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PERIODIC CHANGES IN THE COMPACT RADIO STRUCTURE OF SS 433

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ABSTRACT

VLBI observations of SS 433 at 2.3 GHz made on 12 days between 1979 May and 1980 August yield the following results: (*a*) The position angle of the radio "jet" of angular size $\sim 0''.1$ varies approximately sinusoidally about a mean value of $100^\circ.2 \pm 1^\circ.7$ with an amplitude of $19^\circ.3 \pm 3^\circ.4$ for a period fixed at 163.6 days. This resolves the ambiguity in the two angles of the optical model of Abell and Margon and assigns the inclination of the axis of the precession cone to the 79° value. (*b*) The position angle of the radio structure on this scale lags that of the optical model by 17.4 ± 1.6 days. (*c*) At least some of the radio emitting material appears to propagate away from the core in blobs. Using the rate of change of angular separation of the blobs from the core obtained from measurements on four different days, and assuming that the radio emission is traveling at the speed derived for the optical jets from the kinematic model, we obtain a distance to SS 433 of 5.1 ± 0.5 kpc.

Subject headings: radio sources: variable — stars: binaries — stars: radio emission — X-rays: binaries

I. INTRODUCTION

In a previous paper Walker *et al.* (1981) reported VLBI observations of SS 433 which revealed the presence of radio structure on a scale of 2″ and smaller. The data were consistent with a model composed of a compact "core" and collinear elongated "jets" of about $0''.1$ and 2″ in length. The extended components of the model are aligned approximately with the outer bulges of W50, the apparent supernova remnant (SNR) on which SS 433 is superposed, suggesting a physical association between SS 433 and the distortion of the SNR. (Such alignment was also noted by Spencer 1979 and by Gilmore and Seaquist 1980 from observations with arc second resolution.) The existence of the $0''.1$ "jet" provided a strong incentive to look for variation in its position angle, which might be related to the precession inferred for the jets from the optical emission line data (Abell and Margon 1979).

II. OBSERVATION AND DATA ANALYSIS

A total of 12 observations have now been completed (Walker *et al.* 1981; this paper) using the 26 m antenna (DSS-13) of the NASA Deep Space Network at Goldstone, California, and the 40 m telescope of the Caltech Owens Valley Radio Observatory. These telescopes are separated by 257 km in a roughly north-south orientation, giving a minimum fringe spacing of $0''.1$. The observations span the period from 1979 May to 1980 August (see Table 1). All observations discussed here were made at a frequency of 2.29 GHz in circular polarization. Hydrogen maser frequency standards were used at both stations. Typical system temperatures were 25 K and 100 K at DSS-13 and OVRO, respectively. System gain factors at each telescope were determined from observations of 3C 274, and system temperatures were measured hourly. The gain of each telescope was assumed to be independent of elevation angle.

All data were recorded using the Mark II VLBI system and were processed using the Caltech/JPL correlator and postcorrelation software. The correlated flux densities were calibrated as described by Cohen *et al.* (1975). An uncertainty of 5% has been used to account for both the variation in calibration between experiments and the random error in calibration within each day. The unknown bias in absolute scale may be as much as 10%, but it is not included in this paper because it does not affect our conclusions.

Each observing session results in measurements of correlated flux density along all or part of a single track in the (u, v)-plane (shown in Fig. 1). In order to derive the source structure, we have estimated, using a least-squares procedure, values of parameters for the simplest class of model which is consistent with the data from all days. The correlated flux densities for all observing sessions are shown in Figure 2. The error bars indicate $\pm$ one standard deviation. Solid lines represent the best-fit models (discussed below) which are given in Table 1. The main feature of interest from experiment to experiment is the change in location of the maximum in correlated flux density, which occurs at different values of interferometer hour angle (IHA). We interpret this change as resulting from variation in the position angle of the elongated structure in SS 433.

The simplest class of model consistent with the data of each experiment through 1980 August 13 consists of two components: (*a*) an unresolved ($< 0''.03$) core, and (*b*) an elongated Gaussian component, unresolved in width and not necessarily concentric with the point source. Such a model has five parameters: the flux densities of the two

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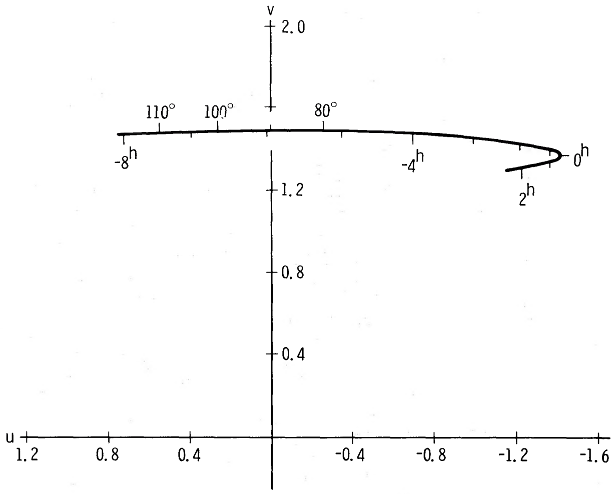

FIG. 1.—(u, v)-diagram for the baseline DSS-13/OVRO at 2.3 GHz. Tick marks above the line indicate the location of the principal maximum for a given position angle. Those below the line give the interferometer hour angle. The quantities u and v are in units of 10^6 wavelengths.

components, and the position angle, offset, and angular length of the extended component. The position angle of the extended component relative to the core is determined by the location of the maximum of correlated flux density (assumed to be the principal maximum) in the (u, v)-plane. We have assumed that the axis of the extended component is aligned with the core. When a clear maximum exists (e.g., 1980 February, March, and July), the position angle is determined to within a few degrees. When the maximum occurs too early in the track to be clearly defined (as for 1979 August and for 1980 May and June), the accuracy is lower. For 1979 November and 1980 January only a lower bound to the position angle may be set. For the experiments through 1980 August 13 the best fitting model is often a concentric core and jet, but significant offsets between component centers do exist in some cases.

The August 27–28 correlated flux densities cannot be reproduced by any simple two-component model. However, a natural combination of the concentric and the offset configuration types does provide a satisfactory fit to the data. Thus, the model is composed of a core and

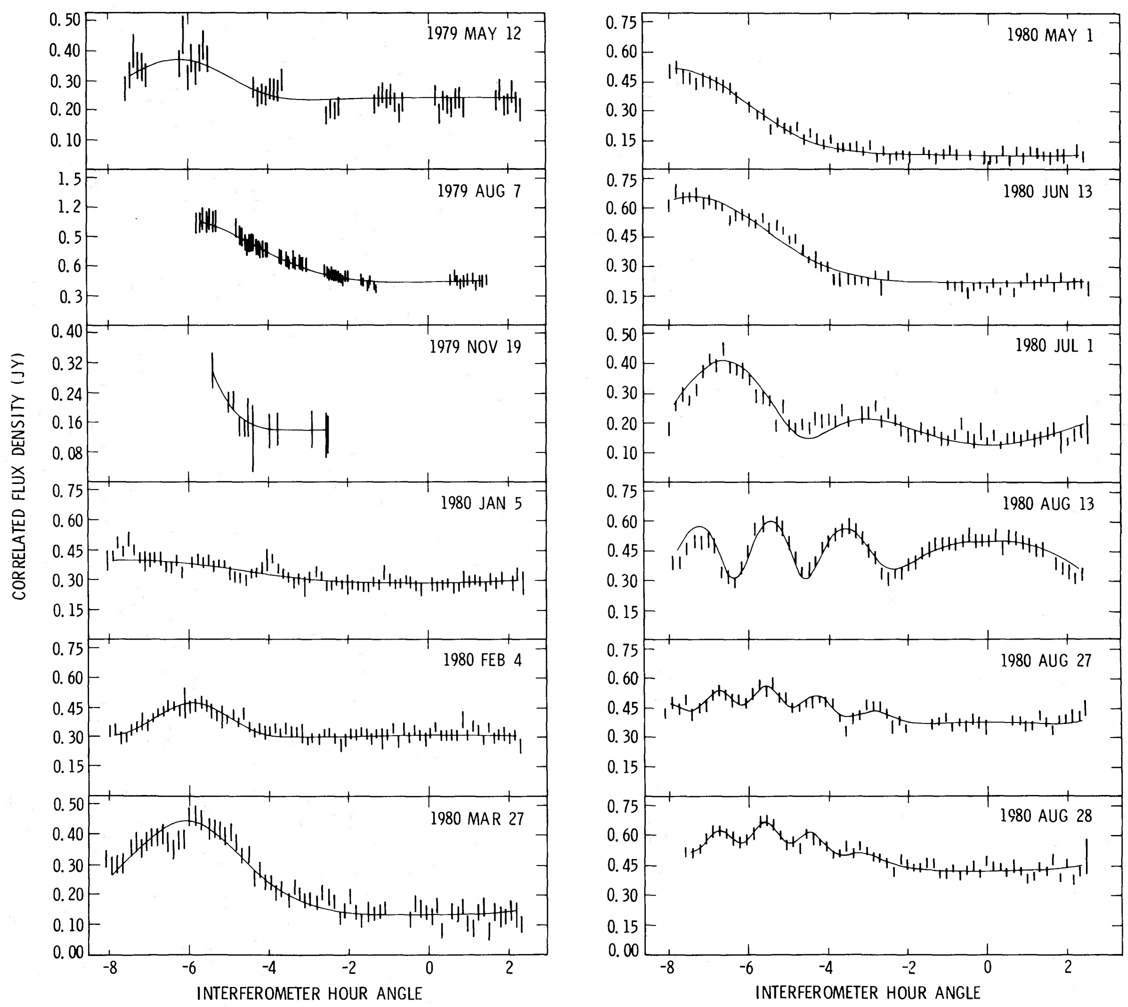

FIG. 2.—Correlated flux densities between DSS-13 and OVRO for 12 observations of SS 433. The solid line represents values corresponding to models discussed in the text and given in Table 1.

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TABLE 1

STRUCTURE MODEL VALUES FOR SS 433

		Extended Components			
Experiment Date (JD – 2,440,000)	Point Source Flux Density (Jy)	Flux Density (Jy)	Offset (10^{-3} arc sec)	Major Axis (10^{-3} arc sec)	Position Angle (degrees)
1979 May 12 (4005.83)	0.24 ± .03	0.13 ± .03	60 ± 30	140 ± 60	92 ± 7
1979 Aug 07 (4092.60)	0.4 ± .2	0.7(+.1/–.4)	<50	<150	90 ± 7
1979 Nov 19 (4197.31)	0.14 ± .05	0.6 ± .3	<50	>200	>90
1980 Jan 05 (4244.18)	0.25 ± .05	0.15 ± .05	<50	80 ± 10	>100
1980 Feb 04 (4274.10)	0.30 ± .03	0.17 ± .03	75 ± 20	190 ± 20	88 ± 3
1980 Mar 27 (4325.96)	0.12 ± .03	0.33 ± .05	<50	50 ± 30	91 ± 3
1980 May 01 (4360.86)	0.07 ± .02	0.43 ± .05	<50	130 ± 20	118 ± 5
1980 Jun 13 (4403.74)	0.22 ± .03	0.43 ± .05	<50	125 ± 25	110 ± 10
1980 Jul 01 (4421.70)	0.09 ± .05	0.32 ± .05	150 ± 10	80 ± 10	100 ± 3
1980 Aug 13 (4464.58)	0.45 ± .04	0.15 ± .04	315 ± 15	80 ± 30	83 ± 2
1980 Aug 27 (4478.54)	0.35 ± .04	0.16 ± .04	<50	120 ± 30	87 ± 3
		0.05 ± .02	455 ± 25	100 ± 50	84 ± 3
1980 Aug 28 (4479.54)	0.37 ± .03	0.24 ± .02	<50	105 ± 10	85 ± 3
		0.05 ± .02	477 ± 25	135 ± 60	85 ± 2

two elongated components. One is again found to be concentric with the core; the offset of the other, which is determined by the spacing of the adjacent maxima of the correlated flux densities (see Fig. 2), is larger than for any of the earlier observations. The position angle of the extended component which is concentric with the core was allowed to differ from the position angle of the offset component, as would be expected from the different time of emission.

Although the models with a significant offset of the elongated component are asymmetric, a nearly identical fit would be obtained in most cases by placing half of the flux density of the offset component symmetrically on the opposite side of the core. This ambiguity arises because we have no phase information and thus are unable to distinguish between symmetric and asymmetric models. However, the exact model is not crucial for the following discussion; only the position angles and angular distances from the core, which are the same for both models, are important.

III. MODEL FITTING RESULTS

Values of the parameters obtained from the model fittings are given in Table 1. Those values were found to give the best least-squares fit to the correlated flux densities. Estimates of the uncertainties in the parameters were obtained as follows. One or more parameters were fixed at values different from those given in Table 1. Other parameters were allowed to vary to compensate, and the new fit was compared to that of the best fit. The quoted uncertainties correspond to the range of parameter values for which the observed and modeled correlated flux densities differ systematically by about one standard deviation of the estimated data noise. We feel that these uncertainties are conservative for the specific model used.

If the radio emission is the result of activity in the core which continued for more than a few days, the axis of the extended components would not necessarily point to the core, due to the precession of the source of the jet. This deviation from collinearity would not be detectable in our measurements until the separation of the extended components from the core was greater than at least 0".2. Only for the 1980 August data might we expect to see this, and a marginally better fit to the data could be obtained by rotating the offset component. However, this did not significantly change the values of any of the other parameters, and in our final models we have restricted all components to be colinear with the direction to the core.

At a distance of 5 kpc (see § VI) 0".1 corresponds to a linear distance of 7×10^{15} cm. Thus the observed structures have dimensions in the range of less than 200 AU to 2000 AU. From previous observations (Walker *et al.* 1981) the core itself is known to have a size of less than 10 AU.

IV. POSITION ANGLE VARIATION

The values for position angle obtained from the models are plotted in Figure 3 as a function of time and in Figure 4 folded to the optical period of 163.6 days (Margon 1981). The variation of position angle can also be clearly seen in the change of location of the principal maximum of the correlated flux densities. Since there is no phase information for the VLBI data, the orientations of the asymmetric models are ambiguous by 180°. We have arbitrarily chosen to use the values nearest 90°. For the nine well determined values of the position angles for the components less than 0".2 from the core (omitting the two which are lower limits) we have made a weighted least-squares fit of a sinusoid with the period fixed at 163.6 days. The angular size restriction excludes the values for 1980 August 13 and for the distant component of August 27–28. We find a mean position angle of 100°.2 ± 1°.7 and an amplitude of variation of 19°.3 ± 3°.4 (χ^2 for six degrees of freedom is 0.6). This resolves the ambiguity in the two angles of the optical model of Abell

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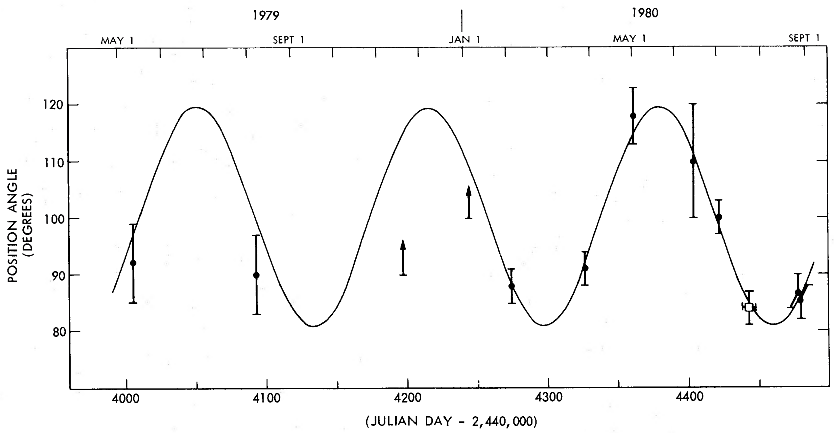

FIG. 3.—Position angle variation of the compact radio jet in SS 433. ●, Direct measurement of the structure less than 0".2 from the core; □, inferred position angle at 0".1 from the core deduced from the component seen at ~ 0".3 on 1980 August 13 and ~ 0".5 on 1980 August 27/28.

and Margon (1979) and assigns the inclination of the axis of the precession cone to the 79° value (see also Niell and Lockhart 1980; Hjellming and Johnston 1980, 1981). Assuming that the axis of the cone of the optical kinematic model projects onto position angle 100°, we find that the position angle of the radio emission lags the optical position angle by 17.4 ± 1.6 days. The uncertainties are 1.5 days for the radio model and 0.6 days in the optical ephemeris. To check the validity of the approximation of the position angle variation by a sinusoid, we compared the values for a relativistically correct model with a delay of 17.4 days. The largest difference is 1°.2, which is small compared to the errors of observation.

Schilizzi *et al.* (1981) also found that models of SS 433 derived from VLBI observations made on two epochs at 6 cm wavelength, when combined with the result of Walker *et al.* (1981), were consistent with the 164 day precession period of the Abell and Margon data if the inclination of the precession axis were 79°. However, their calculation of the delay of the radio emission relative to the optical (5 ± 4 days) was based on a typographical error in the reference epoch of the optical ephemeris in Margon, Grandi, and Downes (1980). For the correct epoch (JD 2,443,555.6) of Margon, Grandi, and Downes (1980), their position angle of 98° ± 3° on 1980 January 9 corresponds to a lag of 9 ± 4 days if the precession cone is centered on position angle 98°; 114° ± 3° on June 1/2 corresponds to 13 ± 8 days. Using the more recent ephemeris of Margon (1981) and the center value of 100° obtained from our data, the delays would be 7 ± 4 and 11 ± 8 days, respectively, with a weighted mean of 8 ± 4 days. This agrees well with our value of 17 ± 2 days since their higher resolution corresponds to one-half the linear scale of our observations.

These observations provide physical evidence for the precessing jet model (Miligrom 1979; Fabian and Rees 1979) and were predicted by Begelman *et al.* (1980) to be a consequence of their "beam bag" model. The lag in the radio position angle can be attributed to the observed radio emission occurring farther from the core than the optical emission. Since the mean position angle, 100° ± 2°, coincides with the axis of the SNR W50, as defined by the bulges, and since the angle subtended at the position of SS 433 by the bulges agrees with the opening angle defined by the extreme directions of the radio jet (see the radio map of Geldzahler, Pauls, and Salter 1979), these observations provide strong evidence of a causal relation between SS 433 and the bulges of W50.

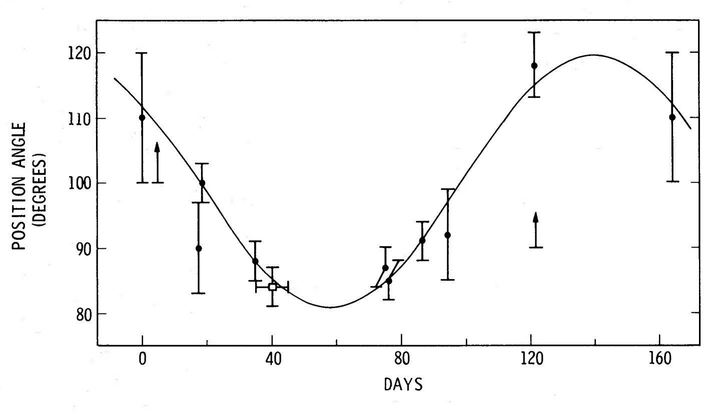

FIG. 4.—Same data as in Fig. 3 folded to a period of 163.6 days. Day 0 corresponds to 0000 UT on 1979 December 31 (JD 2,444,238.5)

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V. EVIDENCE FOR EJECTED BLOBS

The 1980 August 13 and 27–28 data give a position angle of 84° for the extended components which are offset from the core. If these features are actually the same component observed at different times, the deduced angular rate of separation from the core is $0''.010 \pm 0''.0016$ per day. [Note that this poses problems for attempts to measure the very compact structure of SS 433: any maps made with resolution of better than a few milli-arcseconds will be smeared unless "snapshots" using data from a sufficiently short time interval ($\ll 1$ day) are used. This was also noticed by Schilizzi *et al.* 1979.] As a check on the assumption that the same component is being observed at different angular separations on the three days in 1980 August, we can extrapolate back to find the date on which the component was at an angular separation from the core of $0''.1$, corresponding approximately to the scale of the structure observed on previous dates. This would have occurred on 1980 July 23 ± 5 days (JD 2,444,443; indicated by an open square in Figs. 3 and 4). The component would have originated on 1980 July 13 ± 5 days (JD 2,444,433). An inspection of the total flux densities measured at 11 and 4 cm wavelengths with the Green Bank interferometer (Johnston *et al.* 1981) shows that this date corresponds closely to a short period of flaring at the beginning of renewed activity in SS 433 following a long period of quiescence.

VI. DISTANCE TO SS 433

From the 1980 August observations there is evidence that at least some of the compact radio emission appears to move as distinct regions of enhanced emission, or blobs. Similar moving features in the optical emission have been inferred by some authors from the persistence of certain components of the line profiles at a given wavelength for several days (Begelman *et al.* 1980; Murdin, Clark, and Martin 1980). Consequently, the distance to SS 433 can be deduced by using all observations which appear to contain an ejected component. There are four epochs (1980 July 1, August 13, August 27, August 28) for which our models have (*a*) a significant offset for the extended component and (*b*) a well determined position angle. The distance is given by $D = \beta_{\rm obs} c\Delta t/\Delta\theta$, where $\beta_{\rm obs} = \beta_0 \sin i/(1 - \beta_0 \cos i)$; $\beta_0 = 0.258c$ from the optical data; i is the inclination to the line of sight of the jet at the time of the ejection of the observed bloc; Δt is the elapsed time between ejection and observation, which is determined by matching the observed radio position angle to the optical ephemeris; and $\Delta\theta$ is the angular offset from the core to the extended component. Since we are not able to tell whether the components correspond to the blue- or redshifted jet, we have calculated the distance separately, accounting for the different light travel times, and obtain 5.0 and 5.1 kpc for the two possibilities. The standard deviation for both is 0.3 kpc, resulting from the uncertainties in offset and in travel time estimated for the individual observations. Systematic errors, which might arise from assuming no deceleration of the optically derived jet velocity or from using the simplified structure model, are difficult to evaluate but are unlikely to contribute more than 10%. The resulting distance estimate is 5.1 ± 0.5 kpc. The observed 17.3 day lag between the orientation of the radio and optical emission produces a less accurate but consistent estimate of the distance.

Other distance estimates to SS 433 are: (*a*) 1.6–3.2 kpc, based on interstellar reddening and the assumption that SS 433 and Cir X-1 are of the same optical absolute magnitude (Clark and Murdin 1978); (*b*) greater than 3.5 kpc, from high resolution observations of the Na D lines (Margon *et al.* 1979*b*); (*c*) 3.7–4.7 kpc, from H I absorption measurements (van Gorkom, Goss, and Shaver 1980); and (*d*) 5.5 ± 1.1 kpc from observations of the arc second structure made with the VLA (Hjellming and Johnston 1981). The distance to the SNR, based on the surface brightness–diameter relation, was estimated by Caswell and Lerche (1979) to be 3.3 kpc. All estimates except (*a*) of the distance to SS 433, and thus to W50, are consistent and suggest a value that is 20 to 60% greater than that derived from the surface brightness–diameter relation. This approximately doubles the already large energy requirements for SS 433, which have most often been calculated for a distance of 3.2 kpc.

VII. JET PARAMETERS

For the models whose parameters are given in Table 1 the elongated components were assumed to be unresolved perpendicular to their length, i.e., less than about $0''.05$. An upper limit to the width can be determined by subtracting from the total flux density the model flux density for the core, which is the minimum consistent with the data, and comparing the difference with the flux density in the jet. Assuming a Gaussian shape for the cross section, we find limits of $0''.04$ to $0''.08$ for the widths of the elongated components (not including the widely spaced components of August 27/28), which at 5 kpc correspond to less than 2 light-days. This is a conservative upper limit since the total flux densities were obtained with the Green Bank interferometer (Johnson *et al.* 1981) and include a contribution from structure up to a few seconds of arc in size. The best limits on the degree of collimation for the radio emission are given by the data of 1980 July 1 and August 13 for which the ratios of the width limit to the distance from the core (as defined previously) are 0.25 and 0.20, respectively, giving an opening angle of less than 15°. Although this is not as tight a constraint on the collimation as that obtained from the optical emission lines (~ 3° [Margon *et al.* 1979*a*]), it still requires the collimation of the radio emission to be comparable to that of the optical even at a distance two orders of magnitude farther from the origin.

With an upper limit to the width of the extended components we can calculate only a lower limit to their brightness temperatures, which for dimensions of $< 0''.05$ by $0''.1$ and a flux density of 0.3 Jy implies $T_b > 10^7$ K. We cannot rule out the possibility that they in fact consist of several or many smaller blobs, in which case the brightness temperatures would be significantly higher.

It is of interest to know how often the ejection of blobs such as were seen in 1980 August occurs and whether it is

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correlated with other observed activity in SS 433. Two other dates for which there is evidence for more complex structure are 1980 January and March. However, the variations in correlated flux density with hour angle, although probably real, were not large enough to constrain additional parameters.

VIII. DISCUSSION

SS 433 demonstrates the existence of precessing beams of radio emission emanating from a compact object, a model which has been suggested to explain the inversion symmetry of the very large scale structure (hundreds of kiloparsecs) of some extragalactic radio sources (e.g., 3C 315 [Northover 1976], NGC 326 [Ekers *et al.* 1978], 3C 196 and 3C 305 [Lonsdale and Morison 1980]). Although the jet is well collimated out to a distance of several seconds of arc (~ 0.1 pc), the similarity to extragalactic sources with well collimated beams may not be so obvious: at distances from the core of SS 433 greater than a few arc seconds the spiraling beams will appear to fill the cone leading to the outer radio lobes (since there is one rotation of the beam every $1\overset{''}{.}6$ from the core). However, in terms of general features the similarities are striking: both exhibit (*a*) an active core and (*b*) a knotty, relativistic jet (or jets) leading outward toward (*c*) extended radio lobes. The observed change in position angle *with time* in SS 433 supplies some basis for the interpretation of the change in position angle *with distance* from the core which has been seen in a few superluminal radio sources (e.g., 3C 273, 3C 345 [Readhead *et al.* 1979]) as a precession (Linfield 1981), rather than as resulting from density gradients in the medium through which the jet passes (Readhead *et al.* 1978).

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