alpha_{s2}$ . For most reasonable choices of model parameters, the inverse Compton scattered spectrum begins at a relatively low frequency ( $\sim 10^{13}$  Hz) with spectral index  $\alpha_0$ , extends beyond the gamma-ray range, and dominates over synchrotron radiation at X-ray frequencies and above. The spectral index in X-rays is  $\alpha_{c2} \approx (\alpha_0 - 0.5)$ .

Assuming that the millimeter through infrared emission is dominated by synchrotron radiation from the core (component D), we estimate  $\alpha_{s2} \approx -0.8$ . The 1 mm flux density of 3C 273 is highly variable (Robson *et al.* 1983; Sherwood *et al.* 1983), as might be expected in this picture. Since the optical continuum appears to be quite distinct (§ Va above), the synchrotron spectrum must steepen to  $\alpha \lesssim -1$  above  $\sim 10^{14}$  Hz, so that the emission falls well short of the observed optical. From Figure 8 we measure  $\alpha_{s1} = 0.65 \pm 0.15$ . The indices  $\alpha_{s1}$  and  $\alpha_{s2}$  constrain  $\alpha_0$  to lie between  $-0.3$  and  $-0.5$ , and we choose  $\alpha_0 = -0.4$ ,  $m = 2.0$ , and  $n = 1.8$ . These are representative of the allowed values, and the solution is insensitive to the exact choice. No combinations come close to the case  $m = 1$ ,  $n = 2$ , which was discussed by Blandford and Königl (1979). This combination can maintain energy equipartition in the moving jet material, provided that the energy distribution of the particles is maintained by continuous acceleration. The value  $m = 1$  is often assumed for the magnetic field in a free jet, since this is the rate at which the transverse component should decay (Blandford and Rees 1974). If the flow is turbulent the decay should be faster, but  $m = 2$  should be a limit, reached when the field is purely longitudinal. With our values,  $m = 2.0$  and  $n = 1.8$ , the magnetic energy will decay more rapidly than the electron energy, and the flow should rapidly become dominated by the particles. (We remarked above that particle energy dominates over the magnetic field in components  $C_3$  and  $C_5$ .) The value  $n = 2$  gives a constant flux of energetic electrons with constant flow velocity, and continuous reacceleration to the same energy spectrum. Our value  $n = 1.8$  is quite close to this value.

The model has several parameters that are not all constrained, and these can be selected in various ways. To derive the geometric parameters, we assumed that the superluminal motion is evidence for a relativistic flow with constant  $v/c = 5.6 h^{-1}$  (see Table 2) which extends from the core to the knots. This fixes  $\gamma$  and  $\delta$ , provided that the jet is straight and does not accelerate. We then picked values of the angle to the line of sight  $\theta$ , and cone semiangle  $\phi$  (cols. [1] and [2] in Table 4), which then determine the model. The table shows four representative cases, for increasing values of  $\theta$ . Case *b* follows the usual assumption made for relativistic beams and superluminal motion:  $\csc \theta \approx \gamma \approx \delta \approx v/c$ , but the others depart from this scheme. In one sense case *d* is more probable *a priori* because  $\theta$  is greatest; but it is also unreasonable because of the large corresponding  $\gamma$  (col. [3]) required by the superluminal motion. Because  $\delta < 1$ , the line of sight lies *outside* the main Doppler-

TABLE 4  
KÖNIGL JET MODEL FOR CORE OF 3C 273

| CASE           | ASSUMED GEOMETRY       |                          | DERIVED QUANTITIES <sup>a</sup> |                 |                                                                      |                       |                                        |                                              |                                                      |
|----------------|------------------------|--------------------------|---------------------------------|-----------------|----------------------------------------------------------------------|-----------------------|----------------------------------------|----------------------------------------------|------------------------------------------------------|
|                | $\phi$<br>(deg)<br>(1) | $\theta$<br>(deg)<br>(2) | $\gamma$<br>(3)                 | $\delta$<br>(4) | $S_{\text{calc}}$<br>(ergs s <sup>-1</sup> cm <sup>-2</sup> )<br>(5) | $B$<br>(gauss)<br>(6) | $2\phi r$<br>(mas) <sup>b</sup><br>(7) | $r \sin \theta$<br>(mas) <sup>b</sup><br>(8) | $\Delta(r \sin \theta)$<br>(mas) <sup>c</sup><br>(9) |
| <i>a</i> ..... | 2                      | 5                        | 6.6                             | 9.9             | $6 \times 10^{-13}$                                                  | 0.039                 | 0.27                                   | 0.34                                         | 0.21                                                 |
| <i>b</i> ..... | 2                      | 10                       | 5.7                             | 5.8             | $4 \times 10^{-12}$                                                  | 0.035                 | 0.22                                   | 0.54                                         | 0.33                                                 |
| <i>c</i> ..... | 2                      | 15                       | 6.5                             | 3.4             | $2 \times 10^{-11}$                                                  | 0.033                 | 0.20                                   | 0.74                                         | 0.46                                                 |
| <i>d</i> ..... | 2                      | 20                       | 25.5                            | 0.6             | $4 \times 10^{-10}$                                                  | 0.039                 | 0.27                                   | 1.35                                         | 0.83                                                 |

<sup>a</sup> Assumed quantities:  $S_m = 25$  Jy,  $\nu_m = 70$  GHz,  $h = 1.0$ ,  $v/c = 5.6 h^{-1}$ ,  $\alpha_{s1} = 0.6$ ,  $\alpha_{s2} = -0.8$ ,  $S_{\text{obs}} = 2 \times 10^{-10}$  ergs s<sup>-1</sup> cm<sup>-2</sup>, over 2–10 keV band in observer's frame. Derived quantities:  $m = 2.0$ ,  $n = 1.8$ ,  $\alpha_{c2} = -0.64$ ,  $\alpha_0 = -0.4$ .

<sup>b</sup> At 10.7 GHz.

<sup>c</sup> Between 10.7 and 5.0 GHz.

boosted lobe and the radiation is redshifted rather than blue-shifted. Note that the X-ray flux  $S_{\text{calc}}$  (col. [5]) calculated from the model approaches the observed value only for case *d*; for the others it is at least one or two orders of magnitude less.

Column (6) gives the magnetic field in the region responsible for most of the radiation at 10.7 GHz. The corresponding apparent radiation lifetimes are roughly 10 years, much longer than the observed time scale for changes in component D (Fig. 6). The Königl (1981) model requires that the radiation lifetime cannot be longer than the observed variation time scale. The observed rapid variations are in conflict with the simple picture of a steady jet, and a more realistic model would probably have to allow for rapid transverse expansion.

The transverse size of the jet at 10.7 GHz is  $2\phi r$  (col. [7]), and the sizes are comfortably below the observed limit, 0.8 mas. This comparison restricts  $\phi$  to angles less than about  $5^\circ$ , although in any event it cannot approach  $5^\circ$  without violating a fundamental assumption of the model ( $\phi \ll \theta$ ). Column (8) gives the apparent displacement ( $r \sin \theta$ ) of the 10.7 GHz emitting material from the origin, and column (9) gives the differential displacement  $\Delta(r \sin \theta)$  between 10.7 and 5.0 GHz. Figure 4 shows that a limit  $\sim 0.2$  mas can be placed on this relative shift of the core position, unless the positions of core and knots all show the same frequency dependence, which seems unlikely in view of the above discussions. Limits of  $\lesssim 1$  mas can also be placed on  $\Delta(r \sin \theta)$  by considering the spectral index (Readhead *et al.* 1979) and curvature (Cohen *et al.* 1983). This limit in turn restricts  $\theta$  to  $\lesssim 5^\circ$  (Table 4). The position shift characteristic of jet models can be tested using absolute VLBI astrometry; the present accuracy of the technique is probably adequate (Bartel *et al.* 1984).

The derived quantities in Table 4 do not change rapidly with changes in the input parameters. If the Hubble constant is reduced to  $h = 0.5$ , the main changes are a restriction on the allowed range of  $\theta$ , and a reduction in the X-ray flux by less than a factor of 2. If the spectral maximum is changed to  $\nu_m = 40$  GHz,  $S_m = 20$  Jy, the model X-ray flux  $S_{\text{calc}}$  decreases by about a factor of 5. If  $\alpha_0$  is changed to  $-0.3$  ( $-0.5$ ) (with appropriate changes in  $m$  and  $n$ ), the differences are small except that  $S_{\text{calc}}$  is reduced (increased) by a factor of 2 or 3. In fact,  $S_{\text{calc}}$  is an upper limit to the model flux, because further assumptions about the extent of the electron energy spectrum are required to calculate it exactly. However, this limit is still at least one to two orders of magnitude below the observed value ( $S_{\text{obs}} = 2 \times 10^{-10}$  ergs s<sup>-1</sup> cm<sup>-2</sup>), for reasonable values of  $\theta$  and  $\phi$ . The calculated X-ray flux can be increased by making

the jet narrower (decreasing  $\phi$ ), but it exceeds the observed value only if, in addition,  $\theta \gtrsim 20^\circ$ . However, for narrow jets  $\Delta(r \sin \theta)$  is much larger than in Table 4, and we can rule out  $\phi \lesssim 0.5^\circ$ .

Apart from contrived cases, the inhomogeneous jet is therefore incapable of producing the observed X-rays. In addition, homogeneous sphere models for C<sub>3</sub> and C<sub>5</sub> can produce the observed X-ray flux only if  $\delta$  is as small as 2.5. This is an allowed geometry: for  $h = 1$ , and taking  $\delta = 2.5$  and  $v/c = 5.6$ , we find  $\gamma = 9$  and  $\theta = 16^\circ$ . However, unless  $\gamma$  is this large (and larger still for  $h < 1$ ), it appears that the inverse Compton process cannot contribute substantially to the observed X-ray flux. This conclusion could be tested with further observations which would search for correlations between radio and X-ray variations and spectral indices. Königl (1981) pointed out the similarity of the overall spectrum to that of Seyfert 1 galaxies, and concluded that both the X-rays and the infrared-ultraviolet continuum are probably unbeamed.

#### VI. COMPARISON WITH 3C 345

Although superluminal sources have been recognized for over 10 years, very few have been found, and as of 1983 June only seven examples had been published (Cohen and Unwin 1984). Until a large enough sample for statistical studies has been observed, we must concentrate on detailed studies of the known sources. The quasar 3C 345 is an obvious choice for detailed comparison, because (1) it has been monitored with VLBI as often and at the same frequencies as 3C 273 and (2) many of its other properties are remarkably similar.

Both sources have arcsec-scale radio jets (Browne *et al.* 1982). The quasar 3C 273 also has an optical jet, but such a jet if present in 3C 345 probably could not be detected by a ground-based optical telescope, since the bright quasar is too close at  $\sim 2''$ . Weak "counterjet" emission has been found in 3C 345 (Schilizzi and de Bruyn 1983), but none in 3C 273; this is a significant observation, because it means that the 3C 345 jet cannot be entirely one-sided on long time scales. The absence of a counterjet could result from beaming: both sources have strongly one-sided jets, and even a relatively modest jet speed yields a large jet/counterjet ratio.

There is substantial misalignment between the VLBI scale and the arcsec-scale jet, and curvature within the VLBI structure, in both sources. In 3C 345 the radius of curvature increases rapidly with distance from the core, so that most of the bending occurs within  $R = 1.5$  mas (Biretta *et al.* 1983). A similar monotonic curvature is seen in the present observa-

tions, although it is not noticeably sharper near the core. The arcsec-scale jet in 3C 345 shows about  $4^\circ$  of curvature, while the 3C 273 jet has  $\leq 1^\circ$ . Readhead *et al.* (1978) have shown that this relative straightness most likely results from a less extreme projection, as is also suggested by the large ratio of projected linear sizes (the 3C 273 jet is a factor of 3 longer). One significant difference in appearance is that the 3C 273 jet is detached from the core, whereas the 3C 345 jet is continuous; this cannot be attributed to projection effects, unless beaming is also involved.

Another major difference between the two sources is the relative strength of the X-ray emission: in 3C 345 the emission is two orders of magnitude less than that of 3C 273, although they are comparable at millimeter wavelengths, and within a factor of 3 at centimeter wavelengths. In 3C 345 a simple homogeneous sphere model explains the X-ray flux as inverse Compton emission, with a Doppler factor  $\delta \gtrsim 18$  (U83). The large value of  $\delta$  is consistent with the geometry required by the superluminal motion. In 3C 273 the X-ray emission cannot be explained in this way, either with the same sphere model (§ Vc), or with an inhomogeneous jet model (§ Vd). It seems likely that 3C 273 contains an additional powerful source of X-rays. This is probably related to the fact that 3C 345 is an optically violent variable and highly polarized, whereas 3C 273 is relatively stable (Moore and Stockman 1981).

Further VLBI observations of both sources are being made at higher frequencies (22 GHz and above), and these will help to constrain the Königl (1981) model further, in at least two ways: (1) The spectral turnover of the core can be measured more accurately, and since the spatial structure is simpler at higher frequencies, it should be possible to perform the decomposition more accurately. (2) Higher angular resolution will place smaller limits on the core size. Since the size of the emitting region decreases only slowly with increasing frequency, stronger limits to  $\phi$  and  $\theta$  may be deduced.

## VII. SUMMARY

1. A series of high-resolution VLBI maps of the nucleus of 3C 273 at 5.0 and 10.7 GHz, made at 6 month intervals from 1977 through 1981, shows the well-known "core-jet" morphology, and structural variations on time scales of months.

2. The VLBI jet curves through  $\sim 20^\circ$  within 10 mas of the core, then straightens out to point within  $1^\circ$  of the  $20''$  optical jet.

3. A weak limit of  $\gtrsim 10:1$  may be set on the ratio of jet to (undetected) counterjet brightness. Relative to the core, the limit is  $\sim 50:1$ .

4. At least two and probably three "knots" in the VLBI jet show superluminal motion away from the core at speeds  $\sim 6 h^{-1} c$  ( $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). No acceleration is detected.

5. The knots decay with half-lives of 2–3 years as they move out from the core. The decay rates are consistent either with adiabatic expansion or with adiabatic expansion plus continuous injection. There is currently too little angular resolution to measure any component expansion directly. Because new components continually replace the decayed ones, the total flux density shows much smaller variations than do the individual knots.

6. A simple homogeneous sphere model for the knots predicts inverse Compton X-ray flux which we compare with the observed value. In this way, we deduce that significant "Doppler boosting" ( $\delta > 2.5$ ) is required in knot C<sub>5</sub>.

7. For the core, the inhomogeneous jet model of Königl (1981) explains the shape of the radio spectrum, but the inverse Compton effect cannot be the mechanism producing the observed X-ray flux. The coincidence of the positions of the core at 10.7 and 5.0 GHz limits the jet angle to the line of sight to  $\theta \lesssim 5^\circ$ .

8. Evidence for bulk relativistic motion of at least one knot in the 3C 273 jet comes both from superluminal motion and from X-ray measurements; the derived limits on the kinematic parameters are  $\gamma \gtrsim 6 h^{-1}$  and  $\theta \lesssim h^{-1} \times 16^\circ$ .

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