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THE 1983 SEPTEMBER RADIO OUTBURST OF CYGNUS X-3: RELATIVISTIC EXPANSION AT 0.35c

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ABSTRACT

MERLIN and VLA observations of Cygnus X-3 during 1983 September and October are reported. The radio emission consisted of several intense flares occurring on October 1.3, 2.8, 8.6, and 10.8. The structure of the resulting emission at 6 cm was found to be unresolved (<20 mas) until October 5. The size of the structure increased linearly from <20 mas on October 8 to an unresolved uniform double with a separation of 75 mas on October 15. The data is consistent with an expansion or separation at a rate of 4.6–18 mas per day depending on which flare was associated with the expansion. A rate of 12 mas per day is favored. A model of symmetrical expansion about the star at a velocity of 0.35*c*, with a later outburst accompanying the formation of hot spots in the jet, possibly by means of interaction with a surrounding gas shell best fits the observations.
Subject headings: radio sources: variable — stars: radio radiation — X-rays: binaries

I. INTRODUCTION

Extensive study of the radio outbursts of Cygnus X-3 has shown that the outbursts are nonthermal and are most likely produced by the sudden injection of relativistic electrons into an expanding plasma cloud containing nonrelativistic gas (Seaquist and Gregory 1977; Marscher and Brown 1975). These electrons may be generated in the plasma clouds from high-energy γ-rays emitted by a central "engine" in the source (Vestrand 1983). We thus expect to observe an expanding radio source immediately after the onset of the outburst. An indication of such an expansion was found by Geldzahler *et al.* (1983) using the VLA where the emitting region became resolved 21 days after a large outburst in 1982 September, giving an apparent expansion speed of 0".01 per day or $\geq 0.35c$.

An international collaboration was set up in the autumn of 1983 with the aim of following the evolution of further outbursts with the Green Bank interferometer, the VLA, Cambridge, and MERLIN. The results of flux density measurements during September, October, and November have been presented by Johnston *et al.* (1986). We present in this paper the angular structure measurements obtained by MERLIN[1] at 6 cm (resolution $\approx$0".05) and the VLA[2] at 2 and 1.3 cm (resolution 0".1 and 0".07, respectively) during 1983 September and October.

II. OBSERVATIONS

Cygnus X-3 was observed with 27 telescopes of the VLA in the A configuration and with MERLIN during 1983 September and October following the onset of a flare first observed with the Green Bank interferometer. The VLA observations consisted of short tracks of 5 minutes at each VLA wavelength of 20, 6, 2, and 1.3 cm. These observations were made on September 15 and 21, October 6, 19, and 30, and calibrated by observations of 2005+403. In each case Cygnus X-3 proved to be unresolved with no evidence of large-scale structure at 1% of the peak brightness.

The MERLIN observations were made at 6 cm with the MK 2 25 m by 36 m parabolic antenna and the Tabley, Darnhall, Knockin, and Defford 25 m diameter telescopes giving a range of baselines from 6 to 134 km. The receiving system gave typical RMS noise of 30 mJy after 10 minutes' integration on each baseline. Observations commenced on 1983 September 7 and continued through to 1983 October 24, with a mixture of short (~20 minute) and long (~12 hr) observations to enable the flux density and angular structure to be monitored. The data were calibrated by daily observations of 3C 84, the core of which is unresolved by MERLIN at this frequency. The flux density of 3C 84 (58.7 ± 1.0 Jy) was checked by comparison with that of 3C 48 every few days using the short baseline and assuming the Baars *et al.* (1977) value for the flux density of 3C 48.

III. ANALYSIS AND RESULTS

The rapid variability of Cygnus X-3 on the time scale of hours (Johnston *et al.* 1986) precludes the use of normal synthesis mapping techniques where several hours of data are required in order to give adequate *u-v* plane coverage. However, inspection of the visibility records showed that the source became resolved following the strong outburst on October 1. Figure 3 of Johnston *et al.* (1986) shows that the outburst is characterized by a rapid rise followed by decay over ~2 days with a secondary outburst 10 days after the onset, with slower decay rate. It became very obvious from the visibility records that Cygnus X-3 was becoming quite well resolved on the longest baselines after the secondary outburst. The

[1] Operated by the Nuffield Radio Astronomy Laboratories, University of Manchester.

[2] The VLA is a facility of the National Radio Astronomy Observatory which is operated under contract with the National Science Foundation.

source remained unresolved on the three shortest baselines, justifying the use of data on the shortest baseline for total flux density measurements at 6 cm.

An attempt to map the source using the long track data was made. The self-calibration method (Schwab 1980) was used with high weight given to the *u*-*v* data with 1.6 Mλ in order to simulate flux density changes by telescope gain changes. This preliminary analysis showed that the source had double structure with separation $\sim$0″.07 in position angle $\sim$0 on October 13–14 whereas the earlier long track data gave essentially unresolved images. Figure 1 shows the observed visibilities and closer phases over several baselines for October 13–14. Note the double structure on the Defford-Tabley baseline.

The fringe amplitude on long and short baselines were equal to within 10%, and closure phases were zero within the noise on all data before September 30, showing that the size of Cygnus X-3 was $\lesssim$20 mas. We therefore concentrated our attention on the data following the large outburst on October 1.

A model consisting of two Gaussian components was fitted to the data on October 13–14 and produced a reasonable fit to the amplitude and closure phases on all baselines. A gradual decrease of $\sim$20% in total flux density with time on the shortest baselines was clearly seen in comparison with the constant fringe amplitude predicted by the model. The variation of total flux density with time after the flare on October 10 can be closely fitted by a decaying exponential with a time constant of about 3 days. This decay was corrected by scaling the fringe amplitudes for the October 13 run so as to make the fringes on the shortest baseline have constant amplitude. The fit of a

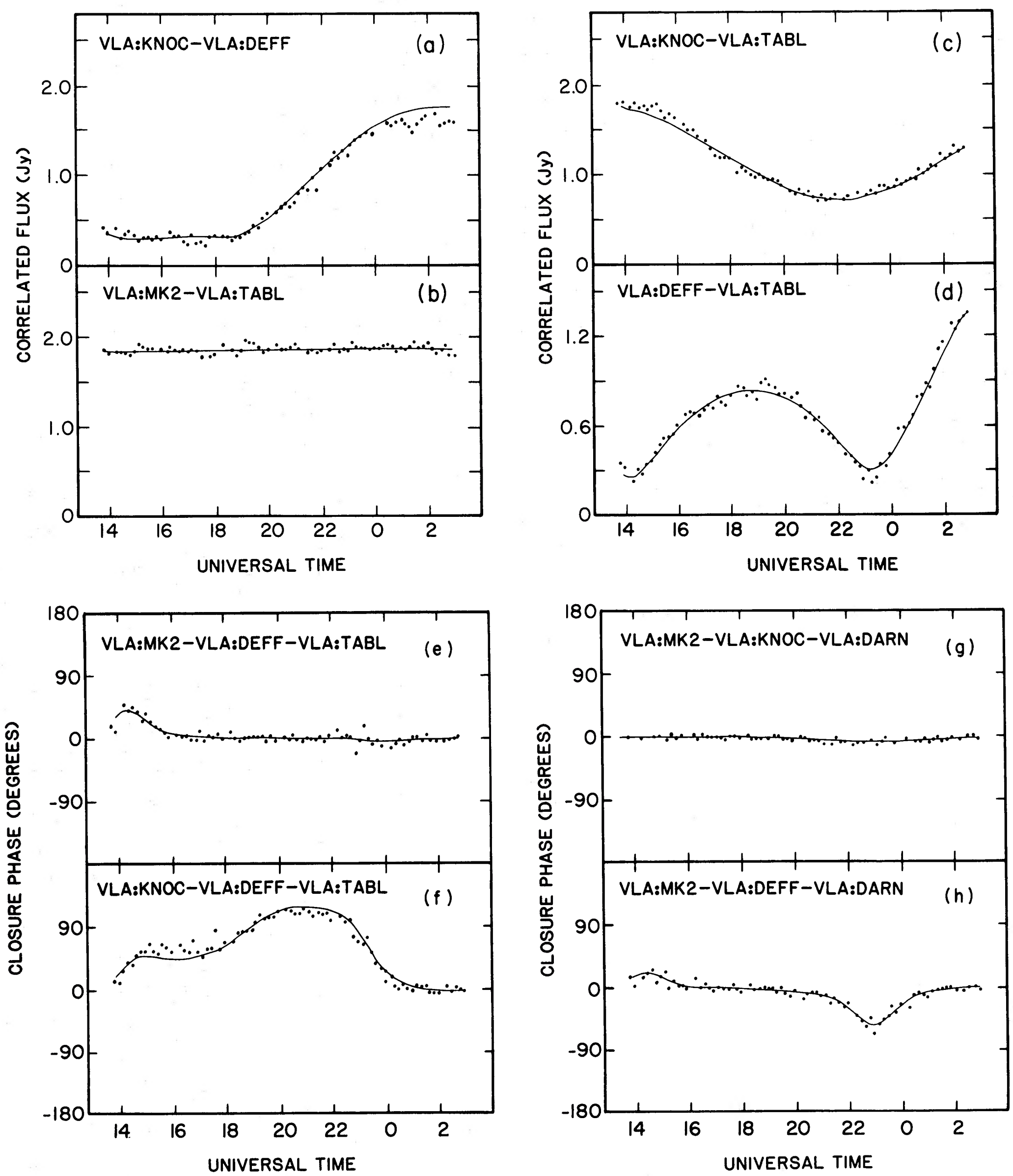

FIG. 1.—Observed and model visibility data for 1983 October 13–14 on a few representative baselines. (*a*)–(*d*) show fringe amplitude data on baselines Knockin-Defford, MK 2–Tabley, Knockin-Tabley, Defford-Tabley, and (*e*)–(*h*) show closure phases on MK 2–Defford-Tabley, Knockin-Defford-Tabley, MK 2–Knockin–Darnhall, and MK 2–Defford–Darnhall, respectively. A total decay of 20% in flux density with time has been subtracted from all the observed data.

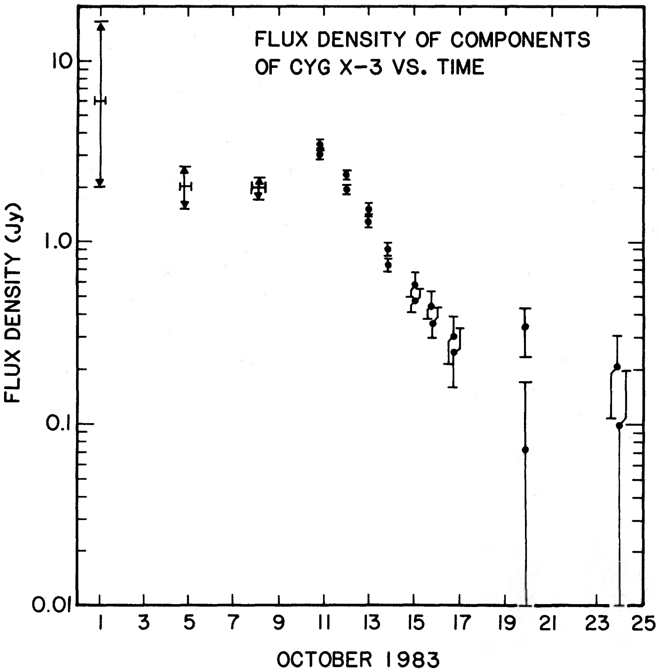

FIG. 2.—Flux density of components of Cygnus X-3 vs. date. The range of flux density variations is indicated for the points before October 9. The flux densities plus errors of the two components found by model fitting after October 10 are shown.

double-Gaussian model to this corrected data was excellent, as shown in Figure 1, and the structure has good agreement in overall size and position angle with the preliminary map, giving us confidence that the model is a good representation of the structure of Cygnus X-3 on October 13. This fit was for two unresolved components separated by 66 mas in position angle 0°. Allowing the size of the components to increase up to 30 mas did not change the goodness of fit or value of other parameters significantly. A similar model was also applied to all the data after October 9, even though only short tracks were available on some days. This results in some unreliability in model fitting for the short tracks. Nevertheless, the source was clearly resolved and flux densities and separation of the double model could be found, as shown in Figures 2 and 3. The position angle remained at 0°, in agreement with Geldzahler *et al.* (1983).

The very high degree of variability plus noise and calibration errors meant that it was not feasible to apply conventional model fitting techniques to the data on October 1, 5, and 8. The closure amplitude (Cornwell and Wilkinson 1981) obtained from four telescopes in an array is independent of gain and calibration errors and the flux density of the source and is unity and constant for all antenna quads if the source is unresolved. Any resolution results in the closure amplitude varying with hour angle. Figure 4 shows a plot of the closure amplitude observed with the Defford, Tabley, MK 2, and Knockin telescopes obtained on October 5. The source is clearly resolved and comparison with a single line Gaussian model of size 0″03 by 0″00, position angle 0° gives a reasonable agreement. Estimates of angular size on October 1 and 8 were made by a similar method, and it is interesting to note that the closure amplitude was within 4% of unity during the large outburst on October 1. The resulting angular sizes obtained by model fitting and from the closure amplitude are plotted in Figure 3 and component flux densities in Figure 2. Therefore the values in Figures 2 and 3 refer to a single Gaussian component before October 9 and to a point double after. The difference between the fitted size of a single Gaussian and the separations of a point double is negligible when the angular size is close to the resolution of the instrument as in this case.

An exponential decay following the second outburst in the flux densities of the two components found by model fitting is clearly seen. The components follow a similar decay (time constant 2.6 ± 0.1 days) justifying the assumption made in the scaling of the data for October 13.

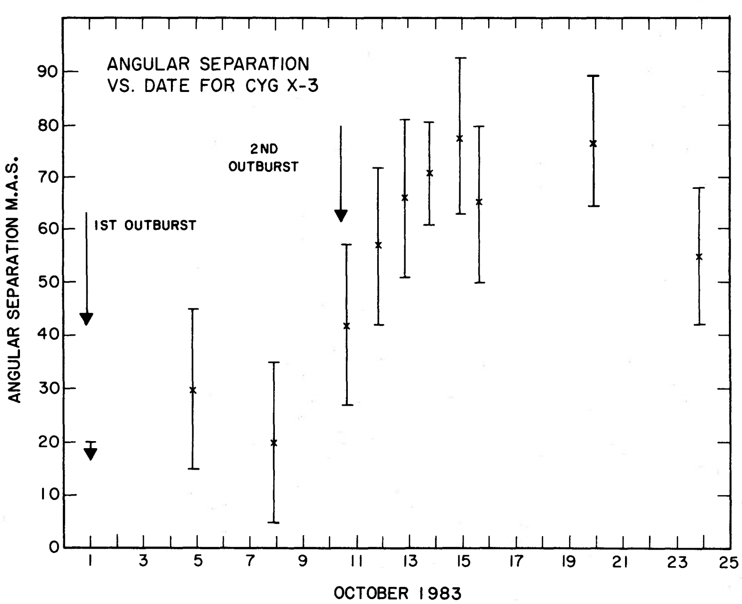

FIG. 3.—Angular separation vs. date. The values before October 9 are the FWHM size of a single component fitted to the closure amplitudes, whereas those after October 10 refer to the separations of double component models.

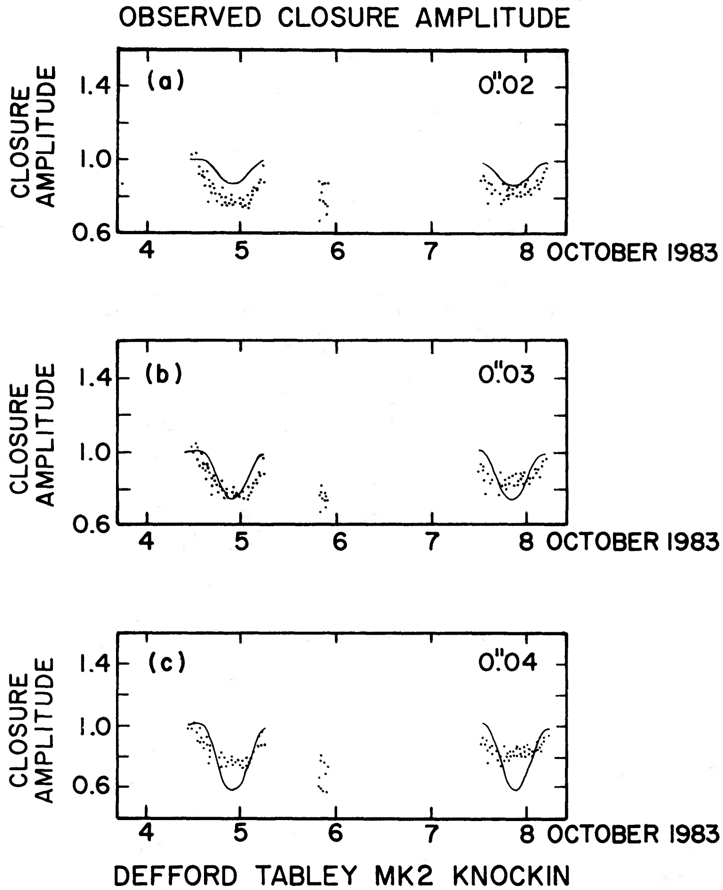

FIG. 4.—Plots of closure amplitude on the antennas Defford-Tabley-Darnhall-Knockin for MERLIN data taken October 4–9. Comparison with a line Gaussian model, in position angle 0° is given for FWHM sizes in the north-south direction of (*a*) 20 mas, (*b*) 30 mas, and (*c*) 40 mas.

IV. DISCUSSION

The minimum observable size for Cygnus X-3 at 6 cm is probably ~20 mas. Figure 5 displays the measured size of the minor axis of the 1982 outburst at 20, 6, 2, and 1.3 cm versus frequency. The size of the 1972 outburst as measured by Anderson *et al.* (1972) at 74 cm is also shown. The straight line between the 20 and 74 cm obeys a λ^2 law as would be expected for scattering by electron inhomogenities along the line of sight to the source. The amount of scattering along this line of sight is exceeded only by that to the Galactic center (Backer 1978). This is in conflict with the reported size of the quiescent radio emission of 0″.0013 ± 0″.0002 at 3.6 cm (Geldzahler, Kellermann, and Schaffer 1979). Figure 5 would indicate a size of ~10 mas. Further measurements are needed to clarify this discrepancy.

Figure 5 indicates that scattering limited the minimum observable size for any flaring event at 6 cm to 20 mas. Figure 4 shows that this value is significantly exceeded after October 11. Depending upon which flaring event the expanding double source is associated with, the linear expansion velocity can vary from 4.6 mas per day (October 1) to 18 mas per day (October 10.8). The linear expansion rate found by Geldzahler *et al.* (1983) was 10 mas per day for the 1982 flare. This was based upon the assumption that the flare of 1982 September 28 evolved into the structure observed on 1982 October 20. The radio emission during the 1982 outburst was dominated by a single intense flare. Figure 3 shows the total angular size in 1983 changing from almost unresolved at 20 mas on October 8 to 75 mas on October 15. By October 8, the earlier events on October 1.3 and 2.8 had already decayed. We favor the expansion as originating with the October 8.6 flare. This gives an expansion rate of 12 mas per day.

The MERLIN measurements do not contain information on the absolute position of the source and so the structure could be such that (1) one component is fixed in the sky while the other moves away from it at a projected velocity of 0.7*c* (assuming a distance of 10 kpc; Dickey 1983), or (2) they both expand away from a central object at 0.35*c*.

A central source could have a flux density of up to ~100 mJy before it would be noticeable in our model fitting, so a jet joining the components or a central unresolved component cannot be excluded.

In case (1) one would expect the fixed component to exhibit different evolutionary behavior than the moving component since it is likely to be much nearer to or coincident with the X-ray binary. However, the two components found in the model fitting decay with remarkably similar form for 6 days after October 10 (Fig. 2), each falling by over a decade in flux density with a similar time constant. This suggests that the emitting regions have similar physical conditions and were perhaps ejected simultaneously on either side of a central object, as in case (2). The velocity of jets in Cyg X-3 is very similar to those of SS 433. If the distance of Cyg X-3 were 7.4 kpc, then its velocity would be that of SS 433!

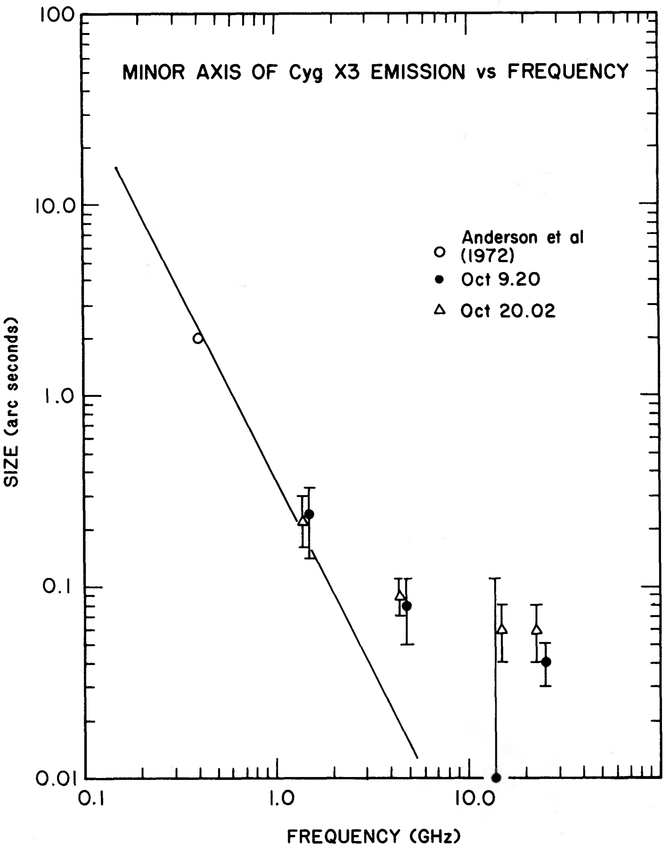

FIG. 5.—The size of the minor axis of the emission from Cyg X-3 during the 1982 outburst. Two measurements were made in October 9 and 20 at all four VLA frequencies. The 74 cm size (Anderson *et al.* 1972) of the 1972 outburst is also shown. The solid line between 20 and 74 cm obeys the λ^2 law expected from scattering. This line shows the minimum observable size for Cyg X-3.

The southern component is consistently brighter being on the average 19% stronger in flux density. An emitting region moving towards the observer is doppler boosted in flux density by $D^{3-\alpha}$ where $D = \gamma/(1 - \beta \cos \theta)$, γ is the Lorentz factor $\beta = v/c$, θ is the angle to the line of sight, and α is the spectral index. If the components are moving at $0.35c$, then the angle to the line of sight is 84°. The preferred range of orbital inclinations for wind (Pringle 1974) and cocoon (Milgrom 1976) models for X-ray emission is 20°–60°. Thus the radio axis may not be perpendicular to the orbital plane indicating nonaligned angular momenta if the radio axis is defined by an accretion disk. We would then expect precessional effects as shown, for example, by the changing position angle in SS 433. The earlier measurements by Geldzahler *et al.* (1983) also show the emission to be along a position angle of 0°. Further observations are required to ascertain whether the position angle of the radio emission varies with time.

Figure 3 of Johnston *et al.* (1986) shows that the ratio of S band to X band flux density increases from October 10 to October 20. The spectral index α ($S \propto \nu^{+\alpha}$) decreases from -0.2 on October 10 during the secondary outburst, to -0.5 on October 20. It is likely that the spectra of both moving components steepen with time, as expected if high-energy electrons responsible for the radio emission undergo energy loss by synchrotron radiation. Marscher and Brown (1975) show that the exponential part of the decay of the 1972 September outburst could be explained by an expanding source provided that synchrotron radiation losses dominate over energy loss due to adiabatic expansion. The magnetic field, assuming equipartition of high-energy particle and magnetic energy, is more than 0.08 G for each of the components (size $\approx$ 30 mas; flux density $\approx$ 1 Jy). The lifetime of electrons radiating predominantly at 6 cm is therefore $\sim$16 yr. This is much greater than the measured decay time of 2.6 days and shows that synchrotron losses appear to be unimportant, contrary to the theory of Marscher and Brown (1975) for the early part of the decay. Adiabatic and perhaps collisional losses must play a more important role in the emission than hitherto considered.

The behavior of Cygnus X-3 can be summarized then as a dramatic outburst on October 1 during which the source was unresolved. A radio-emitting cloud was produced which decayed in flux density and expanded in the north-south direction. This was followed by subsequent outbursts. This jetlike expansion became resolved into two high brightness components by October 10 separating from the central source at $0.35c$ until October 15 when it became too weak to be measured spatially. Conversion, via shocks, of kinetic energy into relativistic particles and hence radio emission as the jet enters the surrounding shell could explain the secondary outburst and formation of hot spots.

The apparent expansion of relativistic electrons out to distances of 10^{16} cm would appear to be in disagreement with the claim that the quiescent radio emission in Cygnus X-3 is probably due to individual flaring events (Johnston *et al.* 1986) that are ejected along the jet axis of Cygnus X-3, but decay before their emission moves far enough away from the binary star system. This emission probably originates at distances of 10^{13} cm in a blast wave caused by the X-ray emission due to matter accreting onto the compact object.

The high degree of collimation shown by the radio structure is contrary to that expected if the radio emitting electrons are secondary particles from gamma rays as in the model of Vestrand (1983), since unrealistically large amounts of matter would be required to collimate the gamma rays.

V. CONCLUSIONS

Observations of Cygnus X-3 with MERLIN, the VLA, the Green Bank interferometer, and the Cambridge 5 km telescope during 1983 September to November have shown that large flares occurred on October 1.3, 2.8, 8.6, and 10.8. The radio emission became resolved with MERLIN on October 5 and expanded in the north-south direction thereafter, reaching a maximum size of 77 mas in position angle 0° on October 15. The expansion rate was between 5 and 18 mas per day, but a rate of 12 mas per day is favored. Not every flare can be associated with the radio expansion; indeed, the favored flare was not the strongest during the 1983 September–October period. The structure of the source plus evolutionary behavior of hot spots found by model fitting led us to believe that the expansion was symmetric about the X-ray binary system and became affected by a surrounding shell of gas. Confirmation of this can be made by further observations of outbursts preferably with higher resolution than currently available with MERLIN. The objects show well-collimated relativistic expansion similar to that of SS 433, and the prospect of being able to find precession periods, distance, etc., as for SS 433, is tantalizing.

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