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INTENSE SUB-ARCSECOND STRUCTURE IN THE GALACTIC CENTER

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ABSTRACT

The detection of strong radio emission in the direction of the inner 1-pc core of the galactic nucleus is reported. The structure is bright (brightness temperature $\gtrsim 10^7$ ° K), unresolved ($\theta \lesssim 0''.1$), and distributed within a few seconds of the brightest infrared and radio emission seen previously.

Subject headings: galactic nuclei — radio sources

I. INTRODUCTION

The nucleus of the Galaxy is a region of great interest both because of its possible dynamical effects on our own Galaxy (Sanders and Prendergast 1974) and because it might provide insight into the processes governing other more energetic galactic nuclei (Saslaw 1973). The interesting inner portions are now being observed in some detail at several wavelengths. Rieke and Low (1973) have shown there exist at least five small-diameter sources and an extended background of infrared (IR) emission located within a 20″ region. Radio synthesis observations with resolutions of 10″ or less have been made of this same vicinity (called Sgr A West by radio astronomers) at 2.7, 5.0, and 8.1 GHz (Downes and Martin 1971; Balick and Sanders 1974; Ekers 1974); these show that there exists structure over a wide range of scale sizes in the region of the IR emission (we refer to this inner 2- or 3-pc core as the IR/radio complex). Although the interpretation of the observations is far from unambiguous, it seems clear that the IR fine structure is generically related to that at radio wavelengths.

Balick and Sanders (1974) have suggested that the structure they observed on size scales between 2″ and 20″ in Sgr A West is predominantly ionized gas typical of fine structure in other H II regions. Therefore we included the IR/radio complex as part of a program searching for "super-bright radio knots" in H II regions (Miley *et al.* 1970) using the new 35-km baseline interferometer of the National Radio Astronomy Observatory (NRAO). For Sgr A West, the fringes were so strong as to be detectable above the noise level in only a few seconds.

II. OBSERVATIONS AND DATA REDUCTION

The NRAO interferometer consists of three 85-foot (26-m) telescopes separable by up to 2.7 km and a new 45-foot (14-m) telescope located about 35 km southwest of the other dishes on top of a mountain. The instrument operates simultaneously at 2695 MHz (11 cm) and 8085 MHz (3.7 cm), and the lobe separations vary between 2″ and 0″.2, depending on frequency and projected baseline length. Because the 45-foot and associated systems have not been described previously, we present a short description here.

The 45-foot telescope is a portable, fully steerable telescope with an aperture efficiency of ~70 percent at both 2.7 and 8.1 GHz. The local oscillator signal is transmitted to (and from) the remote 45-foot from Green Bank over a phase-stable 1.3475-GHz radio link. A second wide-band 18-GHz link carries instructions uplink and the IF signals and digital data downlink. Except under conditions of inclement weather the radio links are quite stable, and the 45-foot system is operated remotely from the Green Bank site. Aside from the lower sensitivity and relatively narrow field of view (see below), the 45-foot system can be considered identical to the 85-foot systems.

The present observations were conducted on 1974 February 13 and 15 under conditions of excellent weather and minimal instrumental difficulties. Phase and gain calibrations were made by reference to NRAO 530 which was observed every half hour, and which is essentially unresolved on the present baseline. Its flux (4.3 fu at 2.7 GHz, 5.4 fu at 8.1 GHz) and position ($\alpha_{1950} = 17^h30^m13^s.542 \pm 0^s.003$, $\delta_{1950} = -13°02'45''.83 \pm 0''.07$) were determined by comparison with 3C 84, 3C 120, 3C 138, 3C 345, and BL Lac whose fluxes and positions had been accurately measured earlier.

Data reduction of 45-foot data consists essentially of the same process used for reducing data from the 85-foot telescopes, and will not be described here. Since the 45-foot signals are correlated with signals from each of the 85-foot antennae, three closely spaced baselines (of length 35.2, 33.8, and 33.2 km) at each of two orthogonal polarizations (left-hand, or L, and right-hand, or R, circular) are obtained, so that consistency and repeatability tests can be made on each of six independent correlators. Because of the wide 30-MHz bandwidth and long baseline length, the

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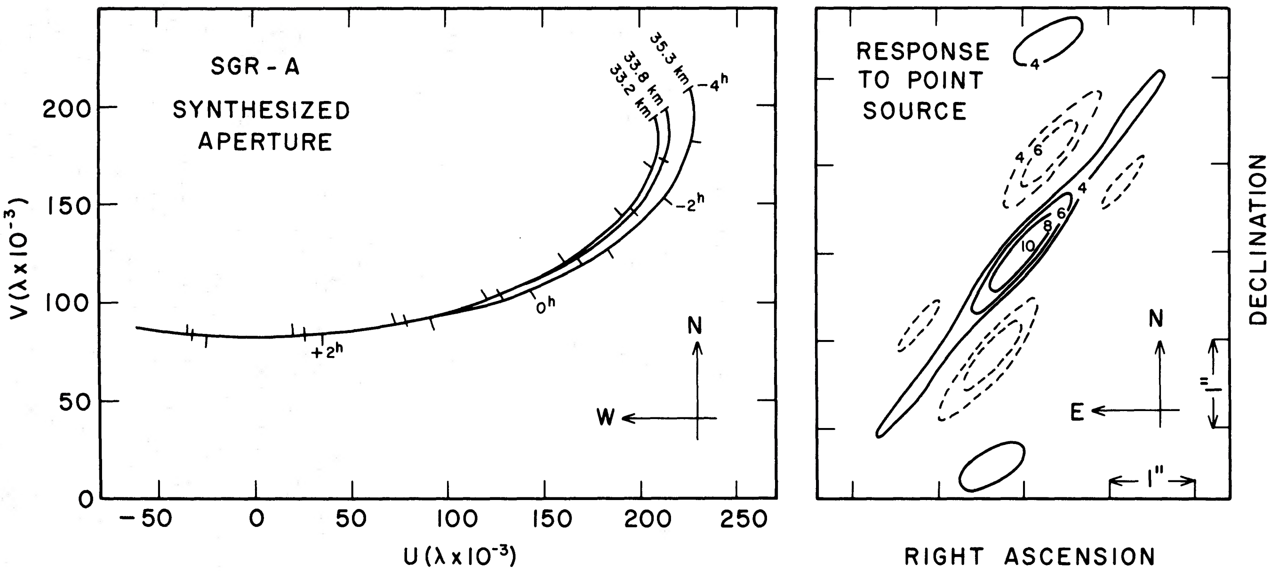

FIG. 1.—The projected baseline coverage and resulting synthesized beam pattern available for Sgr A at 2695 MHz. Hour angles are indicated along the ellipses. The axes are u, the east-west, and v, the north-south projections of the baseline, measured in wavelengths. At 8085 MHz the ellipses are identical in shape but larger by a factor of 3 so that the resulting synthesized beam is smaller by a factor of three.

width of the "white light lobe," or effective field of view, is only $\geqslant 35''$. The measured system noise is 0.2 fu in 30 s of integration. The instrumental performance was found to be very stable, with the largest source of systematic error arising from atmospheric effects, especially at low elevation angles.

The projected baseline coverage, i.e., the synthesized aperture available for Sgr A, and the resulting synthesized beam pattern at 2.7 GHz are shown in figure 1. The projected baseline varies from $\sim 300{,}000\ \lambda$ in position angle 51° (measured east from north) to a minimum of $\sim 85{,}000\ \lambda$ in position angle 0°. The axes in the figure are u, the east-west, and v, the north-south projections of the baseline.

The observational results of Sgr A West are shown in figure 2. The phase reference position was chosen in order to minimize the phase variations at 2.7 GHz. Each data point is a vector average of 5 minutes of observation (arithmetic average amplitudes normally differ by only a few percent). Not included in the figure are some 25 five-minute observations made by offsetting the beams 15″ to the north, south, east, and west whose agreement with the data shown is excellent at 2.7 GHz. The scatter and repeatability of the points in the figure are consistent with that of the calibrators. The greatest disparities occur at large hour angles ($|\mathrm{HA}| > 3^{\mathrm{h}}$) for which the elevation angles are less than 10°; these points should be ignored. The fringe amplitudes reported here have been increased by 25 percent at 2.7 GHz and by 5 percent at 8.1 GHz over their directly measured values to compensate for the effects of an automatic gain control circuit which keeps the IF power to the correlators constant (i.e., Sgr A increases the system noise temperature by 25% at 2.7 GHz).

Aside from atmospheric noise, the amplitudes and phases appear to show little structure, especially at 2.7 GHz. The 8.1-GHz phase excursions are similar in form and about 3 times as large as those at 2.7 GHz indicating that some of the phase variations could be atmospheric in origin at both frequencies. No believable systematic differences exist between the LL and RR correlators, and the LR and RL correlator results (not shown) appear to be dominated by noise. Any polarized intensity is therefore much less than 10 percent of the total intensity.

For later reference we shall define the fringe visibility V in the standard manner:

$$V(u, v) = A(u, v) \exp [i\phi(u, v)] , \qquad (1)$$

where A is the fringe amplitude and ϕ is the fringe phase measured at projected baseline (u, v). The source brightness distribution is given by the Fourier transform of the visibility. Since, of course, we sample only small portions of the (u, v)-plane (fig. 1), our ability to reconstruct the true source brightness distribution is rather limited.

III. SOURCE STRUCTURE

In this section we investigate possible configurations for the source structure consistent with the observations. Less emphasis will be placed on the 8.1-GHz results in formulating the possible models because of the relatively greater importance of noise at this frequency.

There are, of course, an infinite number of source models consistent with the data. The more difficult problems of reconstructing the brightness distribution will be deferred until later. We begin the discussion by

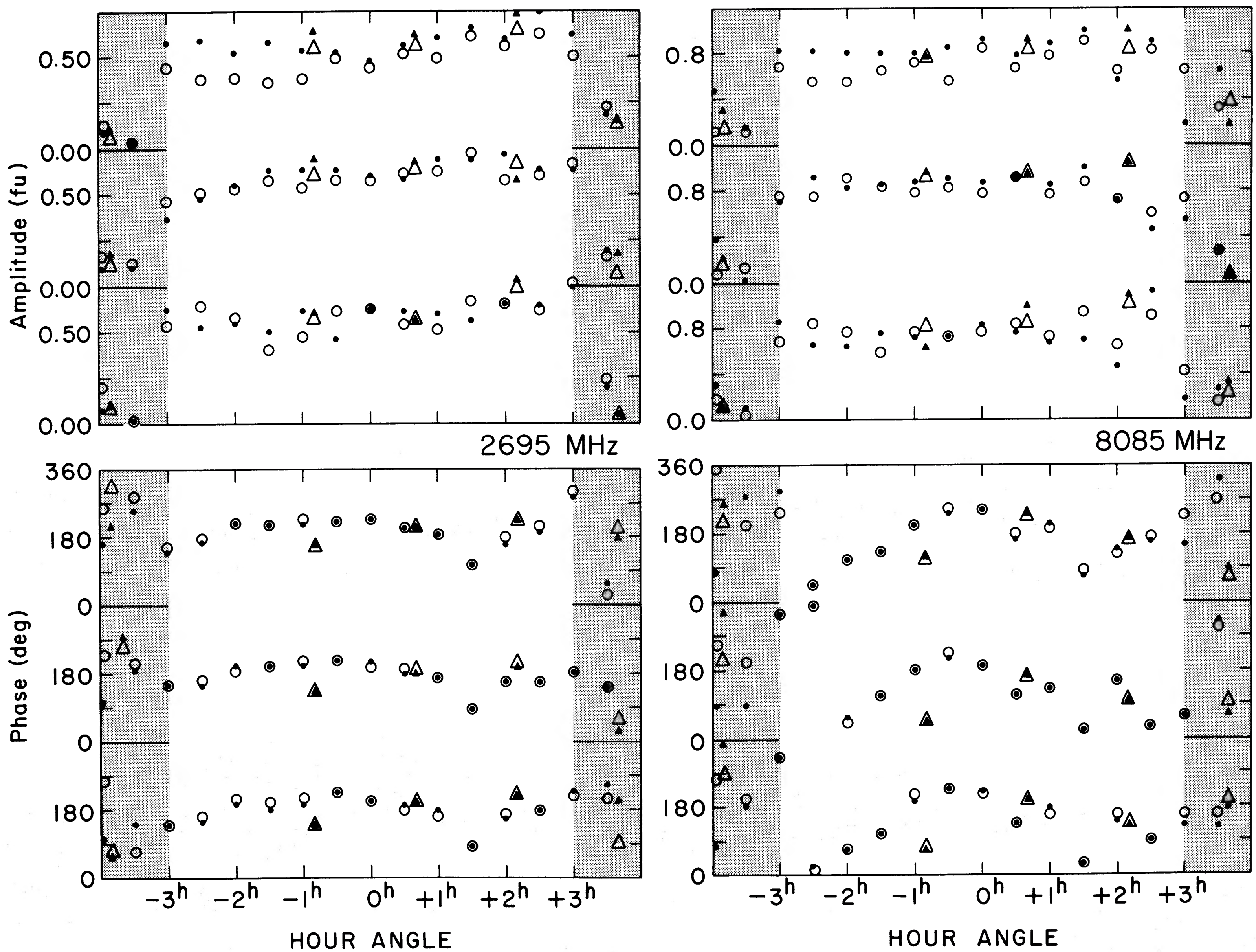

FIG. 2.—Observations of Sgr A at 2695 and 8085 MHz on February 13 (*circles*) and February 15 (*triangles*). The upper, middle, and lower portions of each graph correspond to the 35.2-, 33.2-, and 33.8-km baselines, respectively. The RR and LL correlators are indicated by filled and open symbols, respectively. Shaded portions of each graph indicate that the elevation angle of the observation was less than 10°. The phase reference position is $\alpha_{1950} = 17^h42^m29^s.264$, $\delta_{1950} = -28°59'16''.38$.

TABLE 1

MODEL SOURCE PARAMETERS

Model	2695-MHz Flux* (f.u.)	Right Ascension* (1950)	Declination* (1950)
Single point source......	0.60 ± 0.05	17ʰ42ᵐ29ˢ.291 ± 0ˢ.005	−28°59′17″.63 ± 0″.10
Double point source.....	0.29 ± 0.07	17 42 29.238 ± 0.007	−28 59 15.13 ± 0.14
	0.31 ± 0.07	17 42 29.279 ± 0.007	−28 59 17.48 ± 0.14

* All errors are one standard deviation.

listing some of the more obvious features of the structure.

1. Because of the lack of structure in the fringe visibilities, it appears that the brightness distribution is simple and consists of one or two dominant components. More complicated models would require complex variations of the visibility in the $(\boldsymbol{u}, \boldsymbol{v})$-plane except along the projected baselines we happened to sample.

2. The component sources are probably unresolved since the fringe amplitudes remain nearly constant even though the projected baseline changes by more than a factor of three at each frequency. A conservative upper limit to the source angular diameter θ is 0″.1. If the source is at the distance of the galactic center (~10 kpc), its diameter is less than 10^3 a.u. ($10^{-2.3}$ pc).

3. The components are contained within a 1″ × 3″ region centered at the phase reference position. Sources located outside this region would have shown substantial phase variations at 2.7 GHz. Thus the subarcsecond structure is coincident (within the rather large IR errors) with the centroid of the 10-μ extended source and slightly west (0ˢ.2 ± 0ˢ.15) of the IR point source number 1 discussed by Rieke and Low (1973).

4. The total flux density of the sub-arcsecond structure, S_ν, is on the order of 0.6 fu at 2.7 GHz and 0.8 fu at 8.1 GHz. In addition, the ratio of fluxes, $S_{8.1}/S_{2.7}$, is approximately 1.3.

5. Assuming the angular diameter of the sources is less than 0″.1, then the brightness temperature, T_b, is given by

$$T_b \sim \frac{\lambda^2}{2k}\frac{S_\nu}{\theta^2} \sim 10^{3.1}\left(\frac{\lambda}{\mathrm{cm}}\right)^2\left(\frac{S_\nu}{\mathrm{fu}}\right)\left(\frac{\theta}{''}\right)^{-2} > 10^{7.2}\,{}^\circ\mathrm{K}, \nu = 2.7\,\mathrm{GHz}$$
$$> 10^{6.3}\,{}^\circ\mathrm{K}, \nu = 8.1\,\mathrm{GHz}, \quad (2)$$

where λ is the observing wavelength.

Were it not for the observed fringe phase of ~180° at 2.7 GHz, we would have concluded immediately that one unresolved source located at the phase reference position dominates the structure at both frequencies. In order to explain the observed phase, we are forced to explore other source configurations.

We first consider single-component models. In order to match the 2.7-GHz phases, we seek to locate a point source with an offset $(\Delta x, \Delta y)$ such that

$$\boldsymbol{u}\cdot\Delta x + \boldsymbol{v}\cdot\Delta y \sim \pm 0.5 \quad (3)$$

for all sampled points in the $(\boldsymbol{u}, \boldsymbol{v})$-plane. The best such model consists of a point source displaced about 1″.3 to the south of the phase reference whose position is given in table 1. The predicted amplitudes and phases

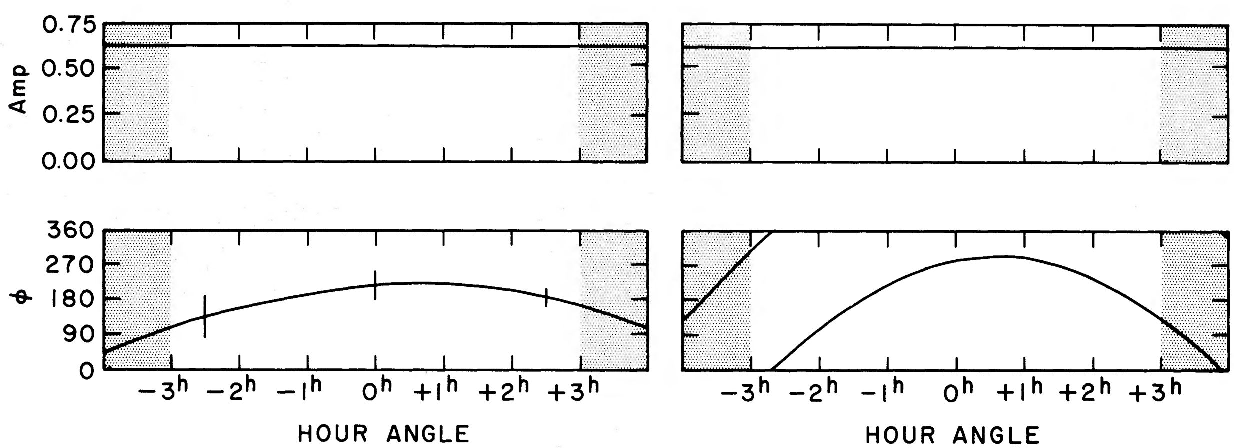

FIG. 3.—Predicted amplitude and phase for the single component model (see text and table 1) on the 35.2-km baseline. The phase reference is the same as in fig. 2. Vertical bars denote the range of phases corresponding to the positional uncertainties given in table 1. At 8.1 GHz these bars are 3 times larger. The amplitude units at 8.1 GHz are arbitrary.

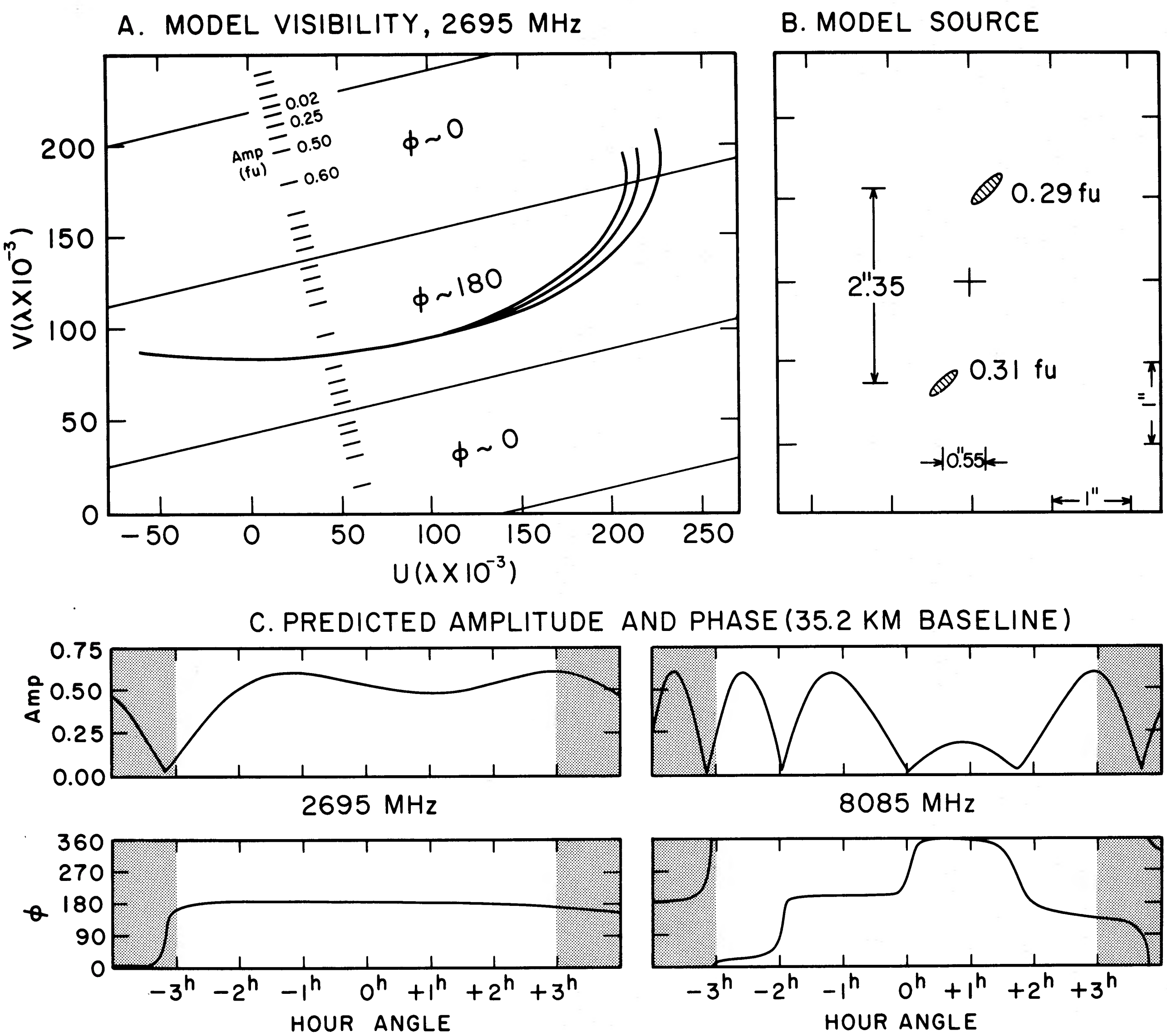

FIG. 4.—The model visibility (*a*) depicted in the (*u*, *v*)-plane for (*b*) the double source distribution which gives the best fit to the data. The amplitudes and phases expected for the model c are shown for comparison with the data (fig. 2). Details of the model are given in table 1. The components are assumed to have the same flux and position at both 2695 and 8085 MHz.

for the model are shown in figure 3. Although the average difference between the measured and predicted phase at 2.7 GHz is small, the residuals vary systematically (these residuals may be the result of atmospheric noise). At 8.1 GHz the agreement between the predicted and measured phases is the best of all models that are also consistent with the 2.7-GHz data (note especially the agreement at negative hour angles).

Another single-component model that is more consistent with the 2.7-GHz phases consists of a point source located at the phase reference position and which is seen in absorption against an emission source of at least equal brightness. This model is also consistent with the 8.1-GHz data. However, no trace of the emission source is evident in the present data. Consequently this model can be ruled out because the emission source must be quite large ($\theta > 2''$) and therefore very luminous (radio flux > 100 fu); no such source is observed in Sgr A West on shorter baselines between 3 and 8 GHz (Balick and Sanders 1974).

A double component model can be constructed to give quite good agreement with the 2.7-GHz fringe visibility observed. The fringe phase of such a model is very nearly 180° over large portions of the (*u*, *v*)-plane provided the component sources are unresolved and have nearly equal flux. In figure 4 we illustrate such a model that gives an excellent fit to the 2.7-GHz data. Details of the model are presented in table 1.

However, no variations in the 8.1-GHz amplitude, which are predicted by the model (fig. 4*c*), were observed. Moreover, a moment's reflection shows that the double-source model forces the displacement between components to be essentially the same as the displacement of the innermost sidelobes of the synthesized beam pattern at 2.7 GHz. Hence the possibility of observational selection effects is indicated, for it is unlikely that the components would be found with the requisite separation and orientation.

IV. DISCUSSION

The high brightness temperature, small angular diameter, and intimate association with strong IR and nearby radio continuum sources makes the sub-arcsecond structure unique in the Galaxy. Other types of galactic radio sources, such as pulsars or detectable X-ray sources, resemble the sub-arcsecond structure in at most one or two of these respects. Unfortunately, the nature of this structure cannot be ascertained from its radio spectrum as determined by the present observations alone. For example, one should not attempt to use the spectral information $S_{8.1}/S_{2.7} \sim 1.3$ to infer a magnetic field or electron density in the source in view of the fact that Balick and Sanders (1974) have shown that the nearby structure of scale size about 10″ has an optical depth near unity between 3 and 8 GHz; hence it is probable that the ratio of fluxes is the result of foreground absorption and is not indicative of physical conditions in the structure itself.

The unusual nature of the sub-arcsecond structure and its positional coincidence with the inner 1-pc core of the galactic nucleus strongly suggests that this structure is physically associated with the galactic center (in fact, defines the galactic center). The available information shows that there exist some intriguing morphological similarities between this structure and the more energetic nuclei of other galaxies in terms of their size and brightness. Sanders and Prendergast (1974) have hypothesized that although now quiescent, the galactic center may once have been the site of energetic processes similar to those now seen in the quasar BL Lac by Oke and Gunn (1974) and others. The possible reasons for such activity have recently been reviewed by Saslaw (1973).

The nature of the sub-arcsecond structure cannot be established until observations are substantially improved. More complete coverage on baselines between 10^5 and 10^6 λ are a necessity. Preliminary very long baseline (VLB) observations of Sgr A have been made at 5 GHz on a baseline of $10^{6.7}$ λ by Lo (1974) and collaborators with marginal results. Additional VLB observations with other baselines and frequencies, as well as infrared and X-ray observations of higher spatial resolution, would be most useful. Finally, we note that since the dimensions of the sub-arcsecond structure are $\lesssim 1$ light-day, and since the size of the region in which the structure is found is $\lesssim 1$ light-month, variations in the radio flux and structure are an interesting possibility. Or perhaps more speculatively, if one wishes to search for pulsed radio emission from the galactic center, one must observe at frequencies ~ 5 GHz or greater and expect to encounter dispersion measures at least as high as 10^4 cm^{-3} pc.

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