OCCULTATION OBSERVATIONS OF THE GALACTIC CENTER REGION AT 327 MHz

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Abstract. Lunar occultation observations of the thermal sources Sgr B2, G0.9+0.1 and G1.1−0.1 at 327 MHz have been used to estimate their electron densities and temperatures. A new nonthermal source of size ~10×5′ has been found about 7′ to the south of G1.1−0.1. A brightness contour diagram with a resolution of approximately 25×6′ is presented for the background radio emission near the sources Sgr A and Sgr B2.

I. Introduction

The region near the galactic centre consists of several thermal and nonthermal radio sources which have been studied at centimeter wavelengths with narrow pencil-beam antennas (Downes and Maxwell, 1966; Whiteoak and Gardner, 1973). We report here lunar occultation observations of the region made at 327 MHz using the Ooty radio telescope (Swarup *et al.*, 1971). Occultations of Sgr A, Sgr A-E, G0.1+0.0 and G0.2−−0.0 were observed on 1970, September 9 (hereafter referred to as OCC.I) and of sources G0.7−0.0, G0.9+0.1 and G1.1−0.1 on March 19, 1971 (OCC.II). Results for Sgr A and Sgr A-E have been reported elsewhere (Gopal-Krishna *et al.*, 1972). The data have provided information on spectrum and size for these sources. A new extended nonthermal source about 7′ to the south of G1.1−0.1 has been found which is perhaps a supernova remnant.

II. Observations

The observations were made at 327 MHz with the Ooty radio telescope, which provides twelve simultaneous beams separated by $4'/\cos\delta$ in declination. The radio telescope has a half-power beamwidth of 2° in the east-west direction. Its north-south beamwidth is $5\overset{'}{.}6/\cos\delta$ and $4'/\cos\delta$ for the total-power and phase-switched modes respectively.

In Figure 1, lines *AB* and *CD* show the apparent path of the Moon for the two occultations. Positions of the 12 beams in declination are shown in the margin. During the observations the telescope tracked regions at these 12 declinations and at R.A. (1950)$=17^h42^m40^s$ for OCC.I and at R.A. (1950)$=17^h44^m55^s$ for OCC.II. The telescope was calibrated on PKS 1309-22 (for OCC.I) and PKS 0859-25 (for OCC.II), taking their flux densities at 327 MHz as 26.4 and 19.9 Jy respectively. These values are based on Wyllie's (1969) measurements at 408 MHz extrapolated to 327 MHz using spectral indices from the Parkes catalogue.

III. Results

Figure 2 shows the observed occultation records for OCC.I and OCC.II. The records

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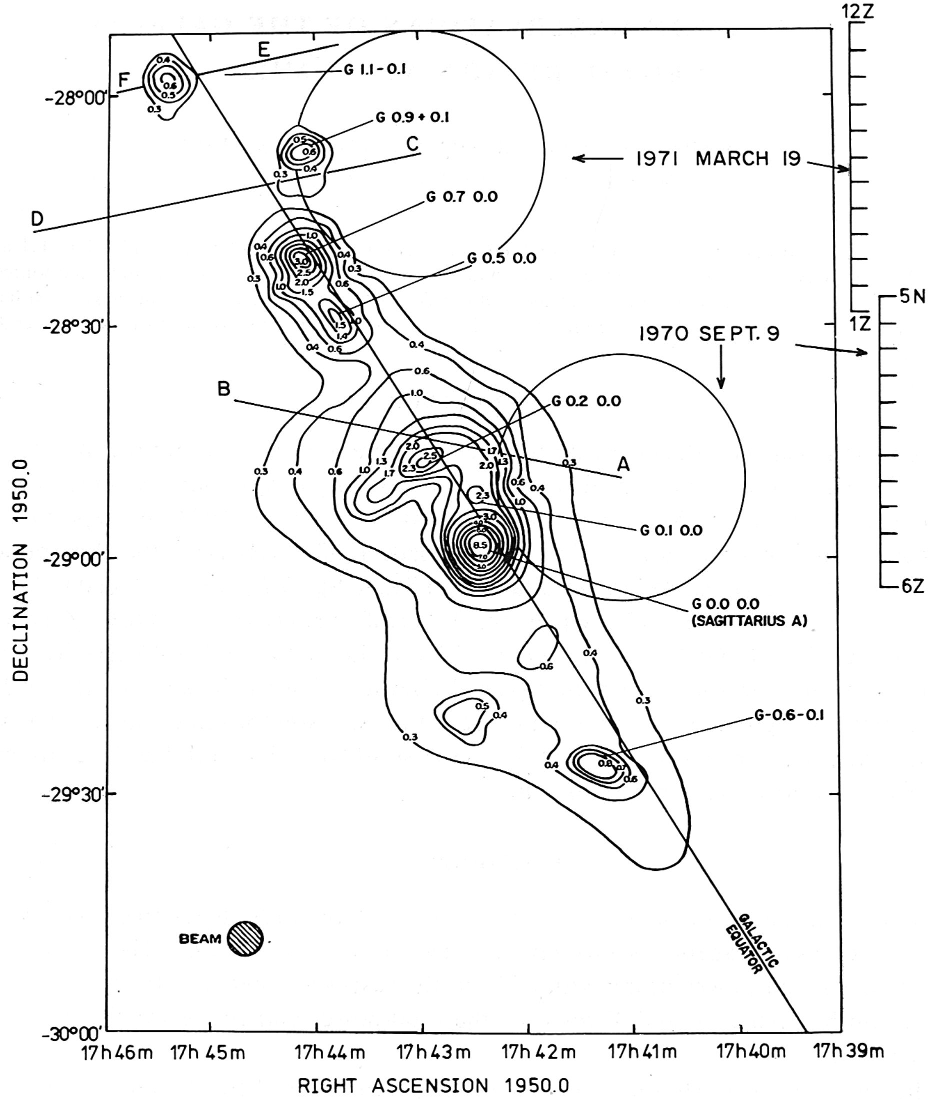

Fig. 1. Lines *AB* and *CD* show the path of the Moon for the occultation observations on 1970, September 9, and 1971, March 19, and are superimposed on a map at 8 GHz taken from Downes and Maxwell (1966). Positions of the twelve beams of the Ooty radio telescope are shown by 6 *Z* to 5 *N* and 1 *Z* to 12 *Z* on the right hand side.

have been smoothed with a gaussian of 4 min half-power width in order to reduce the effects of reciever instabilities and of the ionospheric scintillations seen on both occasions. The curves for OCC.II have been differentiated and plotted in Figure 3, where the sources G0.7 – 0.0, G0.9 + 0.1, G1.05 – 0.1 and G1.1 – 0.1, marked as G0.7, G0.9, G1.0 and G1.1 respectively, can be seen superimposed over a background indicated by broken curves. The background was determined from two considera-

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tions: (a) by comparison with the occultation profiles for the neighbouring beams, particularly those in which discrete sources are not evident, and (b) by ensuring that the resultant immersion and emersion profiles for each source have equal area. The background curves of Figure 3 were integrated and the resultant profiles are shown in Figure 2 by broken curves. These curves represent the occultation profiles for the background without contribution from the discrete sources. Positions, flux-densities and angular widths for the observed sources were estimated from the known apparent motion of the Moon and from their occultation response in successive beams. The results are given in Table I. Position of Sgr B2 (G0.7 – 0.0) derived from the occultation

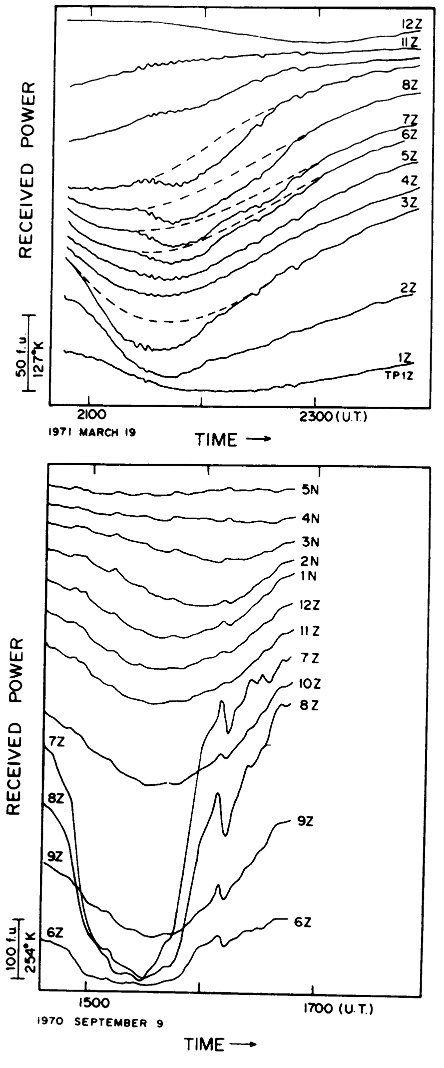

Fig. 2. Records of occultation observations made on 1970, September 9, and 1971, March 19. Flux density and antenna temperature scales are given on the left.

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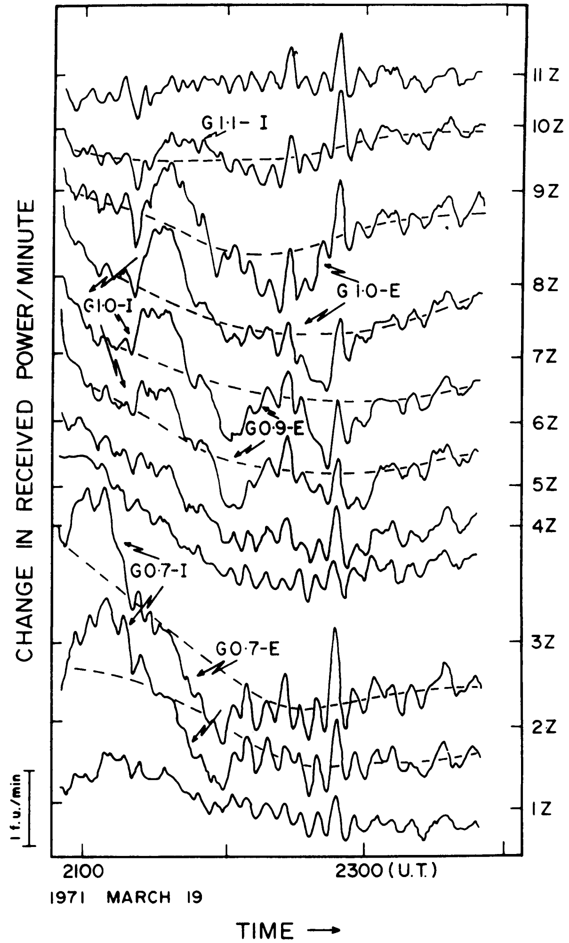

Fig. 3. Differentiated outputs for occultation observations for beams 1 Z to 11 Z made on 1971, March 19. Zero base levels for the curves of different beams are shown by dashes on both sides of the figure. I and E after a source number refer to its immersion and emersion respectively.

observations at 327 MHz agrees with that of the continuum peak at 5 GHz (Gardner *et al.*, 1971; Whiteoak and Gardner, 1973) and also with the occultation positions for the strong 1665 MHz OH emission features (Manchester *et al.*, 1969). The position of G0.9+0.1 at 327 MHz also agrees with the 5 GHz continuum position given by Whiteoak and Gardner (1973), but positions estimated by Downes and Maxwell (1966) from high frequency observations are to the north of the 327 MHz positions by about 1.5′ for both Sgr B2 and G0.9+0.1.

The flux densities were determined from the response of the sources in the differentiated occulation curves after subtraction of the background as described above. For the case of thermal sources, we added a correction ΔS for the estimated absorption of that part of the background radiation which passes through the source. It is assumed

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TABLE I

Measured parameters of the discrete sources at 327 MHz

Source	Position[a] (1950.0)	Flux-density (Jy)	Mean position angle (deg)	Angular half-power width (arcmin)
G0.1 + 0.0 + G0.2 − 0.0 (T)	–	105 ± 30	90	18
			180	8
G0.7 − 0.0 (T)	$17^h44^m10\overset{s}{.}2 \pm 2^s$	28 ± 5	153	5.0 ± 0.3
(Sgr B2)	$-28°23'06'' \pm 40''$		229	5.2 ± 0.3
G0.9 + 0.1 (T)	$17^h44^m09^s \pm 2^s$	11 ± 3	180	4.2 ± 1.5
	$-28°09\overset{'}{.}2 \pm 1'$		286	4.4 ± 0.7
G1.05 − 0.1 (NT)	$17^h45^m30^s \pm 4^s$	27 ± 6	80	5 ± 2
	$-28°05' \pm 1\overset{'}{.}5$		350	10 ± 3
G1.1 − 0.1 (T)	–	16 ± 4	–	–

T = Thermal source; NT = nonthermal source

[a] For G1.05 − 0.1, the given position refers to the peak of brightness which lies about 1′ north of the centroid.

that the sources are located near the galactic center and half of the observed background emission T_b originates behind the sources. Therefore, the correction to the flux-density is $\Delta S = (2k\,\Delta T_c/\lambda^2)\,\Omega_s$, where Ω_s is the solid angle subtended by the source as found from the occultation observations and $\Delta T_c = \frac{1}{2} T_b\{1 - \exp(-\tau)\}$, τ being the optical depth of the source at 327 MHz estimated iteratively. The flux densities given in Table I include a correction $\Delta S = 45$ Jy for (G0.1 + 0.0) + (G0.2 − 0.0) based on $T_b = 2400$ K (see Figure 6), and corrections of $\leqslant 4$ Jy for the other thermal sources for $T_b = 1500$ K. The flux density of Sgr B2 was reported as 9 Jy at 408 MHz by Little (1974), which is much lower than our estimate. We have re-examined our records and find it difficult to reconcile with Little's measurements, which might have been underestimated due to an overestimate of the background radiation and underestimate of the size of the source. There are similar difficulties in estimating the background radiation in the occultation observations, but the observed values of the size have small errors.

It may be seen from Figure 3 that there exists a broad structure extended in the north-south direction, marked by G1.1 and G1.0, for which the occultation profiles show response in six successive beams from 5 *Z* to 10 *Z*. The high frequency maps presented by Downes and Maxwell (1966) show a thermal source, G1.1 − 0.1, of $\sim 6 \times 6'$ in size. The beam 10 *Z* was pointed about 1′ to the north of this source. Occultation response in the output of beam 10 *Z* is expected to be mainly due to this source. Its response in beam 9 *Z* was expected to be about the same. Moreover, only about half the extent of this source was occulted on 1971, March 19, as may be seen from Figure 1 in which the path of the northern limb of the Moon is shown by line *EF*. It appears therefore that there exists another source $\sim 7'$ to the south of the thermal source G1.1 − 0.1, which is labelled by us as G1.05 − 0.1. This source is also seen in a

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map of the region at 408 MHz presented by Little (1974) based on observations with the Mills Cross. The source has a nonthermal spectrum because if we assume its spectral index as -0.7, its expected brightness temperatures at 3 and 5 GHz are approximately 3 K and 1 K respectively, evidence for which can be found in the high frequency maps by Cooper and Price (1964) and Whiteoak and Gardner (1973). Figure 4 shows approximate brightness contour diagram for this source derived from the occultation observations after taking into account the curvature of the Moon's limb. The small extension at the northern end is due to the thermal source G1.1 – 0.1. Most of the contribution is from the nonthermal source G1.05 – 0.1, whose parameters are given in Table I. Considering its nonthermal spectrum, large angular extent and location near the galactic plane, we may consider the source to be a supernova remnant. However, it was not possible to identify any characteristics of a supernova remnant in its brightness distribution, probably due to insufficient signal-to-noise ratio of the occultation records. Using the surface brightness and the linear diameter relation for the galactic supernova remnants (Ilovaisky and Lequeux, 1972), we estimate that the distance of G1.05 – 0.1 is about 9 kpc. It may be, therefore, that the source is located close to the galactic center.

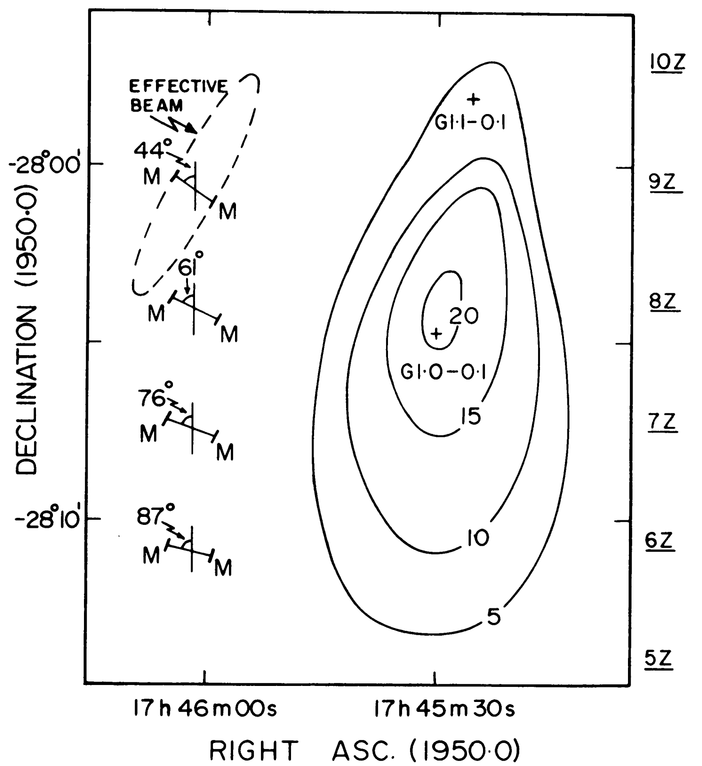

Fig. 4. Contour map of G1.05 – 0.1 and G1.1 – 0.1 at 327 MHz. Contour unit represents 110 K of brightness temperature above the background. Lines MM indicate resolutions and mean position angles of scan for different beams.

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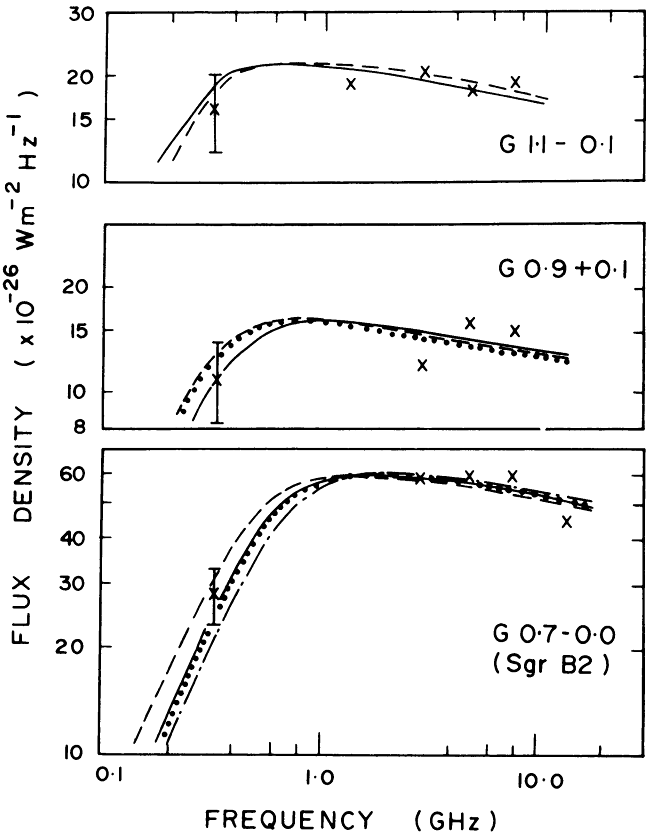

Fig. 5. Observed spectra of the thermal sources are compared with computed spectra for sets of T_e, N_e and θ_e listed in Table II.

The spectra of the sources G0.7 − 0.0, G0.9 + 0.1 and G1.1 − 0.1, shown in Figure 5, indicate that the radiation arises thermally. To derive their physical parameters, we assume that each source has a constant temperature T_e but a spherical gaussian distribution of electron-density with a peak value N_e and half-density angular width θ_e. The observed brightness distribution of such a source will vary with wavelength when the outer parts gradually become optically thick. For several different sets of the above parameters, we have computed spectra and half-power widths for the sources at 327 MHz. In Figure 5 and Table II we present the results of computations for a few of the cases which give a reasonable fit to the observations. The derived values of T_e, N_e, θ_e and the mass of ionized hydrogen ($M_{\mathrm{H\,II}}$) for the sources are given in Table III. For G1.1 − 0.1, the size of the source could not be estimated reliably at 327 MHz, and we have taken $\theta_e = 6'$ to fit the observations by Downes and Maxwell (1966) and Whiteoak and Gardner (1973) at centimetre wavelengths. Considering the uncertainties in measured parameters, estimates of physical parameters for the sources G0.9 + 0.1 and G1.1 − 0.1 may be regarded as not well-determined.

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From the observations made during OCC.I, we do not find evidence of any other source of small diameter except Sgr A and Sgr A-E, results for which have been reported earlier (Gopal-Krishna *et al.*, 1972). From the occultation records we estimate that at 327 MHz the thermal sources G0.1 + 0.0 and G0.2 − 0.0 are almost merged together with a size $\sim 18 \times 8'$. Their estimated optical depth at 327 MHz is $\sim$2.5.

We have also attempted to make a map of the galactic center region using the Moon as a screen (Stankevich *et al.*, 1970). It may be noted that the occultation outputs for the 12 total-power beams, when inverted, simply relate to the brightness temperature averaged over a strip equal to the Moon's area covered by the beam. The distribution of brightness temperature is given in Figure 6. The point $l = 1\overset{\circ}{.}1$ and $b = -0\overset{\circ}{.}8$ was used for zero calibration with estimated $T_b = 450$ K at 327 MHz (Altenhoff *et al.*, 1970). The north-south resolution is 6.4′. The east-west resolution for any point equals the angular width of the Moon's chord at the declination of the beam; the achieved east-west resolutions are shown in the margin of Figure 6 for all the beams for the start and the end of the observations. The background temperature seems higher for

TABLE II

Values of physical parameters used for computations of spectra shown in Figure 5. The calculated and observed values of source widths are also shown.

Source	Physical parameters			Source width θ_a (327 MHz)		Spectral curve of Figure 5
	T_e (K)	N_e (cm^{-3})	θ_e (pc)	Calculated (pc)	Observed (pc)	
G0.7 − 0.0	4000	340	10	14.0	15 ± 1	— · — · —
	6000	360	10	12.7	15 ± 1	————
	4000	255	12	15.5	15 ± 1	. . . .
	6000	270	12	14.0	15 ± 1	.. — ... — ..
G0.9 + 0.1	4000	170	10	10.1	13 ± 3	——— —— —
	5000	130	12	10.5	13 ± 3	. . . . .
	4000	100	14	12.1	13 ± 3	- - - - - -
G1.1 − 0.1	3000	80	17	15.6	–	. . . . .
	5000	85	17	14.3	–	————

TABLE III

Physical parameters of the observed thermal sources[a]

Source	T_e (K)	N_e (cm^{-3})	Diameter (pc)	$M_{\mathrm{H\,II}}$ ($M_\odot$)
G0.7 − 0.0 (Sgr B2)	5000 ± 1000	290 ± 40	11 ± 1	1.1×10^4
G0.9 + 0.1	4500 ± 1000	130 ± 40	13 ± 3	9.4×10^3
G1.1 − 0.1	4500 ± 1500	80 ± 20	17 ± 3	1.2×10^4

[a] Assumed distance of 10 kpc.

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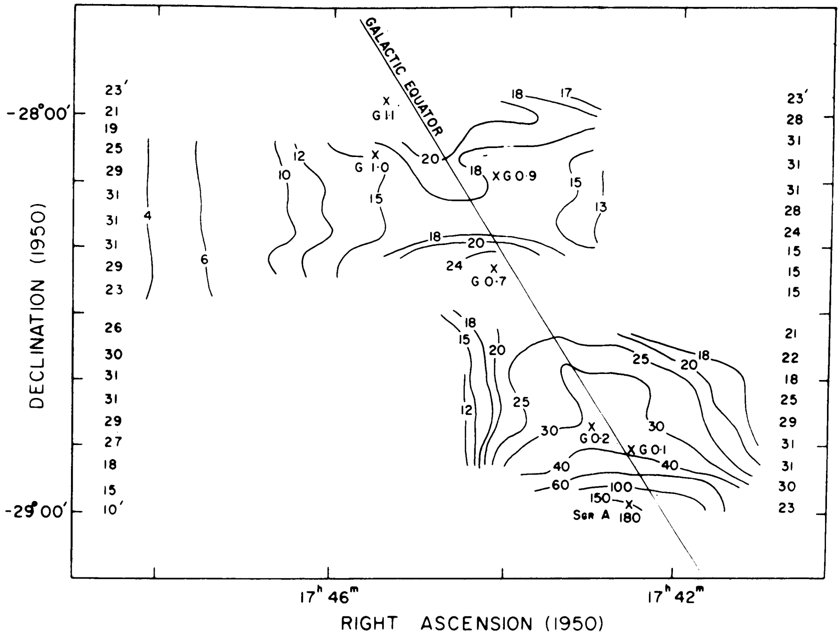

Fig. 6. Contour map of the region near the galactic center made with resolution in declination of 6.4′ and in right ascension as given on either side of the map for different beams. Contour interval represents 110 K of brightness temperature.

positive compared to negative latitudes at $l \sim +1°$ (in the region around G0.9+0.1 and G1.05−0.1). This can be seen also in the occultation records of Figure 2 for 1971, March 19, where the power received is lower at the start of the occultation than at its end.

Values of T_e found for Sgr B2 are of the same order as those estimated from recombination line observations (Mezger and Höglund, 1967; Reifenstein *et al.*, 1970), indicating that departures from local thermodynamic equilibrium in this H II region are not large, as also concluded by Shaver and Goss (1970) for several other H II regions. Values of N_e and T_e determined from the continuum observations need not be the same, however, as found from the recombination line observations, as the two emission processes depend on different power factors of T_e and may not arise in the same regions. Values of N_e and T_e determined from line emission refer to the entire H II region while continuum observations at meter wavelengths give T_e only for its outer part.

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DISCUSSION

Hughes: We have extended our radio observations at 858 MHz in an attempt to confirm the existence of radio pulses from the direction of the galactic center. The previous results showed no correlation with the gravitational events as observed by Weber, though evidence was presented which showed that the radio pulses might have an origin in the direction of the galactic center. More recently, severe doubt has been cast on the evidence presented for the existence of gravitational pulses. Our most recent results with a sensitivity improved by a factor of about 4 show that the radio pulse rate is about the same as before, namely about 0.3 per hour. Though this could mean a real reduction in the pulse rate, at present we consider the origin of the radio pulses to be an open question.

Ekers: Do you know if the recombination line observations you have attributed to Sgr A comes from Sgr A itself, or could it be from the surrounding region?

Gordon: No. But if the background source stimulates the line emission, then the emitting region has the same dimensions as the background source.

Mezger: I want to draw attention to the source G0.9+0.0 which has an apparent thermal continuum spectrum even if the present low-frequency observations are considered. We searched for H109α and H85α lines in this source down to a very low level and within the velocity range $-300 \leqslant V_{LSR} \leqslant +300$ km s^{-1} without success.

Little and Swarup: The flux values from both the 327 MHz occultations and the 408 MHz pencil beam survey are lower than the microwave values for this source. A thermal spectrum fits the data reasonably well. The source is well separated from others in this region, and therefore the spectrum is well established.

Churchwell: Lowinger (1964) from his 15 GHz map has concluded that most of the extended emission

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seen at this frequency is thermal. T. Pauls, P. Mezger and I have detected recombination lines over this whole region, which would seem to confirm the thermal nature of this emission.

Gordon: There are conflicts between continuum maps, but I believe this map that Kapitsky and Dent made in 1973 with a magnificent instrument is highly reliable.

Davies: H166α recombination line observations have been made at Jodrell Bank using the Mark II radio telescope (beamwidth$=32'$) of the galactic center region ($l=359°$ to $+1°$ in $0\overset{\circ}{.}5$ steps). Line emission comes from all these points and appears to originate in the extended thermal emission measured in the high-frequency surveys of Downs and Maxwell. An electron temperature of 10000 K was derived from these observations.

Gordon: The new 2 cm map indicates that the extended region is nonthermal. If so, the recombination lines cannot come from that component.

Parijskij: Now we have direct evidence of the nonthermal nature of at least some portion of the Sgr A complex. Polarization of the west part of Sgr A sources was found at 4 cm (with about $1'$ resolution) at Pulkovo. The angular size of the polarized region was $\sim 2'$, and the amount was $\sim 1\%$. The maximum of the polarized emission is displaced by $\sim 30''$ toward the west from the maximum of the unpolarized emission at that wavelength.

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