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HIGH-RESOLUTION, MULTIFREQUENCY RADIO OBSERVATIONS OF M82

P. P. KRONBERG
David Dunlap Observatory and Scarborough College, University of Toronto
AND
P. N. WILKINSON
Nuffield Radio Astronomy Laboratories, University of Manchester, Jodrell Bank
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ABSTRACT

A supersynthesis radio map of the 8085 MHz emission in M82 is presented. The radio structure is complex, and is dominated by a bright unresolved source which is unpolarized ($< 0.7\%$), becomes optically thick at $\nu \approx 650$ MHz, and emits 65 percent of its 1666 MHz flux from within a region < 1.2 pc in diameter. Nine other discrete radio components near the M82 nucleus have been isolated, and no other radio sources with surface brightness > 5 K exist in the galaxy but outside the main radio source. An upper limit of 5 mJy can be set to any 8085 MHz radio emission from van den Bergh's infrared knots. The compact radio components in M82 may be supernova remnants, the brightest of which (source 41.9+58) is very recent ($\lesssim 150$ years) and has brightness and size limits which are consistent with the Σ-D relationship for known supernova remnants. The absence of a detectable linear polarization on all angular scales $\gtrsim 1''$ suggests that the magnetic field in the M82 nucleus is highly tangled on all size scales down to $\lesssim 20$ pc.

Subject headings: galaxies, individual — polarization — radio sources

I. INTRODUCTION

The nucleus of M82 is known to contain complex radio structure (Kronberg, Pritchet, and van den Bergh 1972; Hargrave 1974) including a compact ($\lesssim 0''.5$) source which dominates the brightness distribution at centimeter wavelengths. The nucleus also contains a source of infrared emission (Kleinmann and Low 1970) whose luminosity is considerably greater than that of the radio source. This infrared source is possibly associated with two remarkably large H II regions in the galaxy (Peimbert and Spinrad 1970; Recillas-Cruz and Peimbert 1970). Further details of the published work on M82 can be found in the paper by Hargrave.

In an attempt to obtain a greater insight into the physical conditions obtaining in the nucleus, we have made radio observations of M82 over a wide range of frequencies. The main observational data are in the form of a supersynthesis map at 8085 MHz and $2''.2$ resolution of the Stokes parameters *I*, *Q*, and *U*, made with the NRAO[1] interferometer. The radio brightness distribution thus revealed, and its relation to optical and near-infrared features, are discussed in § III. The brightest radio component (no. 3 of Kronberg *et al.* 1972) is embedded among other compact radio features, which makes it difficult to establish its properties in isolation from nearby emission. We have therefore made long-baseline interferometer observations at Jodrell Bank at 408, 962, 1663, and 1666 MHz, and these, with the addition of the 8085 MHz data, enable us to investigate the spectrum, polarization, and angular size of this compact source. These results are presented in § IV and discussed in § V.

II. THE OBSERVATIONS

The high-resolution map of M82 was derived by tracking the radio source over the available hour-angle range of the NRAO interferometer ($\pm$ approximately 5^h40^m) using the following antenna separations (in meters): 100, 200, 300, 500, 600, 700, 800, 900, and all succeeding multiples of 300 m to 2700 m, in addition to 1900 m. Calibration of amplitude, phase, and linear polarization was obtained from interspersed observations of 3C 48, 147, 286, 287, and 309.1, and CTA 102, using the calibration values tabulated by Wardle and Kronberg (1974). The operation of the NRAO interferometer has been described in some detail by Hogg *et al.* (1969). The synthesis observations were made between 1971 January and 1972 May.

Interferometric observations of M82 were also made at Jodrell Bank at 1666 MHz, 1663 MHz, 962 MHz, and 408 MHz, in addition to previous ones at 1423 MHz (Wilkinson 1971). The interferometers consisted of the Jodrell Bank Mark I (76 m) and Mark II (38×25 m) at the home station, and the Jodrell Bank Mark III (38×25 m) and a 25 m paraboloid at the Royal Radar Establishment at Defford at the outstations. The telescopes and baselines used are summarized in Table 1. The observations at 408 MHz and 962 MHz covered about 8 of the available 24 hours of hour-angle coverage, and those at 1663 and 1666 MHz

[1] The National Radio Astronomy Observatory is operated by Associated Universities Inc., under contract to the National Science Foundation.

TABLE 1

Interferometer	Frequency (MHz)	Baselines Used* (wavelengths)	Dates of Observing Runs
NRAO 2.7 km........	8085	Full supersynthesis (see text)	1971 Feb.–1972 May
Jodrell Bank Mark II-III........	1663	132,300	1972 Dec.
Jodrell Bank Mark II-III........	962	76,400	1973 Nov.
Jodrell Bank Mark I-Defford.....	408	172,700	1973 Nov.
Jodrell Bank Mark II-Defford....	1666	705,100	1974 Sept.

* These represent the approximate physical telescope separations and do not include the geometrical foreshortening, which varies with hour angle.

totaled 3 and 4 hours, respectively. Each set of observations included several projected interferometer orientations.

III. THE DISTRIBUTION OF RADIO EMISSION IN M82

The radio brightness distribution at 8085 MHz is shown in Figure 1. The Fourier inverted observations described in § II have been restored by a sidelobe-free symmetrical Gaussian beam of half-width 2″.2. This procedure, which has been described by Högbom (1974), removes slight distortions of the small-scale structure caused by convolution with the natural beam, which has sidelobes of up to 12 percent. The effective noise level of ~ 15 K (~ 4 mJy per restored beam) in the radio map is set by the limit in dynamic range imposed by atmospheric phase irregularities at Green Bank at 3.7 cm. The maximum flux seen on the shortest baselines was 2.4 Jy, which is 85 percent of the integrated flux (2.8 Jy) interpolated from the data of Kellermann, Pauliny-Toth, and Williams (1969). The remaining 15 percent of the flux must represent extended radiation of very low brightness whose value at any one place is $< \frac{1}{3}$ of the lowest contour level in Figure 1 (i.e., < 5 K). There is a further broad component underlying Figure 1 amounting to 0.5 Jy which is not reproduced in the restoring process mentioned above. The total radiation visible in Figure 1 (1.9 Jy) thus represents ~ 67 percent of the integrated flux density.

It is clear that the radio structure of M82 contains many compact features lying close to a line in p.a. 65° which is close to the optical axis direction (62°) as determined by Burbidge, Burbidge, and Rubin (1964). The most conspicuous is a strong unresolved source which was previously observed by Wilkinson (1971), and identified as component no. 3 in the preliminary list of Kronberg *et al.* The present map has a general similarity to a radio map at 6 cm published recently by Hargrave (1974). We also find, in agreement with the latter, that the 3.7 cm radio emission is well confined to the axis of M82, and that there are no radio components above or below the boundaries of the main radio source (Fig. 1).

We have also mapped the linearly polarized emission at 8085 MHz. It is not displayed in Figure 1, since no linear polarization was detected down to the limiting sensitivity of ~ 0.3 mJy per beam (~ 1.3 K)—a limit which is considerably lower than that set by any previous measurements. Instead, in Figure 1 we show local upper limits to the degree of linear polarization on the scale of one beamwidth, which are of order 1 to 4 percent along the main ridge of radio emission. In addition to limiting the *local* degree of polarization, we measure an upper limit $m \leqslant 0.8$ percent for the radiation visible at the shortest interferometer baselines, that being 85 percent of the integrated flux density. An even lower limit of $m \leqslant 0.3$ percent obtains for the total radiation (1.9 Jy) visible in Figure 1. These results conflict with the integrated polarization of 5.9 ± 3 percent at $\lambda 3.75$ cm quoted by Hobbs and Haddock (1967).

Our results show that the 8085 MHz radio emission in M82 exhibits a remarkably low polarization on all size scales down to half the restored beamwidth (1″.1) which corresponds at the distance of M82 to ~ 17 pc. A possible explanation for the lack of polarization at 3.7 cm could allow areas of aligned magnetic field, but have the entire radio source filled with ionized gas of sufficient density ($N_e \gtrsim 1$ cm^{-3}) to thoroughly depolarize the radio source at $\lambda 3.7$ cm by differential Faraday rotation (we assume the equipartition magnetic-field value of 3×10^{-5} gauss). However, the same electrons would also cause a low-frequency turnover in the integrated radio spectrum at $\nu \approx 20$ MHz (for which there is as yet no evidence), and fluctuations of N_e should allow some local regions to appear polarized at $\lambda 3.7$ cm, contrary to the present observations. Other ordered-field models can be contrived, but these seem unlikely. Whether or not differential Faraday rotation is occurring at $\lambda 3.7$ cm within or around the source, it is most likely that the magnetic field within the M82 radio source is highly disordered on all size scales down to $\lesssim 20$ pc. Our new low polarization limits at 3.7 cm suggest that, whatever the source of energy is in M82, its effect must be to randomize the interstellar magnetic field very effectively.

In Table 2 we give a list of the local peaks of radio emission at 8085 MHz. Since there are many small-scale radio features, we have used a short-form nomen-

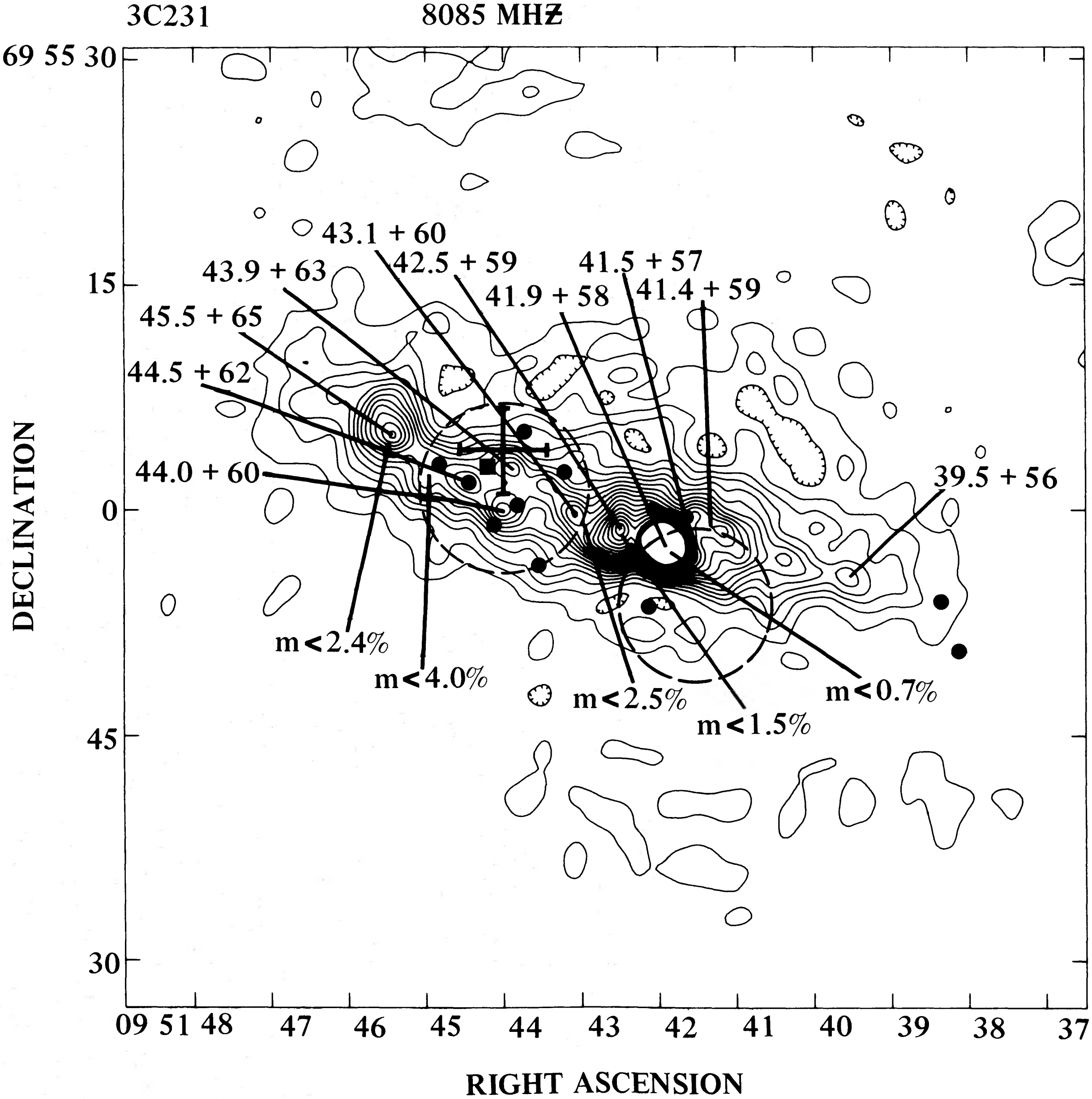

FIG. 1.—Radio map at 8085 MHz and 2″.2 resolution of the radio source in M82. Upper limits to the degree of linear polarization on the scale of one beamwidth are shown at various positions. Discrete components (Table 2) are labeled by their positions relative to $\alpha = 09^h51^m00^s.0$, $\delta = 69°54'00''.0$. The contour interval is 3.94 mJy beam^{-1} (14.9 K). *Circles*, the positions and approximate dimensions of M82-I and M82-II as given by Recillas-Cruz and Peimbert (1970) from Hα observations. *Square*, position of the optical nucleus (error bars not shown) as determined by Burbidge *et al.* (1964); *cross*, position of the center of the 10 μ source (Kleinmann and Low 1970).

clature in column (1), consisting of the seconds (s) and arc seconds (″) of the coordinates of the feature, measured with respect to $\alpha_{1950.0} = 09^h51^m00^s.0$, $\delta_{1950.0} = 69°54'00''.0$. Future intercomparison of features measured in different wavebands will then be easier, since the component names contain their positions to within 0″.5. Columns (2) and (3) give the position, columns (4), (5), and (6) list the spectral index, angular size, and flux density insofar as they can be determined. The upper limits to the degree of linear polarization are given in column (7), and column (8) contains other comments. Since the radio substructure is very complex, it is clearly impossible to isolate all of the small-scale components, and the list in Table 2 is limited to only the few most prominent features, and smaller unresolved peaks of radio emission whose flux

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TABLE 2

LIST OF SMALL-SCALE RADIO FEATURES IN THE NUCLEUS OF M82

Feature Name (1)	Position (1950.0) α (2)	Position (1950.0) δ (3)	Spectral Index (4)	Angular Size (arcsec) (5)	Flux Density mJy (6)	Linear* Polarization (%) (7)	Comments (8)
39.5+56....	09ʰ51ᵐ39ˢ.55	+69°54′55″.7	...	~3	~ 5	...	
41.4+59....	09 51 41.4	+69 54 59.1	...	~2.5 in p.a. 60° × < 2	~15	...	May be two separate components.
41.5+57....	09 51 41.49	+69 54 56.9	...	< 2	~ 8	...	
41.9+58....	09 51 41.95	+69 54 57.5	−1.0	< 0.5	110 ± 20	< 0.7	Source No. 3 of Kronberg *et al.* 1972, "A" of Hargrave 1974. Spectrum and angular size discussed in § 4 of text.
42.5+59....	09 51 42.47	+69 54 58.7	...	~2	~40	< 2	Source No. 5 of Kronberg *et al.* 1972, "B" of Hargrave 1974.
43.1+60....	09 51 43.08	+69 54 59.7	...	< 2	~11	...	Source No. 7 of Kronberg *et al.* 1972.
43.9+63....	09 51 43.90	+69 55 02.8	...	< 2	~ 4	...	} May be one extended feature in p.a. ~150°.
44.0+60....	09 51 44.03	+69 55 00.1	...	< 2	~11	...	}
44.5+62....	09 51 44.48	+69 55 01.9	...	< 2	~11	...	
45.5+65....	09 51 45.50	+69 55 05.5	...	2.5 in p.a. ~40° × < 2	55 ± 10	< 4	Source No. 9 of Kronberg *et al.* 1972 and "C" of Hargrave 1974.

* These are percentages only of the flux densities in column (6), and are therefore slightly higher than the upper limits shown in Fig. 1.

density can be specified. Further observations of the brightest compact component, 41.9+58, are discussed in § IV.

As previously found (Kronberg *et al.* 1972; Hargrave 1974), there is very little correspondence with detailed features in the optical and near-infrared. Only features 44.0+60 and 44.5+62 appear close to three infrared knots superposed on M82-I (Fig. 1), and it is quite possible that these occur by chance. The improved sensitivity of the present radio map over the earlier radio data of Kronberg *et al.* enables us to place a new upper limit at λ3.7 cm of ~8 mJy on the radio flux from any of the infrared knots found by van den Bergh (1971). In Figure 2 we show a superposition of the supersynthesis radio map, and 200-inch (5 m) telescope photographs in the red (shown negative) and infrared (shown positive) taken by R. Racine and S. van den Bergh, respectively. The lack of detailed correspondence is not surprising, since the galaxy is optically thin at 8085 MHz, whereas the nucleus suffers an extinction of ~3 mag in the visual band (O'Connell 1970). Some of the brighter infrared knots can be seen in Figure 2, as can the two large H II regions (M82-I and M82-II) discussed by Recillas-Cruz and Peimbert (1970). Using the parameters determined by the latter authors from the Hα emission, we expect a brightness temperature of ~50 K at 8085 MHz at the center of each region (assuming a homogeneous distribution and electron temperature of 10,000 K). This level of emission is unfortunately swamped by the nonthermal emission superposed on M82-I. An exception is the southern portion of M82-II, which lies outside the main ridge of radio emission (Fig. 2), and the expected surface brightness in this part is 30–50 K, which is very close to the observed surface brightness at ($\alpha = 09^h51^m41^s.7$, $\delta = 69°54'51''$) after allowing for the missing 0.5 Jy smooth component of emission. The upper limits which the observed radio brightness temperature places on $N_e^2\, L\, T_e^{-0.5}$ [$N_e \approx 70$ cm^{-3}, $L = 130$ pc (the line-of-sight depth) and $T_e = 10{,}000$ K] for a homogeneous cloud are therefore similar to those derived by Recillas-Cruz and Peimbert. Since the component 41.9+58 is located near the northern edge of M82-II or possibly outside of it (Fig. 2), it is unlikely that it is the source of energy responsible for the excitation of M82-II. The properties of this compact component receive further discussion below.

IV. SPECTRUM, POLARIZATION, AND ANGULAR SIZE OF THE SOURCE 41.9+58

The phase stability of the Jodrell Bank Mark I-III interferometer at 962 MHz was sufficient to locate the strongest of the compact components to within 2″ of source 41.9+58. It is therefore almost certainly the same source.

The plots of fringe amplitude against hour angle show weak but definite variations at 408, 962, and 1663 MHz for all baselines between 70,000λ and 172,000λ. This is expected from the closeness to 41.9+58 of several other compact features (Fig. 1). There was insufficient baseline coverage at the three lower frequencies to produce a detailed model at these frequencies to compare with Figure 1, although the variations of fringe amplitude with hour angle were consistent with a modulation of the fringes due to the brightest component (41.9+58) by another feature ~4″ away in p.a. ~60°, in the vicinity of 42.5+59, which has the second-highest surface brightness in Figure 1.

By combining these observations with the 8085 MHz flux density and the 5 GHz measurement by Hargrave (1974), we are now able to better define the radio spectrum of 41.9+58, which we have isolated as an unresolved source (<0″.5) at all baselines between ~50,000λ and ~200,000λ between 408 MHz and 8085 MHz (Table 3).

The spectrum is shown in Figure 3, in which the low-frequency cutoff is well defined. The spectral index is ⩾+2 at 408 MHz, and −1.0 ± 0.2 between 1660 MHz and 8085 MHz. Assuming that the latter slope represents the intrinsic spectrum, the source has an optical depth $\tau = 1$ at 650 ± 100 MHz. 41.9+58 is unpolarized to an upper limit of 0.7 percent at 8085 MHz.

At baselines of between 4 and 7 × $10^5\lambda$, the compact source appears to be partly resolved. At least one component has an angular size of ≤0″.08 (≤1.2 pc) and a flux density of ~0.35 Jy at 1666 MHz. The

TABLE 3

FLUX DENSITIES OF THE COMPACT RADIO COMPONENT (41.9+58) IN THE NUCLEUS AT M82

Frequency (MHz)	Flux Density (mJy)*	Epoch	Reference
408	190 ± 20	1973 Nov.	Present paper
962	530 ± 50	1973 Nov.	Present paper
1423	600 ± 100	1969 Dec.–1970 Feb.	Wilkinson 1972
1663	550 ± 50	1972 Dec.	Present paper
5000	180 ± 10	1973 May–Nov.	Hargrave 1974
8085	110 ± 20	1971 Feb.–1972 May	Present paper

* 1 mJy = 10^{-29} W m^{-2} Hz^{-1}.

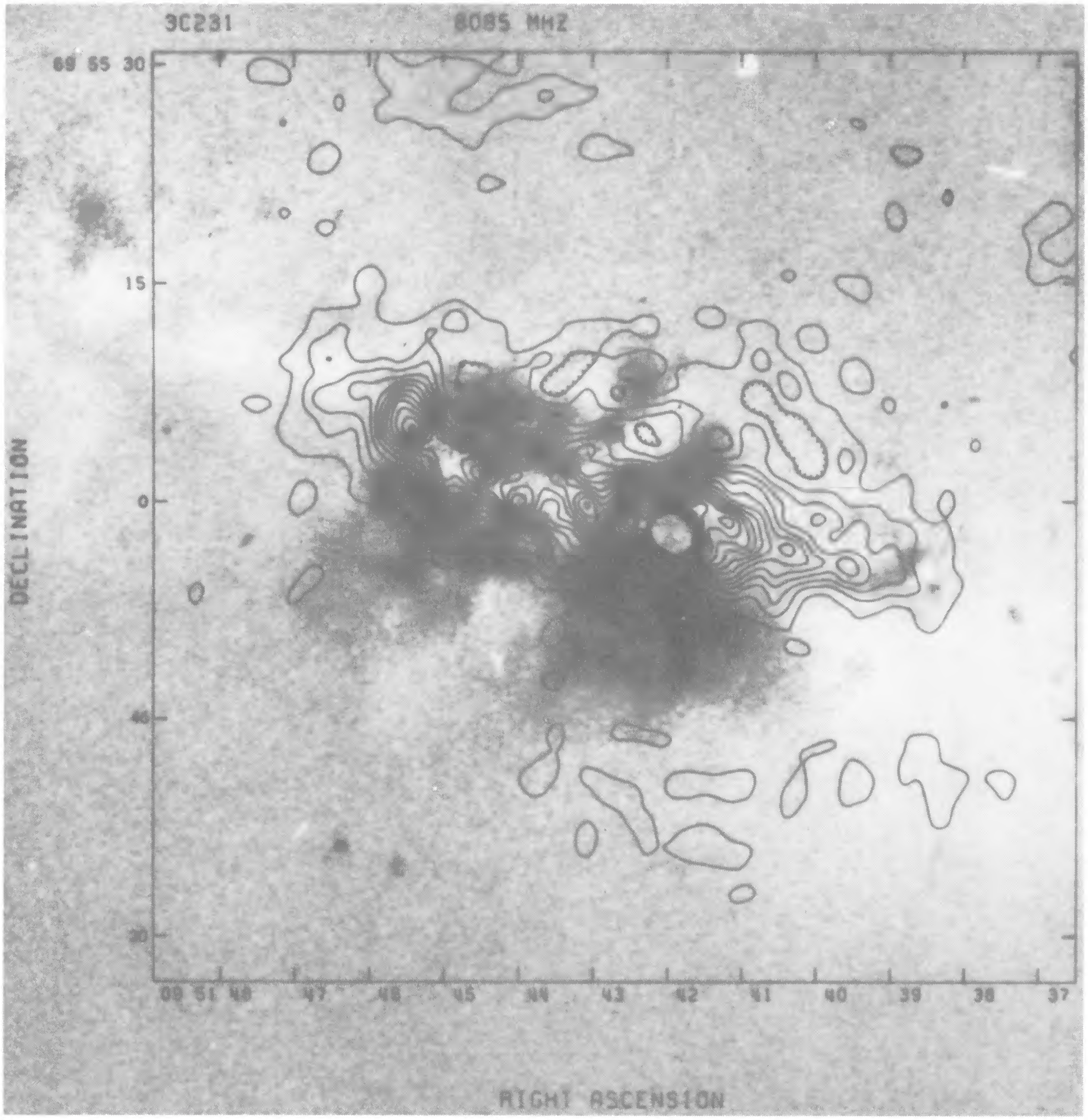

FIG. 2.—The 8085 MHz supersynthesis radio map superposed on an infrared-red composite photograph in which sources prominent in the infrared are bright and the red sources are dark. The red plate (103aE-emulsion and RG-2 filter) was taken by R. Racine and the infrared (IN emulsion and Wr 89B filter) by S. van den Bergh, both with the Hale Observatories 200-inch (5 m) telescope. The exposure was adjusted to show the two large H II regions in isolation from other emission. Some of the infrared knots are also visible.

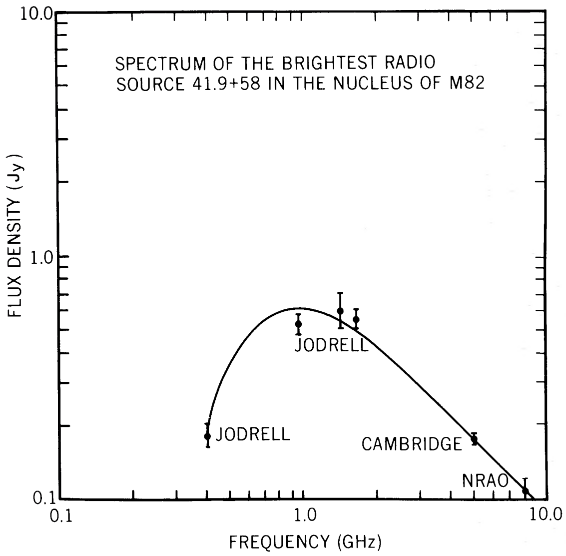

FIG. 3.—The radio spectrum of 41.9+58. The solid line assumes foreground absorption in an ionized plasma. For this curve, $\tau = 1$ at 644 MHz.

remaining 0.20 Jy comes either from a second component also <0".08, or an extended component between ~0".1 and 0".4 in size. The flux densities in Figure 3 represent the combination of these features which are still unresolved at baselines smaller than 200,000λ.

V. DISCUSSION

If we assume that the low-frequency turnover in the spectrum of 41.9+58 is due solely to foreground H II absorption, then the measurement of $\tau = 1$ at ~650 MHz and an assumption of a constant temperature of 10,000 K gives an emission measure ($\int N^2 dl$) of 7.9×10^5 cm^{-6} pc for the absorbing material. Such an emission measure cannot be due to M82-II alone because 41.9+58 is situated close to the edge of M82-II and the path length through the H II is therefore too small. If 41.9+58 is halfway into a disk of radius 300 pc (corresponding to the semi-major axis of the whole radio source), then a *mean* N of ~50 cm^{-3} would give the required emission measure. The fact that we do not see Hα corresponding to this density of H II may well be due to the obscuration known to exist in regions close to the nucleus, and so foreground free-free absorption is still a plausible explanation for the observed turnover. The solid line in Figure 3 is the expected spectrum if this is the case.

The large mass of ionized hydrogen required by this explanation of the turnover would imply that M82-I and II represent only a fraction of the massive H II regions in this galaxy. Recillas-Cruz and Peimbert's estimate of $\sim 1.8 \times 10^4$ main sequence O6 stars required to ionize M82-I and II (already many more than exist in our Galaxy) may therefore be only a fraction of the total number of such stars in M82. As Hargrave (1974) has pointed out, the luminosity of such a large number of young hot stars would be sufficient to power the infrared source (by reradiation from dust particles).

The position of 41.9+58 lies ~13" away in p.a. 246° from the position of the nucleus adopted by Burbidge *et al.* (1964) (Fig. 1), and it also lies somewhat to the west of the center of the brightness distribution at 8085 MHz. It may be a nuclear radio source analogous to compact radio sources situated at the nuclei of other galaxies. Alternatively, it may be the most recent of several supernovae which one might expect to be associated with the large number of hot young stars in the nucleus and with the recent accelerated burst of star formation suggested by van den Bergh (1971). The component which is ≤1.2 pc in size has a radio luminosity 4.8×10^{37} ergs s^{-1} (integrated between 10^7 and 10^{10} Hz) and a minimum total energy in relativistic electrons $\leq 2 \times 10^{49}$ ergs. This is not much greater than that estimated by Rosenberg (1970) for Cas A (1.1×10^{49} ergs) and would be equal to Cas A if its size were 0.5 pc; such a size would also place 41.9+58 close to the Σ-D relationship for known supernova remnants (Ilovaisky and Lequeux 1972). We conclude that 41.9+58 could be a supernova remnant but more energetic, and in an earlier phase of its expansion. Its radio luminosity is about 200 times that of Cas A.

Since M82 appears to contain a very large number of massive stars, it is conceivable that the supernova rate is considerably higher than in our own Galaxy, and may be as high as approximately one every 10 yr, which is sufficient to account for the energy requirements of the entire radio source. Such a rate would imply that many of the other regions of enhanced brightness listed in Table 2 are also supernova remnants. These have a luminosity about an order of magnitude greater than Cas A at 8085 MHz, and are similar in radio luminosity to SN 1970g in M101 (Goss *et al.* 1973). Such a large number of energetic supernovae would imply many weaker ones as well. This possibility seems consistent with the very large number of O and B stars which is inferred to ionize the giant H II regions near the nucleus (Recillas-Cruz and Peimbert 1970). It would suggest that the stellar mass function contains an abnormal number of very massive stars which, in the dense ambient interstellar medium ($N_e \approx 50$ cm^{-3} is consistent with the low-frequency turnover in 41.9+58), may generate a much higher radio luminosity than a typical supernova remnant in an Sb-Sc galaxy. Most supernovae would be invisible optically because of the heavy obscuration of the M82 nucleus. If multiple expanding supernova shells are producing the relativistic electrons, we would expect the magnetic field to be highly turbulent on an interstellar scale, consistent with our polarization results in § III. We therefore find the multiple-supernova explanation for the M82 radio source to be an attractive one.

To test this hypothesis it will be important to define any variation in flux density and, if possible, angular size in 41.9+58. The time base of our flux monitoring program will soon be sufficiently long to establish whether or not 41.9+58 is variable. VLBI systems with baselines $\geqslant 10^6\lambda$ are now sufficiently sensitive that, within the near future, it should be possible to establish the angular size and rate, if any, of expansion.

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P. P. KRONBERG: University of Toronto, Scarborough College, Toronto, MIC 1A4, Canada; presently at Max-Planck-Institut für Radioastronomie, Bonn, Federal Republic of Germany

P. N. WILKINSON: Owens Valley Radio Observatory, California Institute of Technology, Pasadena, CA 91125