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LUNAR OCCULTATIONS OF THE RADIO SOURCE SAGITTARIUS A

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Lunar occultations of the radio source Sgr A, presently identified as the galactic nucleus, have been observed at nine frequencies in the continuum between 230 and 2400 MHz. The results show that the half-power diameter of the source is about 2 × 3 arc min and that the radio contours are remarkably smooth, there being little significant structure down to a resolution of 20 arc sec. The position of the source has been measured to an accuracy of ±15 arc sec and new values for flux densities in the decimeter band have been determined. The new data suggest that the spectral index of Sgr A is about −0.25, while that of the surrounding region is about −0.7.

As is now well known, lunar occultations provide a means for determining the position and angular structure of a radio source to accuracies of the order of a few arc sec. In this paper, we report on results obtained at nine frequencies in the continuum between 230 and 2400 MHz from four occultations of Sgr A. The observing stations were: Fort Davis, Texas; Goldstone, California; Green Bank, West Virginia; and Harvard, Massachusetts. The data have provided more accurate information on the position of Sgr A, its angular dimensions, its brightness distribution and its radio spectrum.

Although a variety of receiving equipment was used at the four observing sites, a uniform method of analysis was used to handle all the data. A digitized version of the occultation curve was convolved with an appropriate restoring function, which corrected for effects of diffraction at the limb of the Moon. The result of the convolution was a strip-integrated brightness distribution of the source, equivalent to what would be observed by a fan-shaped antenna beam oriented parallel to the limb of the Moon at the point of occultation. The angular width of the fan beam was determined by the particular restoring function used, and for these observations was in the range 20 to 50 arc sec.

Figure 1 shows an example of the occultation data. The lower section of the figure shows the raw data obtained from observations made on 11 April 1968 at 2295 MHz with the 210-ft antenna at Goldstone, California. The upper section shows the restored brightness distributions. In this example, as in all the other cases, the restored curves were used to obtain the flux density and angular diameter of the source, together with the precise times of immersion and emersion.

Data summarizing the complete set of observations are given in Table I. Column 1 lists the observing sites, column 2 the dimensions of the radio telescopes at the various sites, column 3 the observing frequencies, column 4 the dates of the occultations, columns 5 and 6 the right ascension and declination (1950.0) of Sgr A determined from the observed times of immersion and emersion, column 7 the angular diameter of the source measured from the restored curves, and column 8 the flux densities of the source at the various observing frequencies, derived from the restored data.

The mean position of Sgr A derived from the occultation data is

$$\alpha\,(1950.0) = 17^{h}\,42^{m}\,30^{s}\!.6 \pm 1^{s}\,0$$

$$\delta\,(1950.0) = -28^{\circ}\,59'\,14'' \pm 15''$$

This position is within the error limits of the microwave position given by Downes and Maxwell (1966) and it is also in excellent agreement with the position of the infra-red source in the galactic center region, detected by Becklin and Neugebauer (1968). There is no indication that the position of the centroid of the source changes significantly with frequency. However, the half-power angular diameter, about 2 × 3 arc min at 1000 MHz, apparently increases slightly with decreasing frequency. Also, as noted by previous observers, the source is somewhat more extended along the galactic plane than it is in the transverse direction.

The radio contours of the source derived from the present data are remarkably smooth, there being little significant structure down to a resolution of 20 arc sec. The contours are also essentially symmetrical, the brightness temperature reaching a

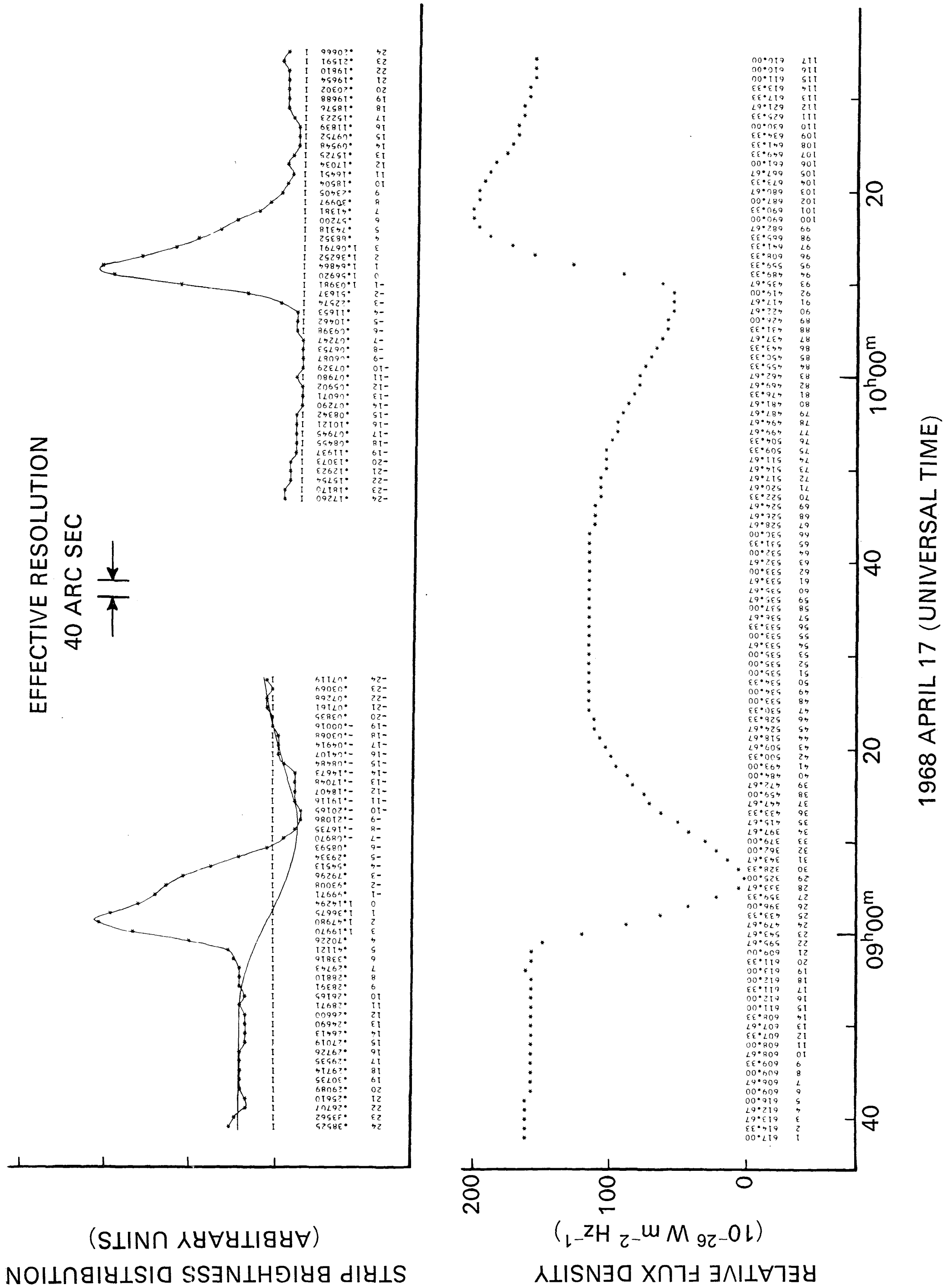

FIG. 1. Lunar occultation of Sagittarius A observed at 2295 MHz with the 210-ft antenna at Goldstone, California. The antenna tracked the source throughout the occultation. *Lower section:* receiver output (raw data). *Upper section:* strip-brightness distribution (restored data).

TABLE I
Lunar Occultations of Sagittarius A

Observatory	Antenna diameter(ft)	Frequency (MHz)	Date of occultation	Right ascension (1950.0)	Declination (1950.0)	Diameter (arc min)	Flux density ($10^{-26}Wm^{-2}Hz^{-1}$)
Goldstone, Cal.	85	2388	9 Oct 67	$17^h 42^m 29^s.4$	−28° 59′ 10″	1.5 × 2.5	140
Goldstone, Cal.	210	2295	17 Apr 68	29.1	59 29	1.8 × 2.3	170
Harvard, Mass.	84	1667	17 Apr 68	—	—	— × 2.5	185
	84	1667	11 Jun 68	29.9	59 30	2.4 × 2.5	190
Green Bank, W. Va.	140	1420	26 Jan 68	30.0	59 25	2.4 × 3.3	170
	140	1420	17 Apr 68	30.8	58 56	2.3 × 2.8	180
Harvard, Mass.	84	1407	26 Jan 68	—	—	— × 3.1	210
Ft. Davis, Tex.	85	950	17 Apr 68	30.1	59 24	2.2 × 3.3	200
	85	950	11 Jun 68	31.9	59 15	2.4 × 3.1	265
Green Bank, W. Va.	140	405	26 Jan 68	30.9	59 13	3.5 × 4.4	235
	140	405	17 Apr 68	32.2	58 51	2.6 × 3.4	225
Green Bank, W. Va.	140	256	26 Jan 68	29.6	59 30	3.2 × 5.1	300
	140	256	17 Apr 68	—	—	— × 3.6	230
Green Bank, W. Va.	140	234	17 Apr 68	32.8	58 51	2.5 × 3.6	220

	Right ascension	Declination
Mean position from occultations	$17^h 42^m 30^s.6 \pm 1^s$	−28° 59′ 14″ ±15″
Microwave position (Downes and Maxwell 1966)	28 ±2	58 30 ±30
Infra-red position (Becklin and Neugebauer 1968)	30 ±1	59 24 ±6

maximum near the center. That is, there is no evidence that Sgr A is a shell source, as is the case with many supernova remnants.

Flux densities for Sgr A obtained from the present observations are plotted as filled circles in Figure 2. In each case, the flux values have been calibrated against known flux densities for M87 or 3C348. Uncertainties in the flux measurements are of the order of ±20 per cent, and most of the error can be attributed to the complex background on which the source lies. Bearing these problems in mind, we derive a revised spectral index for Sgr A of the order of -0.25 ± 0.1.

Figure 2 also shows earlier flux values for the source obtained with antennas having beamwidths of the order of 2–18 arc min. At frequencies $\geqslant 8000$ MHz, these values refer primarily to the core source Sgr A, but at lower frequencies the measurements include a considerable contribution from the surrounding region as well. In reviewing the earlier data, Downes and Maxwell (1966) attempted to correct these flux densities for antenna beamwidths and background radiation, but the corrections were apparently insufficient. The fact that the lower-resolution measurements lead to a spectral index of -0.7, while the occultation data give an index of -0.25, indicates that the region is best interpreted in terms of a core source with a rather flat spectrum, surrounded by a region with a considerably steeper spectrum.

The flux density of the infra-red source at 2.2 microns, uncorrected for interstellar absorption, is 35.0 ± 2.5 flux units for a circular region of diameter 1.8 arc min (Becklin and Neugebauer 1968). Interpretation of the infra-red data is, however, complicated by the large and relatively unknown amount of interstellar absorption over the path to the galactic center, which might require the value of 35 flux units to be increased by a factor of 3–10. Nevertheless, the radio data extrapolate fairly well to the infra-red data. (The infra-red observations have also revealed a point-like source of angular diameter 5 arc sec imbedded in the bright central source, but this does not have any known radio counterpart at present.)

We do not believe that the revised spectrum for Sgr A should be interpreted in terms of thermal emission processes. The spectral curve is very different from that of most H II regions or planetary nebulae, there being no indication that the curve turns over, assuming the slope of +2.0 characteristic of optically-thick thermal sources, at frequencies even as low as 230 MHz. Under such circumstances, for the radio emission to be thermal the electron temperatures would have to be $> 70\,000$°K, which is an order of magnitude larger than the temperatures believed to exist in most H II regions.

The spectrum also differs greatly from that of supernova remnants such as SN 1572, SN 1604 and

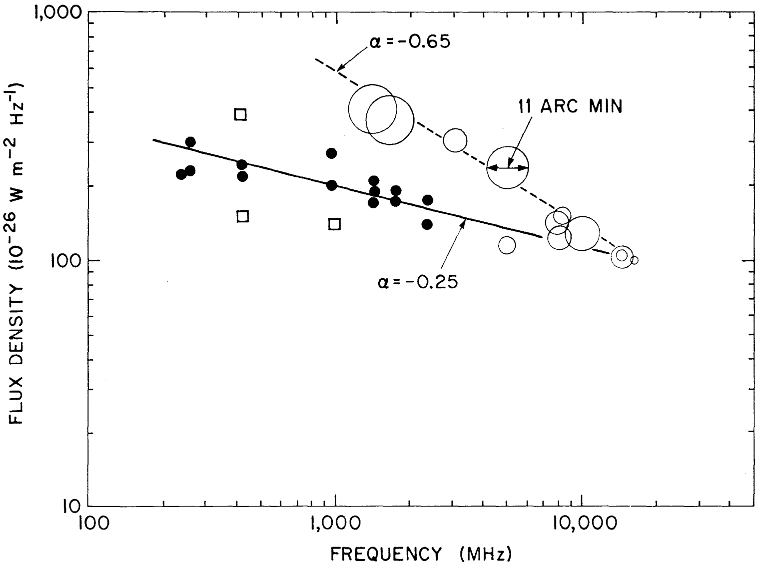

FIG. 2. Spectrum of Sagittarius A. Filled circles are data from lunar occultations; the angular resolutions are < 1 arc min and the uncertainties ±20 per cent. Open circles denote earlier measurements made with antennas of resolution 2–18 arc min; the diameters of the open circles are proportional to the angular resolutions. Open squares denote earlier data taken with interferometers or fan beams. (References for the earlier data are given in Downes and Maxwell 1966, Table I.)

Cas A, which have spectral indices of −0.7, but is somewhat similar to that of the Crab Nebula, which has an index of −0.27 (Conway *et al.* 1963). However, if Sgr A is at the galactic center, at a distance of 10 kpc, it is intrinsically a very much more powerful source than the Crab Nebula. Thus, if the Crab Nebula were at a distance of 10 kpc, rather than 1.5 kpc as is presently believed, it would have an apparent diameter of 1 arc min, compared with 3 arc min for Sgr A, and an apparent flux density at 3000 MHz of 15 flux units, compared with 150 flux units for Sgr A.

For the present, the model we have in mind for Sagittarius A is that of a source where electrons are being accelerated to very high velocities, so that the radio and infra-red flux may be accounted for by intense synchrotron radiation. Beyond the central core source, at distances greater than 30 pc, one might expect the supply of highest energy electrons to be diminished and, in consequence, the spectrum to steepen.

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