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RADIO-SYNTHESIS OBSERVATIONS OF PLANETARY NEBULAE

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ABSTRACT

Continuum radio observations of planetary nebulae are presented with angular resolutions as small as $\sim 2''$. These observations were made at NRAO at 2.7 and 8.1 GHz with aperture-synthesis techniques. Detailed radio maps are presented for 14 nebulae and results of observations are also given for many others. Generally it is found that several nebulae show a "double-source" structure in addition to a normal thin shell. Substantial fine structure is observed on a scale of a few seconds of arc, and central brightness depressions are evident. Emission measures as high as 6.7×10^7 cm^{-6} pc are indicated.

Subject headings: planetary nebulae — radio sources

I. INTRODUCTION

In order to study the true spatial structure of planetary nebulae, we must have a knowledge of the mass distribution inside the nebulae. This can be accomplished in part by observing the detailed surface-brightness distribution of planetary nebulae. Such studies are limited and have been performed mainly at optical wavelengths in the emission lines of atoms and ions. The apparent sizes of many of the interesting planetary nebulae are in the range $\sim 10''$ to $\sim 30''$, hence optical observations with angular resolutions of $1''$–$2''$ can be very useful as discussed by Aller (1956) and Gurzadyan (1969). The overwhelming difficulty in using optical observations is the complete lack of knowledge of the *extinction distribution* over the projected areas of the observed nebulae, which is primarily local to the objects. Recent infrared observations of planetary nebulae clearly show the importance of the spatial distribution of the extinction (Knacke and Dressler 1973).

At radio wavelengths the interstellar extinction is completely negligible and the true energy distribution of the nebulae can be observed. The difficulty at radio waves in obtaining radio maps of planetary nebulae has been the relatively large beam widths compared with the nebular sizes. However, narrow beams at radio waves can be achieved by aperture synthesis. Such a technique was used by Elsmore (1968) who observed several prominent nebulae with a beam as narrow as $23''$ at 1407 MHz. These results did not show any significant radio structure since the beam size was of the order of the sizes of the observed sources. More recently Scott (1973) and Balick, Bignell, and Terzian (1973) have been able to map NGC 7027 with almost optical resolutions (half-power beam width $\simeq 2''$). Kaftan-Kassim (1973) has also produced radio maps of a few nebulae with beams of the order of $\sim 8''$. In this study we present aperture-synthesis observations of a large sample of planetary nebulae at 2695 and 8085 MHz performed with half-power beam widths as small as $\sim 2''$. The observed continuum radio emission is almost totally due to free-free transitions in the ionized gas (Terzian 1968). Since nebulae are composed primarily of ionized hydrogen, the observed brightness distributions at radio waves refer to the hydrogen distribution.

In this paper we present synthesized radio maps for 14 planetary nebulae (referred to in this paper as class I objects), and report on synthesis observations on eight others (class II). We also report on partial observations on many other planetaries. The following sections describe the observational procedures and data reductions. We also discuss the structure of planetary nebulae and give some general conclusions.

II. OBSERVATIONS AND DATA REDUCTION

The observations were performed using the National Radio Astronomy Observatory (NRAO) three-element interferometer at observing frequencies of 2695 MHz (11 cm) and 8085 MHz (3.7 cm) during 1972 November and December. The instrument and its performance have been described in detail elsewhere (Balick 1971; Hjellming 1973). Briefly, the instrument consists of three 85-foot (25.4-m) telescopes (each of effective area of ~ 300 m^2) equipped with degenerate double side-band receivers of noise temperature $\sim 90°$ and 125° K at 2.7 and 8.1 GHz, respectively. In 30 s the rms noise of the real and imaginary components of the measured visibility function are of the order of 50 m.f.u. (1 f.u. = 10^3 m.f.u. = 10^{-26} W m^{-2} Hz^{-1}) at both frequencies. The telescopes can be moved along a linear track (orientation 28° north of east) to form up to 16 different telescope separations from 100 to 2700 meters. For the present experiment the 3, 6, 8, 9, 12, 15, 18, 19, 21, 24, and 27 $\times$ 10^2 m spacings were used.

The data were corrected and calibrated using the standard automated reduction system now available at the NRAO. From observations of calibration sources and from repeatability tests, we have determined that calibration errors result in only inconsequential distortions of the synthesis maps. A quantitative description of the calibration procedure and the effects of calibration errors can be found in the references cited above.

The synthesis maps were generated from the data by the standard Fourier inversion programs available at the NRAO. The maps generated in this fashion contain sidelobes because of the largely unfilled nature of the synthesized aperture (synthesized apertures, i.e., the (U, V)-plane coverage, for each source, are presented with the synthesis maps below). In order to remove sidelobes, these maps were "cleaned" using a pattern-recognition technique described by Fomalont (1973) and Högbom (1973). The effect of this technique on one of our sources is illustrated by comparing the cleaned maps of NGC 7027 (see below) with their uncleaned counterparts published by Balick *et al.* (1973).

The cleaning process is essentially an aperture-filling technique which can be briefly described as follows: beam patterns are subtracted from the original uncleaned maps until either the residual map is dominated by noise or until a maximum number of sources have been subtracted. Following this subtractive phase, simple elliptical Gaussian components (with the same half-power ellipse as the synthesized beams) are added to the residual map. These Gaussians have the same peak brightnesses and positions as the beam patterns subtracted earlier. Ideally, this map is free of sidelobes; however, in practice, noise or poor projected baseline coverage (especially common at low declinations) can affect the cleaning process. The maps presented here are cleaned to a level of 5 percent of the peak brightness except in a few cases where the background noise exceeds this value.

III. THE OBSERVED SOURCES

A survey of small ($\leqslant 30''$) planetary nebulae previously detected at radio frequencies was initially conducted in order to determine the most promising candidates for extensive study. As the observing proceeded, some sources showed little interesting structure and were replaced by more interesting ones. Complete or nearly complete coverage was obtained on the available telescope spacings for 14 sources whose cleaned maps are presented in figures 1 to 14. These are the so-called class I sources. Other sources for which observations were adequate to ascertain sizes, positions, and flux densities are referred to as class II sources.

Figures 1 to 14 present the 2.7- and 8.1-GHz cleaned maps of the observed planetary nebulae. The figures

TABLE 1

Observed Planetary Nebulae

Nebula	Radio-Map Center		Beam Size (HPBW)		Flux Density* (10^{-26} W m^{-2} Hz^{-1})		Central Star†
	R.A (1950)	Decl. (1950)	8085 MHz	2695 MHz	8085 MHz	2695 MHz	(Spectral Type)
			Class I				
IC 418	$05^h25^m09^s.31$	−12°44′15″.0	15″.3 × 1″.8	45″.8 × 5″.4	1.86	1.69	WC 7
NGC 2392	07 26 13.30	21 00 56.7	4.7 × 2.0	13.1 × 5.3	>0.19	0.28	Of
NGC 2440	07 39 41.00	−18 05 23.0	10.0 × 1.5	30.0 × 4.6	>0.53	>0.49	...
NGC 3242	10 22 21.72	−18 23 11.0	11.6 × 1.9	30.2 × 4.6	>0.80	0.93	Contin.
NGC 6210	16 42 23.55	23 53 29.1	4.1 × 1.8	12.2 × 5.4	>0.32	0.36	Of
NGC 6302	17 10 21.31	−37 02 46.5	6.8 × 2.0	20.3 × 6.0	>3.00	>2.80	...
NGC 6369	17 26 17.65	−23 43 20.0	8.1 × 2.0	20.9 × 4.7	>1.64	1.92	...
NGC 6543	17 58 34.20	66 38 05.3	2.5 × 2.2	7.0 × 6.2	>0.58	0.88	W
NGC 6572	18 09 40.60	06 50 25.0	7.0 × 1.9	21.1 × 5.6	1.28	1.07	W
BD 30−3639	19 32 47.50	30 24 20.6	3.5 × 1.9	10.6 × 5.7	0.78	0.52	WC 9
IC 4997	20 17 51.35	16 34 23.0	4.6 × 2.0	13.8 × 6.0	0.17	0.10	Contin.
NGC 7027	21 05 09.50	42 02 03.1	3.0 × 1.9	8.9 × 5.6	5.90	3.65	Not visible
NGC 7354	22 38 27.90	61 01 28.0	2.7 × 2.1	7.6 × 5.7	>0.25	0.57	...
NGC 7662	23 23 29.20	42 15 35.6	3.5 × 2.0	10.1 × 5.8	>0.50	0.66	Contin.
			Class II				
IC 2003	03 53 10.00	33 43 48.0	24.9 × 1.6	74.7 × 4.8	0.045	0.045	W
VV 29	05 02 48.00	10 38 28.0	43.0 × 1.7	129.0 × 5.2	>0.030	0.045	...
M1-5	05 43 46.10	24 21 00.0	23.9 × 1.7	71.7 × 5.2	0.065	0.065	...
IC 2165	06 19 24.40	−12 57 47.0	18.0 × 2.0	54.0 × 6.1	0.260	0.270	...
M1-6	06 33 11.50	−00 03 09.0	41.7 × 3.1	125.0 × 9.2	0.075	0.075	...
M1-9	07 02 42.40	02 51 36.0	5.6 × 2.3	16.8 × 7.1	0.035	0.035	...
M1-11	07 09 05.90	−19 46 01.0	10.0 × 1.6	30.0 × 4.8	>0.200	>0.150	...
M1-16	07 34 55.70	−09 32 05.0	54.0 × 6.0	162.0 × 6.1	0.030	0.030	...

* Errors at both frequencies are ±0.010 f.u. for class I objects and ±0.015 f.u. for class II objects.

† From Böhm (1968) and Aller (1968): W = Wolf-Rayet type star; Of = continuous spectrum with narrow emission lines and possibly also absorption features; Contin. = continuous spectrum with no emission or absorption lines.

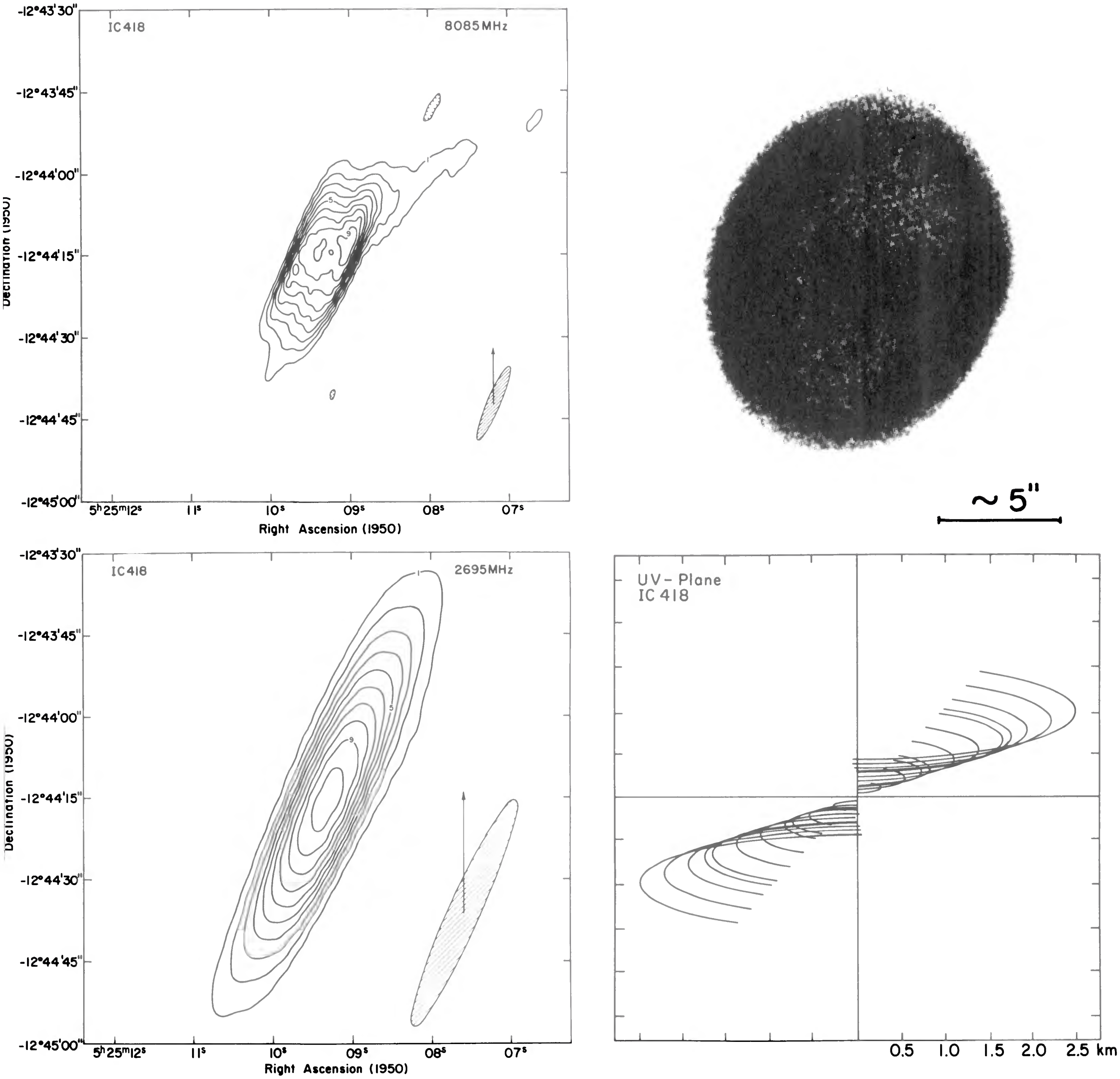

FIG. 1.—The radio brightness distribution at 2.7 and 8.1 GHz for IC 418. The radio maps also show the synthesized beams and their position angles. The contour spacings correspond to 48.0° and 13.6° K of brightness temperature (T_b) at 2.7 and 8.1 GHz, respectively. The figure also shows the (U, V)-plane coverage for IC 418 and an optical photograph from Minkowski (1953). (North is up and east is to the left for all photographs.)

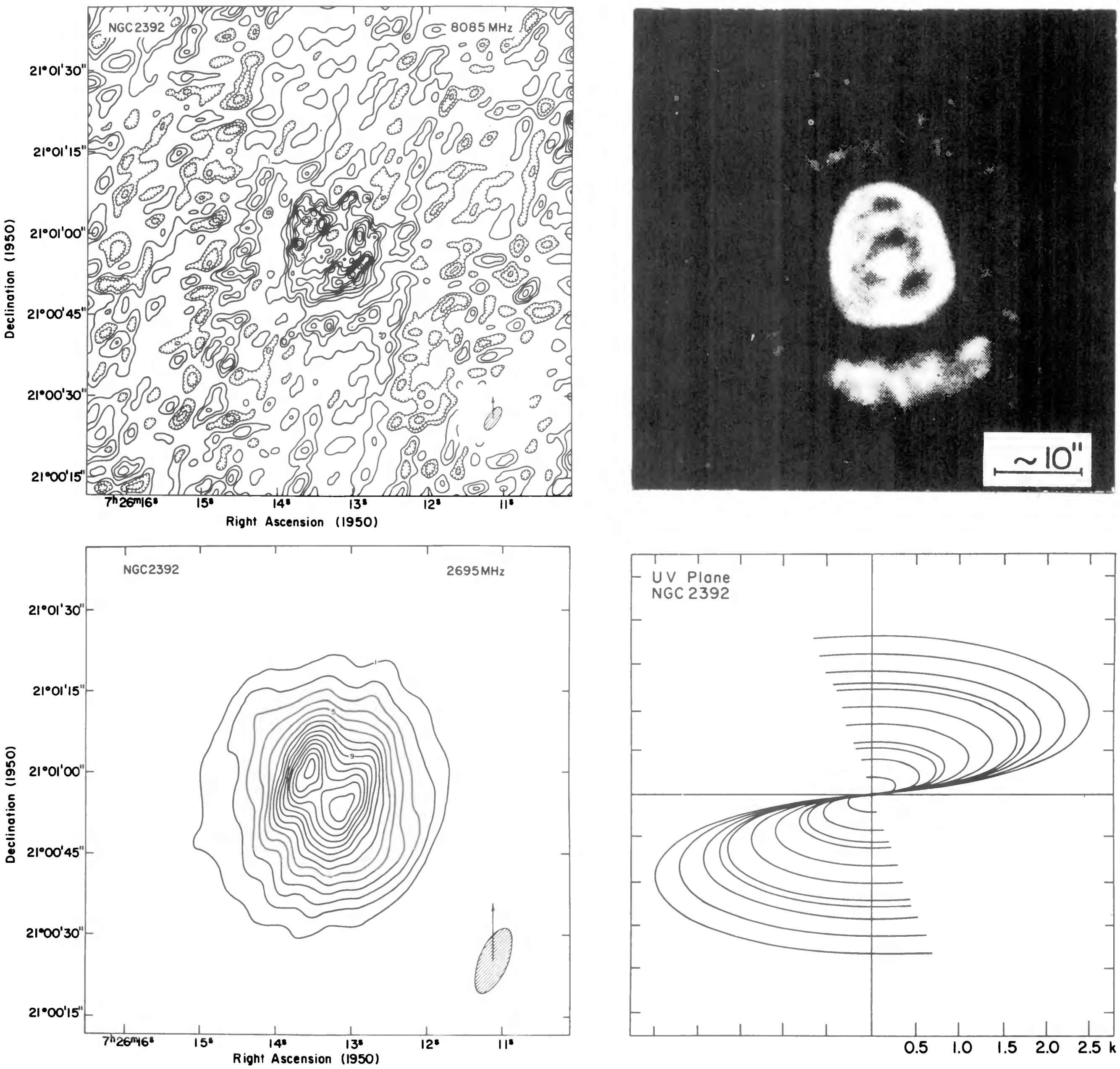

FIG. 2.—Same as fig. 1 for NGC 2392. Contour spacings are 5.2° and 0.96° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Aller (1971).

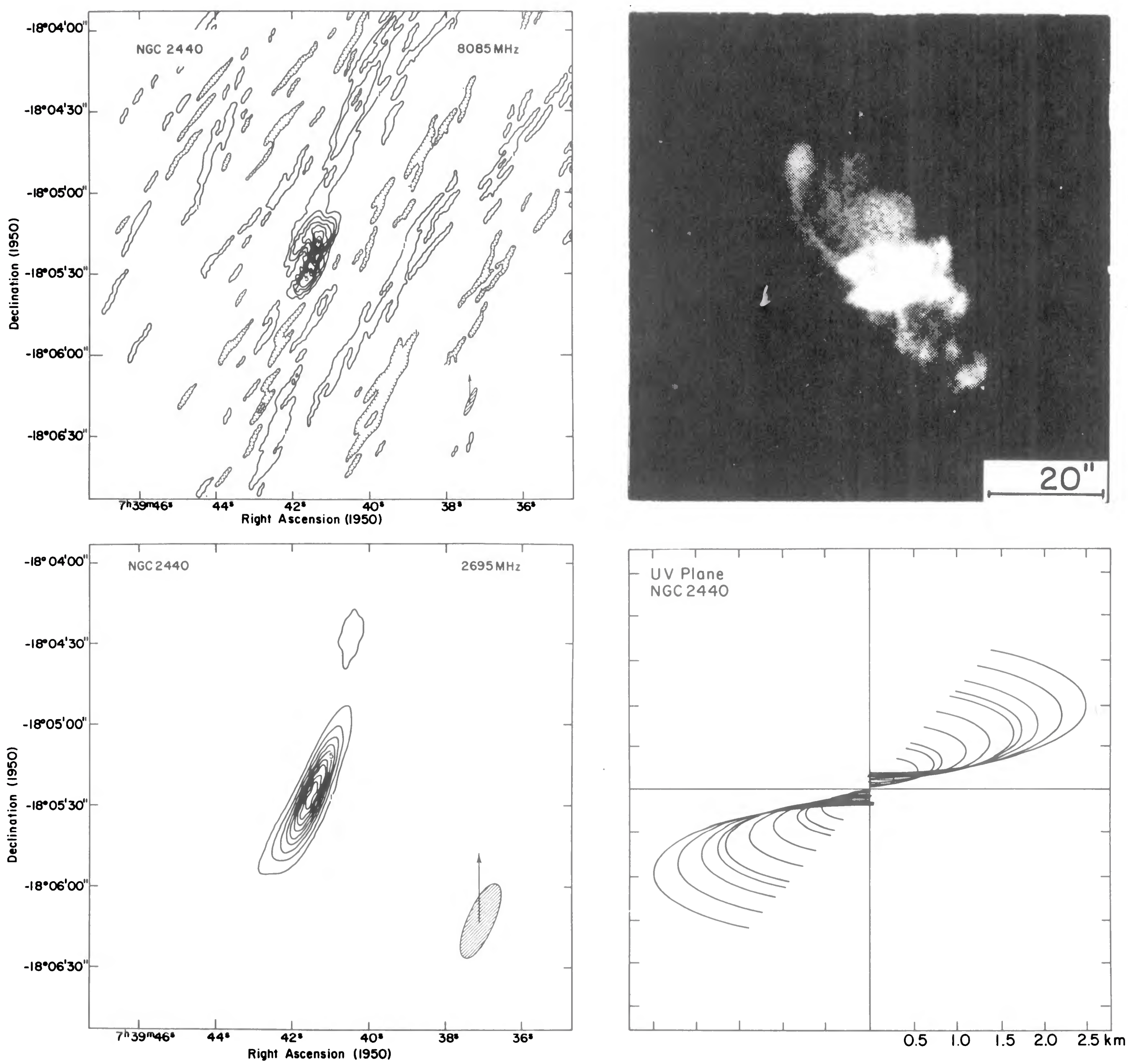

FIG. 3.—Same as fig. 1 for NGC 2440. Contour spacings are 17.2° and 3.7° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918).

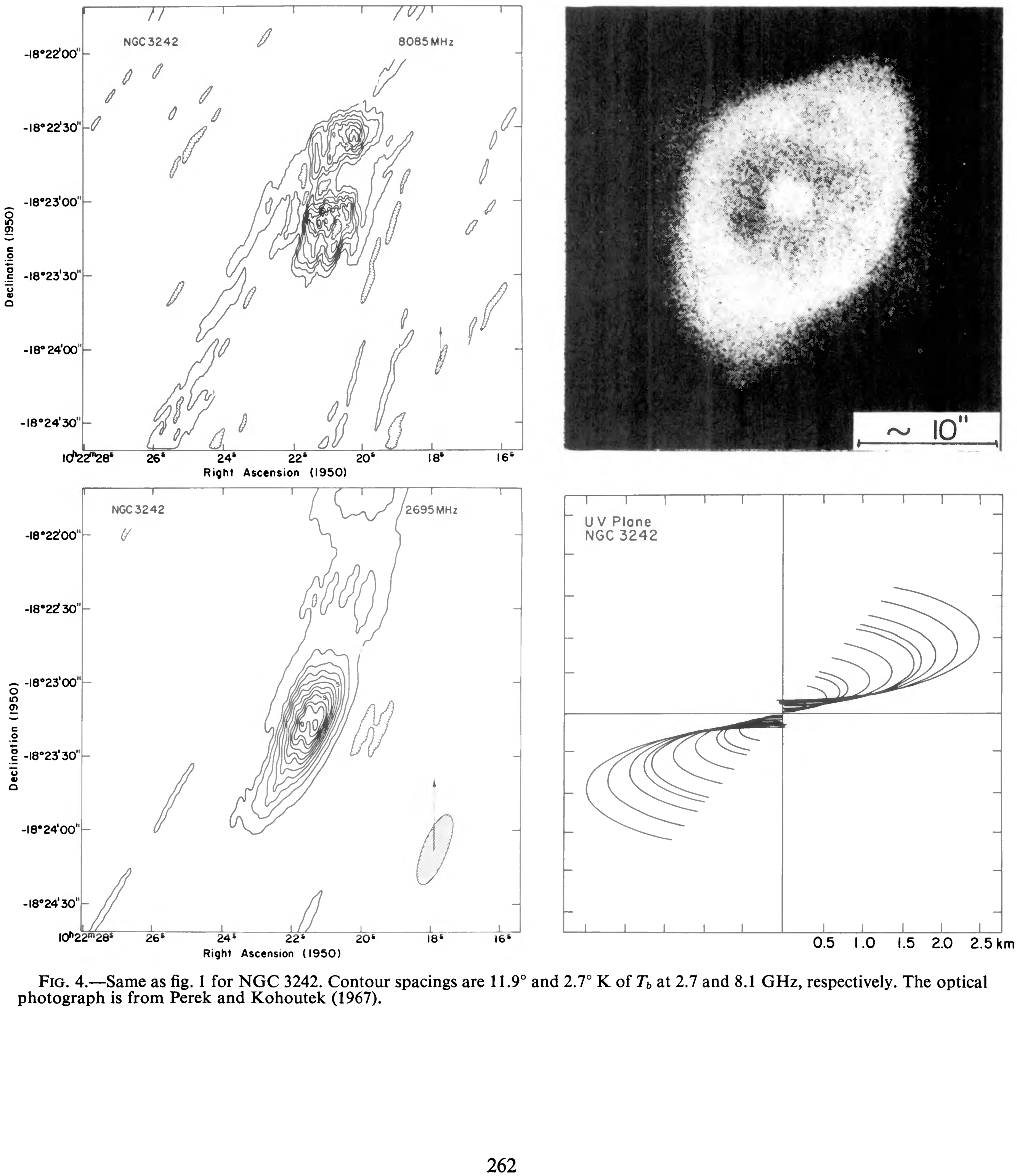

FIG. 4.—Same as fig. 1 for NGC 3242. Contour spacings are 11.9° and 2.7° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Perek and Kohoutek (1967).

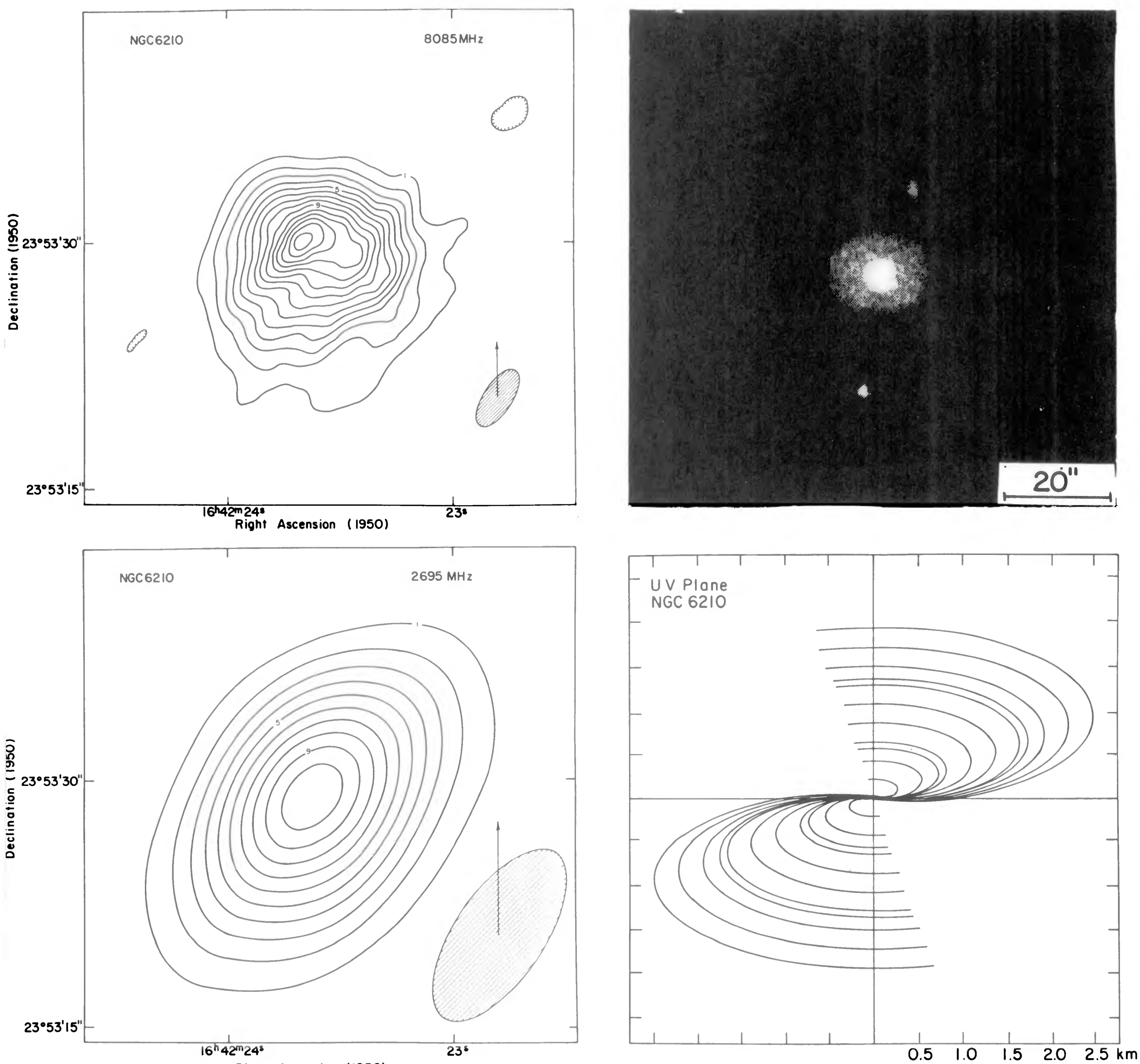

FIG. 5.—Same as fig. 1 for NGC 6210. Contour spacings are 37.3° and 6.3° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918); Aller and Liller (1968) give a series of photographs of NGC 6210 taken by Minkowski.

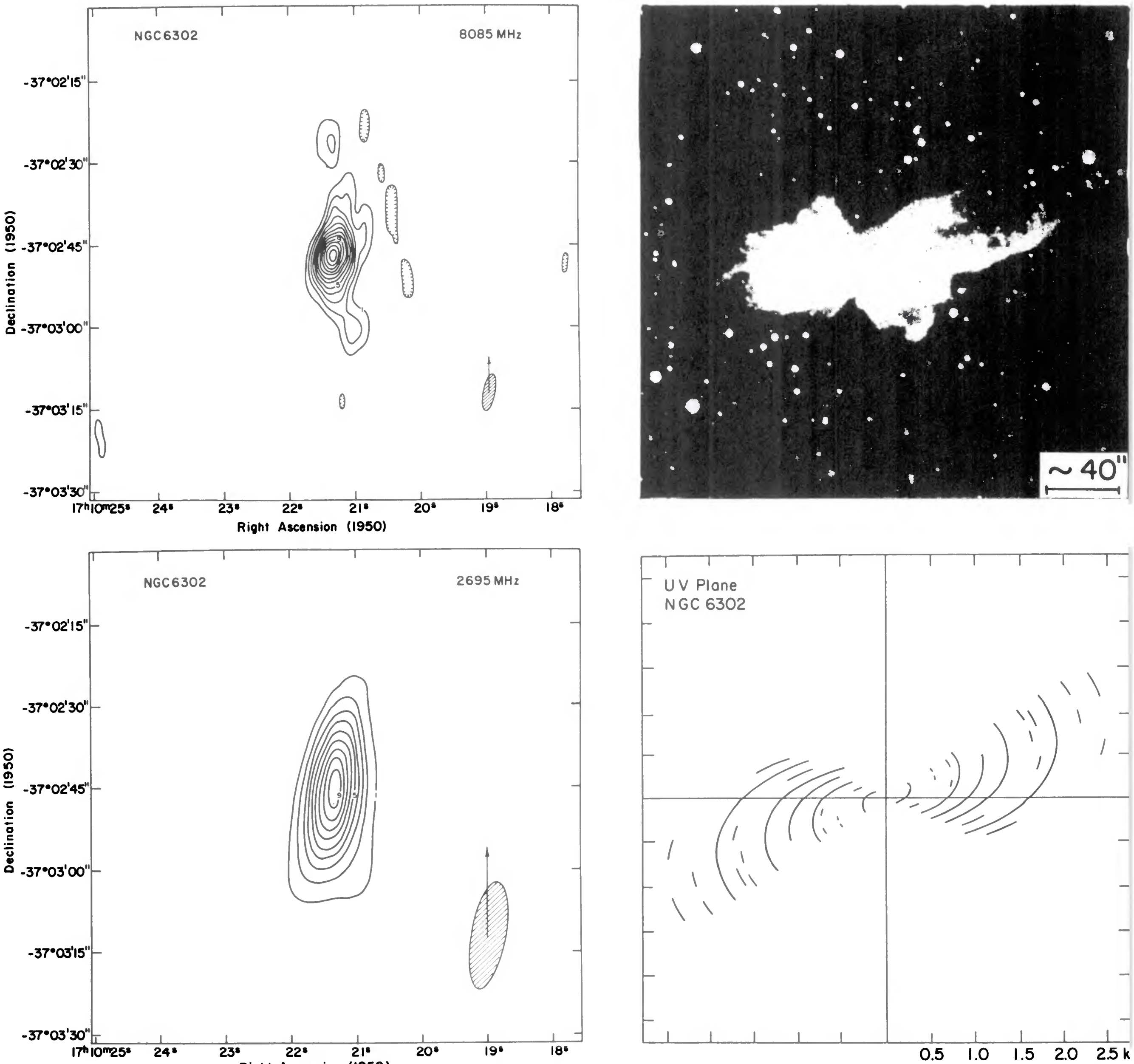

FIG. 6.—Same as fig. 1 for NGC 6302. Contour spacings are 223° and 70° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Aller (1971) taken by Minkowski and Johnson.

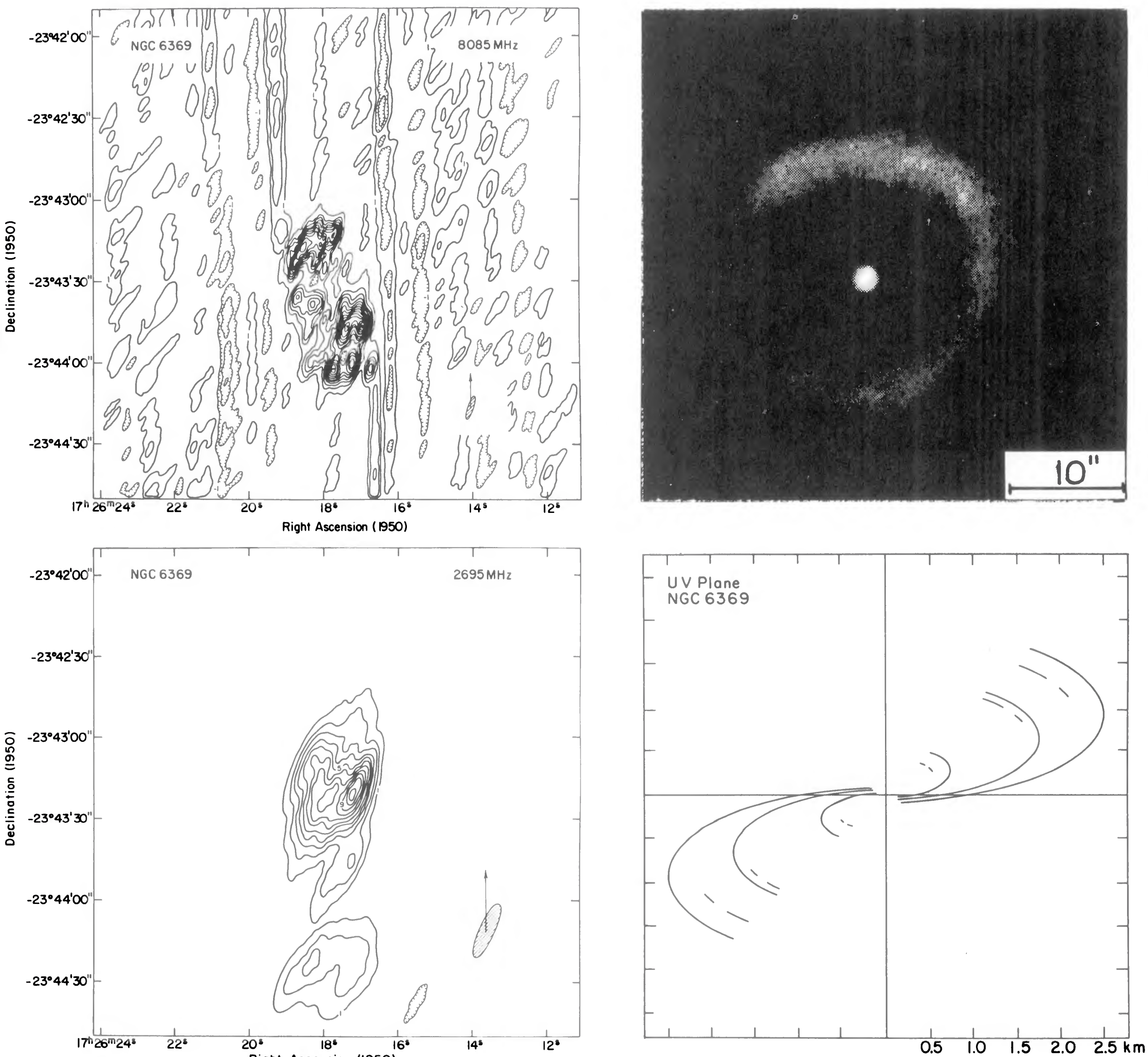

FIG. 7.—Same as fig. 1 for NGC 6369. Contour spacings are 30.5° and 5.4° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918). The 8.1-GHz observations show confusion problems due to a nearby radio source.

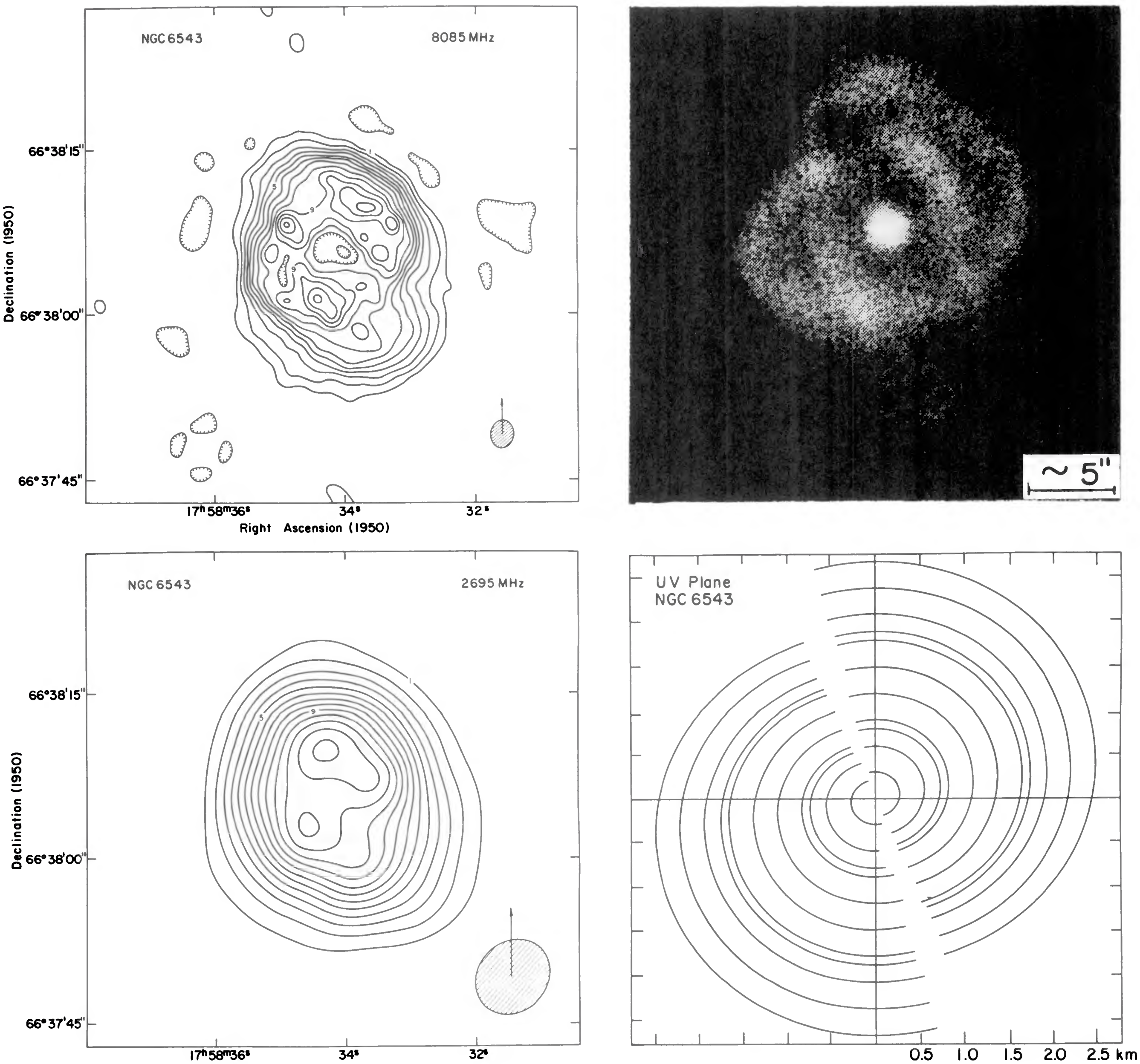

FIG. 8.—Same as fig. 1 for NGC 6543. Contour spacings are 48.8° and 6.7° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Münch (1968).

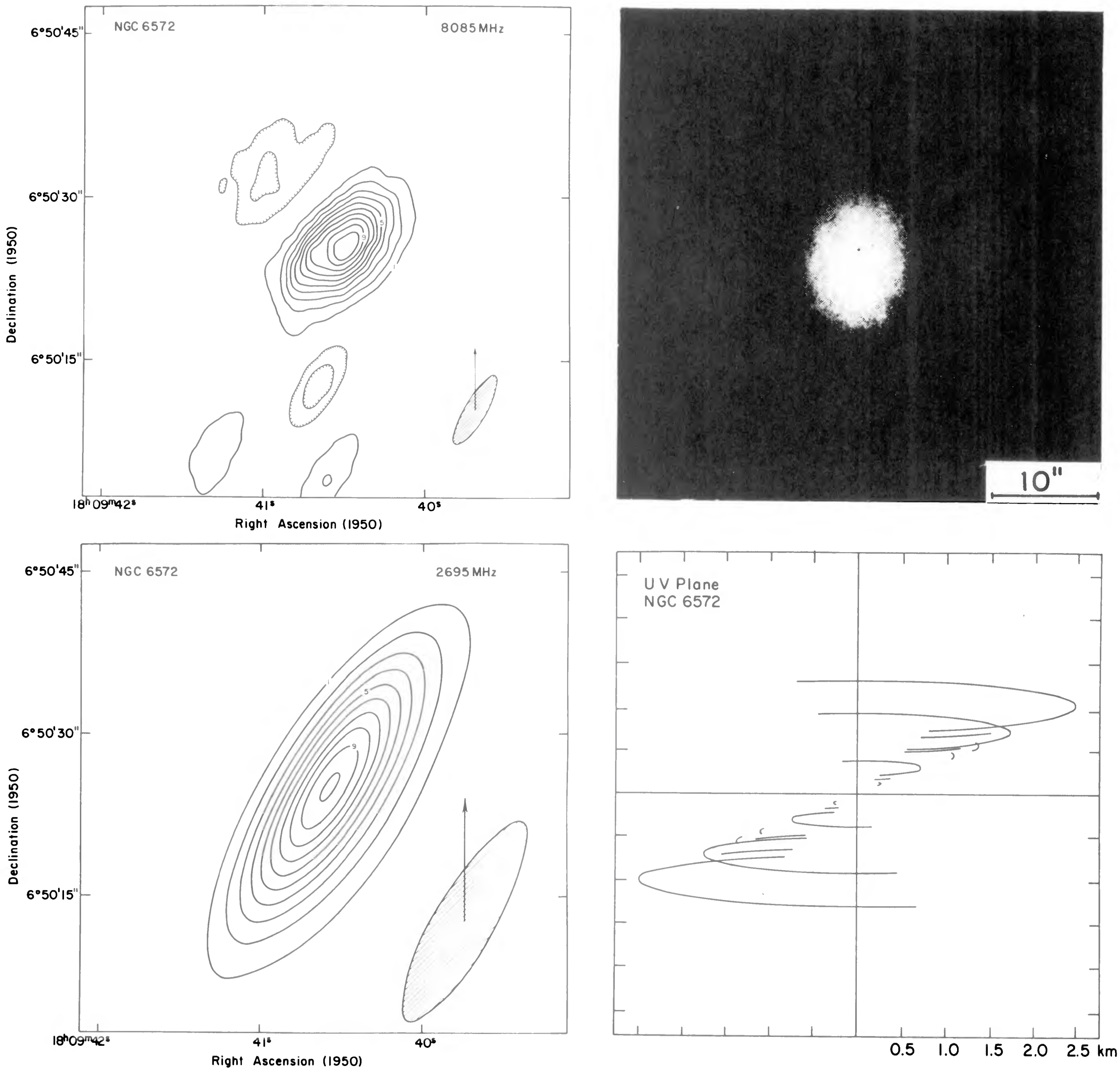

FIG. 9.—Same as fig. 1 for NGC 6572. Contour spacings are 97.1° and 32.8° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918).

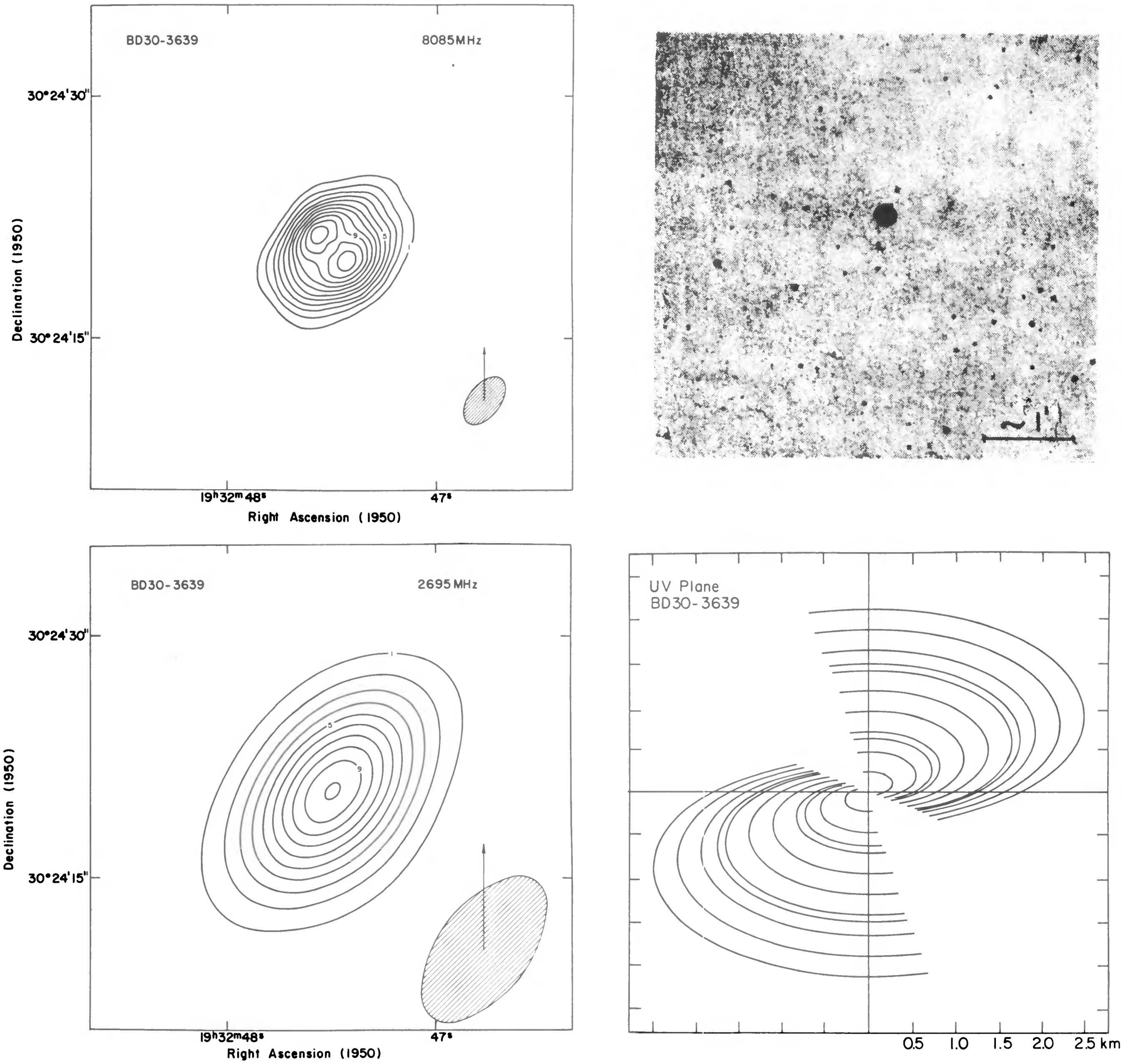

FIG. 10.—Same as fig. 1 for BD 30−3639. Contour spacings are 102° and 35.2° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Perek and Kohoutek (1967).

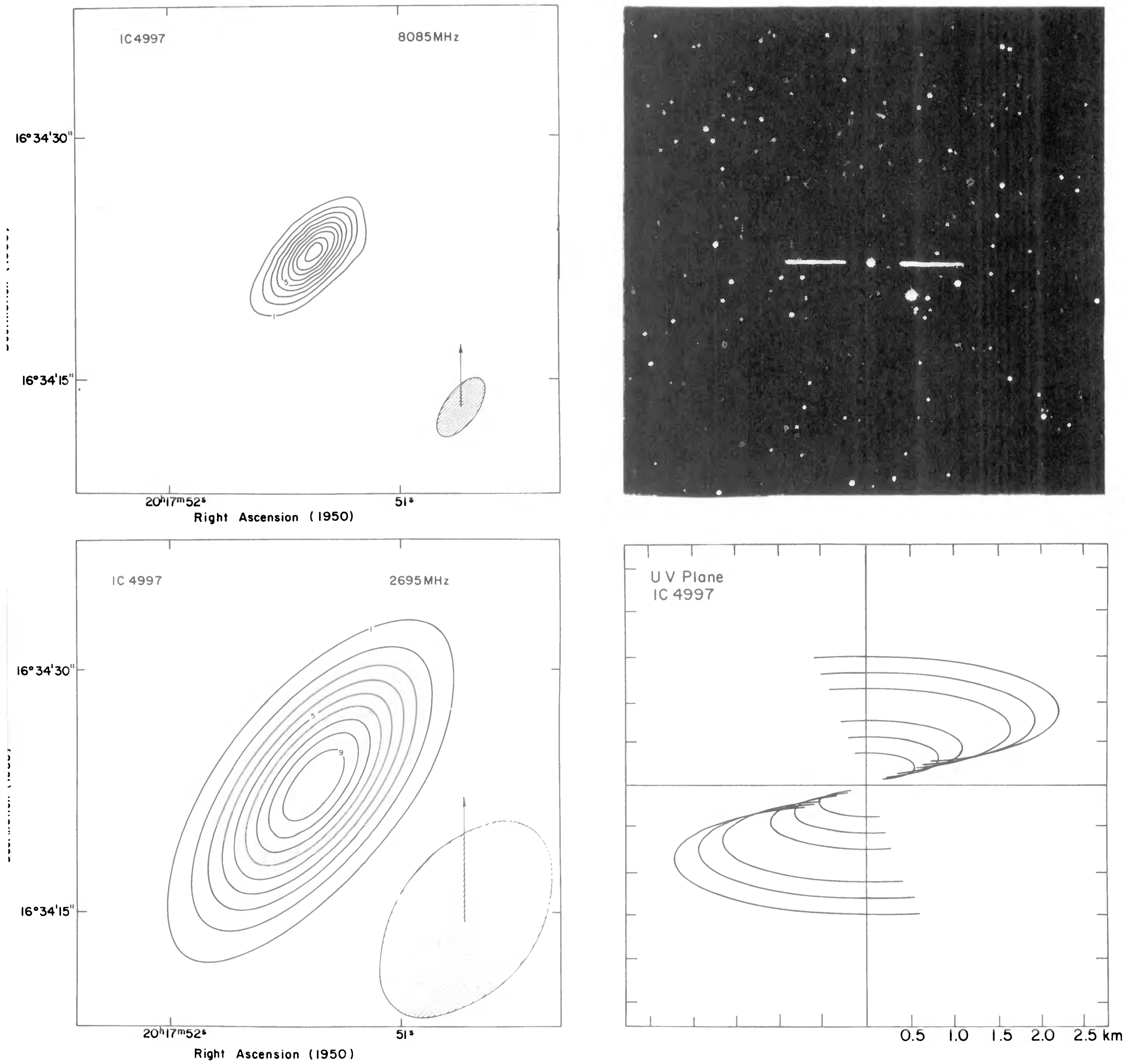

FIG. 11.—Same as fig. 1 for IC 4997. Contour spacings are 16.3° and 16.5° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Curtis (1918). This nebula has a stellar appearance with a size of ~2″.

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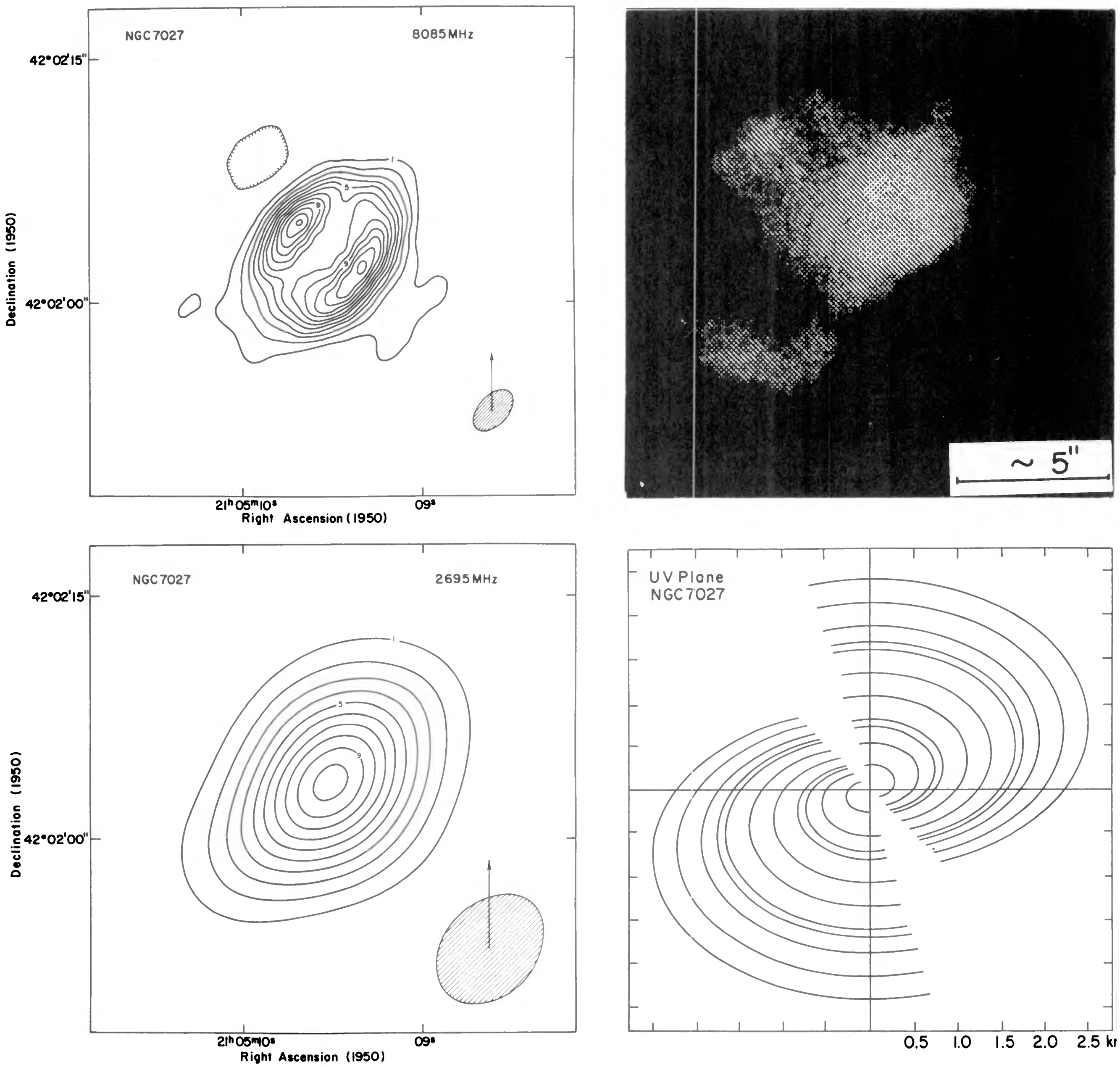

FIG. 12.—Same as fig. 1 for NGC 7027. Contour spacings are 664° and 200° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is from Aller and Liller (1968) taken by Minkowski.

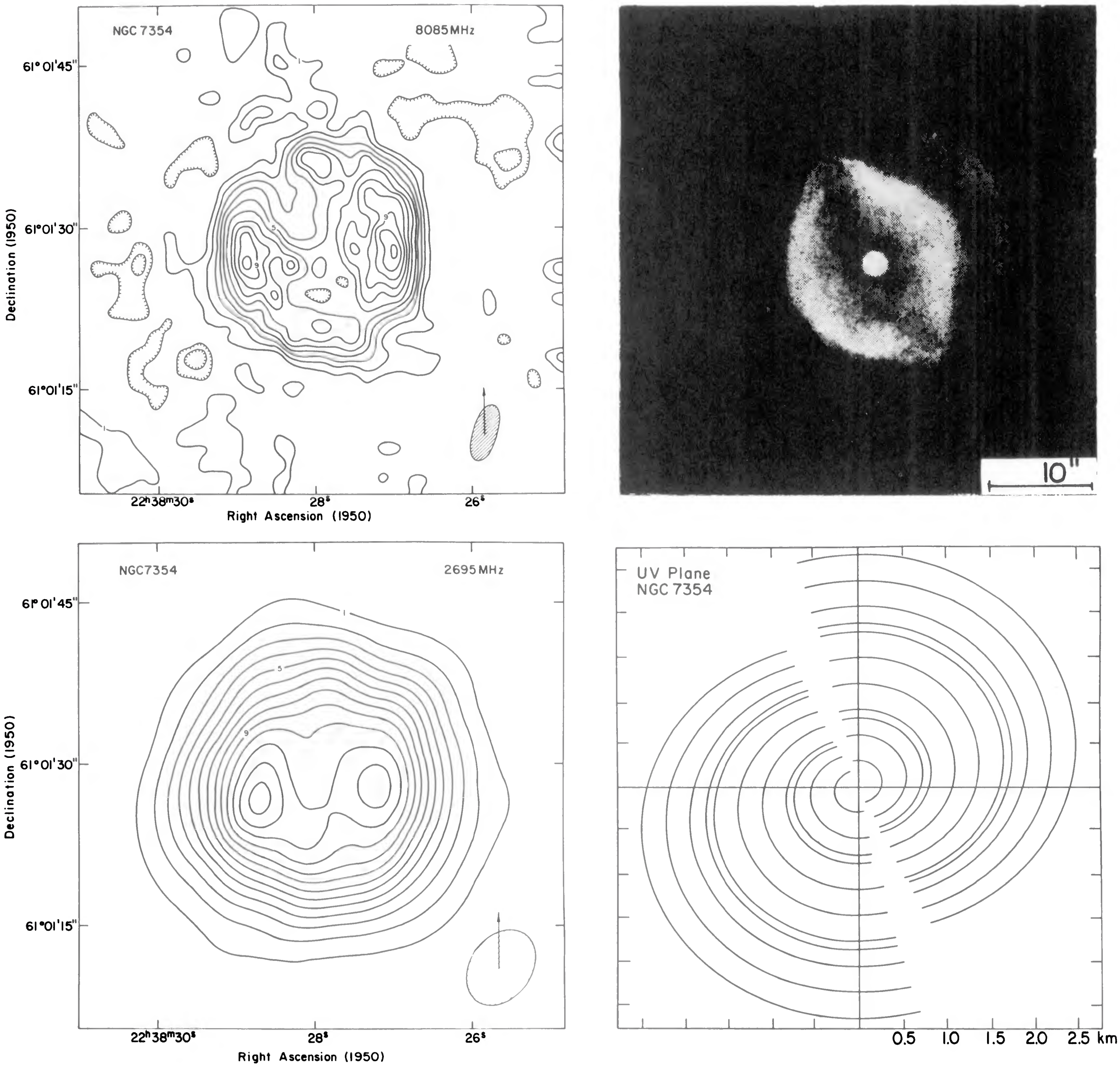

FIG. 13.—Same as fig. 1 for NGC 7354. Contour spacings are 20.2° and 2.9° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918).

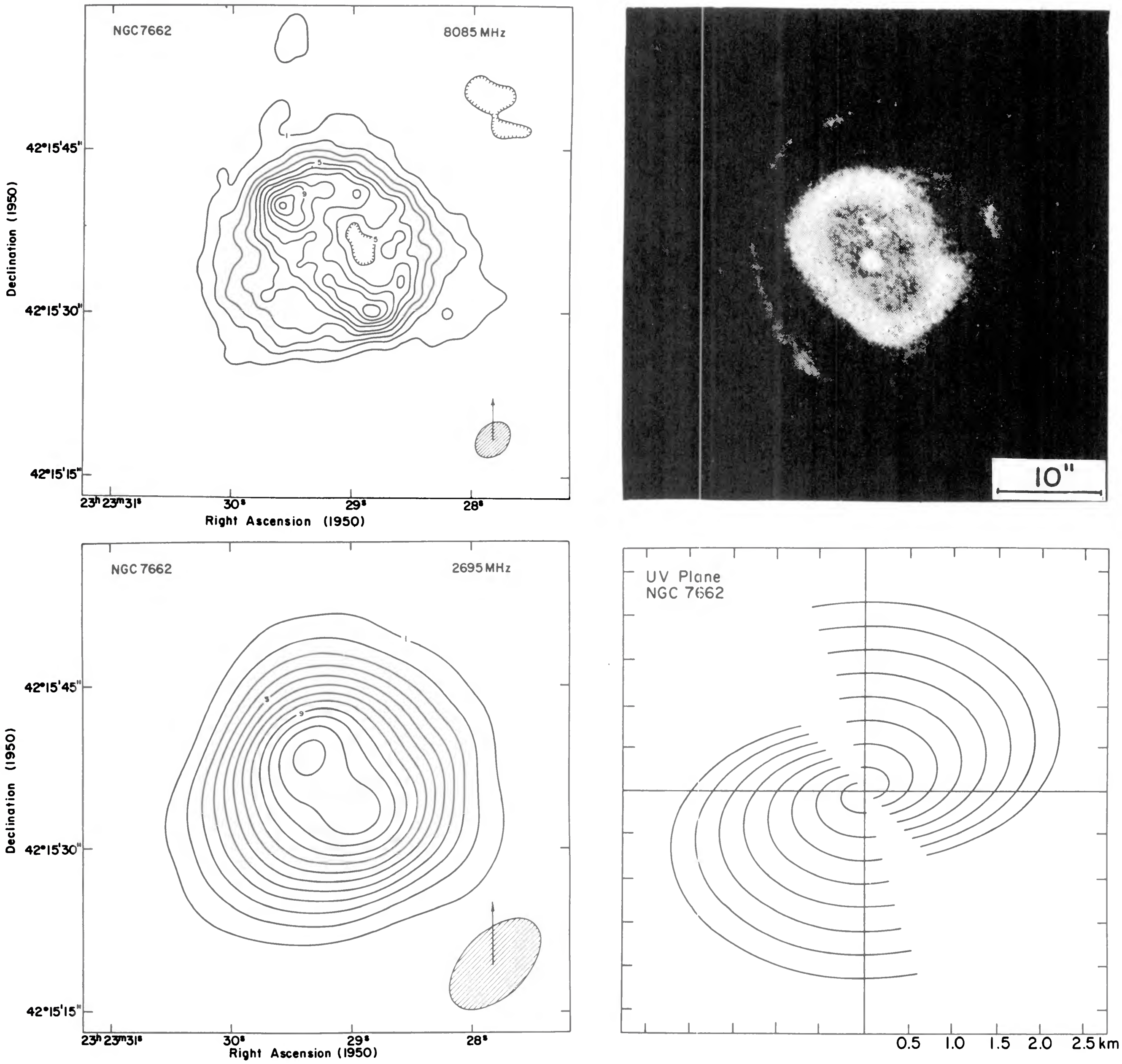

FIG. 14.—Same as fig. 1 for NGC 7662. Contour spacings are 30.3° and 5.83° K of T_b at 2.7 and 8.1 GHz, respectively. The optical photograph is a drawing by Curtis (1918); Aller (1971) shows a photograph of this nebula.

also show the coverage of the (U, V)-plane for each source. An optical photograph (or drawing) of each nebula is also shown for comparison with the radio maps. A summary of the measured parameters for the class I and II objects is given in table 1. For the class I sources the positions listed in table 1 refer to the coordinates of the map center and are not intended to correspond to any particular optical or radio feature. For the class II objects the quoted positions refer to the brightness centroid of each source provided the centroid is unambiguously defined; otherwise the position represents the source positions assumed for the observations (adopted from Higgs 1971).

In table 2 we present the observations for some additional sources for which comprehensive observations were not warranted or possible. Included in table 2 are some prominent nebulae which we were not able to detect; that is, they were initially too weak ($\lesssim$ 10–20 m.f.u.), too large ($\geq 30''$), or were strongly confused with a brighter radio source elsewhere in the primary antenna beam (half-power beam width 18′ at 2.7 GHz; and 6′ at 8.1 GHz). The positions of the nebulae given in table 2 have the same definition as the positions for the class II objects mentioned above. We wish to note that where we refer to radio-source sizes in our comments for each source, these are estimated from model fits to simple Gaussian sources. Considerable uncertainty exists in these sizes since most planetary nebulae show rather complex structure on many size scales.

The flux densities of extended sources are often difficult to determine interferometrically. In theory the flux is obtained as the fringe visibility in the limit on the projected baseline approaches zero (i.e., all sources are unresolved). In practice this so-called zero-spacing flux cannot be measured directly on the NRAO interferometer; rather the flux must be inferred from observations at nonzero spacings. In the event that a source is sufficiently extended to be partially resolved even on the shortest spacing (size $\gtrsim 15''$ at 8.1 GHz, depending on declination), the measurements provide a *lower* limit to the true flux. Generally, sources whose sizes are less than 15″ at 8.1 GHz have visibilities which can be safely extrapolated to zero spacing, and for those smaller than 5″, the maximum amplitude measured on the shortest spacing is an excellent estimate of the total flux. The fluxes quoted in the tables are estimates based on the most justified procedure.

TABLE 2
PLANETARY NEBULAE WITH PARTIAL SYNTHESIS OBSERVATIONS

Nebula	Position*		Flux Density (10^{-26} W m^{-2} Hz^{-1})		Remarks
	R.A. (1950)	Decl. (1950)	8085 MHz	2695 MHz	
NGC 40	00ʰ10ᵐ18.1	72°14′35″.0	> 0.08	> 0.20	Observations severely confused with nearby small source. Weak emission is seen near NGC 40. The reported flux refers to both NGC 40 plus confusion source.
BV 3	01 50 24.0	56 10 00.0	≤0.02	≤0.02	...
M1-2	01 55 32.9	52 39 15.0	≤0.02	≤0.02	...
IC 289	03 06 16.4	61 07 39.0	≤0.02	≤0.02	...
M1-4	03 37 59.0	52 07 26.0	≤0.02	≤0.02	...
NGC 1514	04 06 08.3	30 38 42.2	≤0.02	≤0.02	Possible confusion with weak source ~13″ SSE of nebula.
M4-18	04 21 31.0	60 00 25.0	≤0.04	≤0.04	Possible detection.
H3-29	04 34 18.0	24 57 00.0	≤0.02	≤0.02	...
H3-75	05 37 54.0	12 19 00.0	≤0.02	≤0.02	...
IC 2149	05 52 40.9	46 05 53.0	> 0.13	> 0.20	Source diameter ≃30″. Complex structure.
PB 1	07 00 24.0	−13 40 00.0	≤0.02	≤0.02	...
NGC 2346	07 06 49.7	−00 43 29.4	> 0.10	> 0.15	Observations confused with nearby small source. The reported flux refers to both NGC 2346 plus confusion source.
M1-17	07 38 00.0	−11 26 00.0	≤0.02	≤0.02	...
M3-5	08 00 30.0	−27 32 00.0	≤0.02	≤0.02	...
W16-13	08 06 31.0	−27 32 26.0	≤0.02	≤0.02	...
A26	08 07 00.0	−32 31 00.0	< 0.02	≤0.02	...
W17-15	08 12 37.0	−33 37 43.0	> 0.04	> 0.04	Severe confusion probably by more than one nearby source.
W17-17	08 13 55.0	−33 06 35.0	≤0.02	≤0.02	...
M2-9	17 02 52.6	−10 04 27.0	> 0.06	≥0.06	Evidence of complex structure at 8085 MHz.
NGC 6537	18 02 15.3	−19 50 52.0	≫0.05	> 0.50	Apparent size in right ascension ≃ 5″. Declination poorly determined.
M3-27	18 25 31.6	14 27 11.0	≤0.02	≤0.02	...
NGC 6853	19 57 27.0	22 35 00.0	> 0.02	> 0.05	Evidence of complex structure.
NGC 7009	21 01 27.7	−11 33 52.0	≫0.04	> 0.50	Complex structure. Diameter ≥ 30″.
M1-78	21 19 05.5	51 40 38.5	> 1.00	≥0.70	Apparent size ≃ 5″.
A63	21 30 36.0	55 39 33.0	> 0.05	> 0.05	Apparent size ≃ 3″ (uncertain identification).

* For the detected nebulae the determined position from the present work is shown, otherwise the position given by Higgs (1971) is indicated. In a few cases the positions given above differ slightly from those determined by Milne (1973).

TABLE 3

EMISSION MEASURES AT MAXIMUM BRIGHTNESS

Nebula	Emission Measure (cm^{-6} pc)
NGC 7027	6.7×10^7
NGC 6302	2.6×10^7
BD 30−3639	1.2×10^7
NGC 6572	1.0×10^7
IC 4997	4.6×10^6
IC 418	3.8×10^6
NGC 6210	2.5×10^6
NGC 6543	2.3×10^6
NGC 7662	1.6×10^6
NGC 6369	1.5×10^6
NGC 2440	1.0×10^6
NGC 7354	9.0×10^5
NGC 3242	8.0×10^5
NGC 2392	3.0×10^5

For sources for which no extrapolation to zero spacing was justified, lower limits to the flux are given.

The ratio of the fluxes shown in table 1 indicate that most of the observed planetary nebulae are optically thin at both 2.7 and 8.1 GHz, with the exception of NGC 7027, and possibly NGC 6302 and IC 4997. Assuming complete thermal radiation (free-free emission) the emission measure of the resolved structure in the observed sources can be determined from

$$E = T_b \frac{\nu^2 T_e^{0.5}}{0.0301}\left[\ln\left(0.0495\frac{T_e^{1.5}}{\nu}\right)\right]^{-1}$$

$$\simeq 2.86 \times 10^4 T_b ;$$

$$(T_e = 15{,}000^\circ\ \mathrm{K}\,, \qquad \nu = 8.1\ \mathrm{GHz})\,,$$

where E is the emission measure in units of cm^{-6} pc, ν is the frequency in GHz, T_e is the electron temperature, and T_b is the measured map-brightness temperature.

Table 3 gives the derived emission measures for the class I objects in units of cm^{-6} pc at the positions of the *maximum brightness* temperatures. The emission measures range from 6.7×10^7 cm^{-6} pc for NGC 7027 to 3.0×10^5 cm^{-6} pc for NGC 2392. The planetaries with the highest emission measures are also the ones with highest mean electron densities (O'Dell and Terzian 1970), and most of them have been observed to have very large excess infrared radiation (Woolf 1969). The high-emission-measure compact nebulae appear to be associated with large amounts of dust. Such considerations suggest that these objects are relatively young planetary nebulae, and that the less obscured and larger planetaries are in a more advanced evolutionary state.

IV. THE STRUCTURE OF PLANETARY NEBULAE

Optically a large number of planetary nebulae appear as bright rings; with longer exposures, however, the rings disappear and continuous disks are seen. This indicates that the real forms of the nebulae are probably shells of finite thickness. Usually the projected appearance of the nebulae is somewhat elliptical, which may suggest the presence of magnetic fields. In many cases the brightness at two opposite ends of a nebulous envelope is higher than the rest of the nebula, showing a bipolar structure. In several cases one can detect planetary nebulae which appear to consist of two concentric envelopes. The most numerous group of planetary nebulae are the *stellar* nebulae whose apparent sizes are very small ($\leqslant 2''$). The high-resolution radio observations presented in § III of this paper include examples of the prominent structure types of planetary nebulae discussed above.

In general the radio maps show that several of the observed planetary nebulae have a double-source structure. This is evident in the apparently large and relatively tenuous nebulae like NGC 7354, NGC 7662, and NGC 6543; and in the apparently small and dense nebulae like BD 30−3639 and NGC 7027. Very small nebulae like IC 4997 and NGC 6572 are too small to detect any source structure with the available angular resolution. In some cases the double-source structure can clearly be seen in the lower-resolution 2695-MHz maps. It should be pointed out that the peak intensities of the components of the double-source features do not necessarily appear at the edge of the nebular envelopes, as expected from their shells; rather they are at different locations on the projected brightness distribution. The observations suggest that for the small and dense nebulae the separation of the main radio components is very small, e.g., BD 30−3639, and possibly NGC 6572 and IC 4997. The general double-source configuration may suggest a preferential ejection of matter from the surface of the central exciting star. However, it is also possible that matter is ejected symmetrically around the central star and that the magnetic field around the star is responsible for orienting the gas in a dipole configuration. It should be pointed out here that a true ring distribution observed with an elliptical beam may result into an observed double-source structure in the direction of the beam's minor axis (if the size of the ring is smaller than the beam's major axis). Such situations do not occur for the sources mentioned above, except perhaps in the case of BD 30−3639. A thick cylindrical-shell model, of the type discussed by Scott (1973) for NGC 7027, with some preferential orientation of the cylinder axis to the observer, is still possible. However, we feel that, due to the observed fine structure in many nebulae, this model is too simplified.

Generally the observed nebulae show fine structure when observed with higher resolution. This is demonstrated by comparing the 2695- and 8085-MHz radio maps of NGC 6543, NGC 7354, NGC 7662, and others. In addition, spherical or elliptical shells are present for all the observed nebulae, and central-intensity depressions appear in most of those for which the synthesized beam is smaller than the source dimensions.

Several of the observed nebulae show double envelopes at optical wavelengths; these include NGC 2392, NGC 7662, and NGC 6543. Normally the outer envelopes are fainter than the inner ones and can only be detected with large optical telescopes on very long exposures. With the possible exception of NGC 2392, the present radio maps do not show any significant radio emission from outer faint envelopes; however, this is at least partially attributable to our *U*, *V* sampling which makes our maps insensitive to structure $\gtrsim 15''$ at 8.1 GHz.

A short discussion on each of the observed nebulae is given below.

a) *Class I Sources*

IC 418 (*see* fig. 1).—This nebula is bright and of low excitation with a very symmetrical elliptical ring structure $14'' \times 11''$ in size at optical wavelengths. Aller (1956) gives the Hβ isophotes for this object which show two concentrations at the ends of the minor axis separated by $\sim 9''$. The synthesized radio beam from the present observations is elongated approximately in the north-south direction. The high-resolution 8085-MHz map shows no significant structure in the north-south direction, but is resolved into structure in the east-west direction, which is in general agreement with the optical appearance of the nebula. The position of the optical nebulae quoted by Higgs (1971), and remeasured by Milne (1973) from the *Palomar Sky Atlas* is in good agreement with the position of the center of our radio maps. IC 418 shows a large excess of infrared radiation (Woolf 1969; Gillett, Merrill, and Stein 1972).

NGC 2392 (*see* fig. 2).—This nebula has an obvious double-ring structure at optical wavelengths. The central star is surrounded by an irregular elliptical ring $19'' \times 15''$ in size, and the outer fainter ring which is formed by broken patches has a size of $47'' \times 43''$ at optical wavelengths. Aller (1956) shows Hβ contours for this nebula. The present high-resolution 8085-MHz synthesized map shows a complex structure with a relatively intense inner region and an outer fainter ring-type emission. These two components correspond well with the optical appearance of the nebula. In detail the inner region of the nebula shows significant fine structure on a scale of $\sim 2''$. There is an indication that an intensity depression exists at the center of the nebula. The outer ring is irregular and also shows fine structure on a scale of $\sim 2''$. The lower-resolution radio map at 2695 MHz suggests a double structure for NGC 2392—a characteristic of many planetary nebulae.

The nebula NGC 2392 is a very low-surface-brightness radio source. Although the signal-to-noise level of the 8085-MHz map is not too high, the features describing the structure of the source are clearly above the noise. Maps at 8085 MHz convolved to poorer resolution, which have better signal-to-noise ratios, show that the fine structure indicated near the map center is certainly real.

NGC 2440 (*see* fig. 3).—Curtis (1918) shows a drawing of NGC 2440 which has an irregular and patchy elliptical shape $54'' \times 20''$ in size, with some faint extension in the northeast position. No central star is visible in this nebula. Aller (1956) shows Hβ isophotes for this nebula which show a double-core structure with a faint outer envelope. The two components are $\sim 5''$ apart. The 8085-MHz radio map presented here shows significant fine structure primarily in the north-south direction. This is in fair agreement with the Hβ isophotes which show the double-core structure. No significant radio emission has been detected from the optically visible faint northeast extension of this nebula. Weak radio radiation (not well defined) appears in the north-northwest of the nebula at 8085 MHz. Radio emission from the faint outer envelopes of planetary nebulae seems to be too weak to be reliably detected.

NGC 3242 (*see* fig. 4).—This nebula has a bright double-ring elliptical structure. The inner ring is $26'' \times 16''$ in size, and the outer fainter ring has dimensions of $40'' \times 35''$ at optical wavelengths. The inner ring shows two concentrations separated by $\sim 14''$ (Aller 1956). The 2695-MHz radio map of NGC 3242 presented here shows an extended source with a central double-core structure, somewhat similar to the optical features. The higher-resolution 8085-MHz map shows complex fine structure in the inner portion of the source. A peculiar complex radio source $\sim 35''$ north of the center of NGC 3242 appears distinctly at 8085 MHz, whereas it is only weakly visible at 2695 MHz. The nature of this feature is not known.

NGC 6210 (*see* fig. 5).—Curtis (1918) describes this nebula as having a bright central region $\sim 8''$ in size, and being surrounded by an outer fainter elongated matter $20'' \times 13''$ in size. From the ends of this outer matter two small mass concentrations extending at opposite ends of the nebula appear as shown in the [O III] and Hα photographs given by Aller and Liller (1968). The radio observations resolve this nebula only at the higher frequency of 8085 MHz. The radio contours suggest a somewhat symmetrical structure with a central concentration. This structure is similar to the optical isophotes shown by Aller (1956). No radio emission appears at the location of the two optically intense outer mass concentrations mentioned above. The optical position of NGC 6210 measured by Milne (1973) lies at the southern extremity of the radio source ($\sim 12''$ south).

NGC 6302 (*see* fig. 6).—This peculiar nebula is one of the most highly excited gaseous objects, with an electron temperature $T_e \simeq 18{,}000°$ K. No central star has been detected from NGC 6302. Long-exposure optical photographs shown by Aller (1971) indicate a filamentary structure for this nebula. The optical size of NGC 6302 is $\sim 54''$, but has a very bright smaller central condensation. The radio maps presented here indicate the presence of a very compact central radio source. Some faint radio emission is visible in the 8085-MHz map in the north-south direction (it is possible that these extensions may be due to instrumental effects). The radio spectrum of NGC 6302 is clearly of a thermal nature with indications of high optical depths at relatively high radio frequencies, suggesting unusually high electron densities in the radio component. Although our *U*, *V* coverage for this source is not complete, there are indications that it is similar to NGC 7027 in size and strength. The optical position given by Milne (1973) is 8″ north of the radio position.

NGC 6369 (*see* fig. 7).—Optically this nebula has a faint nearly round ring surrounding a central star. This ring is fainter at the eastern end and brightest at the northern end. Its optical diameter is ~28″. The center of the nebulous ring seems perfectly blank. Surprisingly, the radio characteristics of this nebula are very unlike its optical appearance. NGC 6369 is a relatively strange radio source, with complex radio structure. The 8085-MHz high-resolution map has a complex appearance with fine structure at the expected position and extent of the nebula. The lower-resolution 2695-MHz map suggests a double-source structure. Clearly another complex radio source ~30″ south of NGC 6369 is confusing this region somewhat. The nature of this source is not known. The optical position given by Milne (1973) is ~10″ north-northeast of the radio-map center. (We note that the Sun was close to the main telescope beam during the observations; however, we think that the radio maps are unaffected.)

NGC 6543 (*see* fig. 8).—This helical type nebula studied by Münch (1968) has a complex optical structure. Münch finds that the material is arranged on two helical surfaces moving apart at ~24 km s^{-1}. The optical size of the nebula is 22″ × 16″. The radio map at 2695 MHz clearly shows the characteristic double-peak structure, which appears in several of the nebulae discussed in this paper. The 8085-MHz map shows one of the best-resolved sources in this study. These high-resolution observations show substantial fine radio structure with a clear central-intensity depression. There appears to be some correlation between the bright optical features of the nebula and the radio intensity peaks; however, an improved optical position for this nebula is necessary for a detailed comparison of the radio and optical maps. Woolf (1969) has reported a large infrared excess radiation from NGC 6543.

NGC 6572 (*see* fig. 9).—This nebula has a central bright disk of ~6″ in size, and a much fainter outer envelope of ~16″ in diameter at optical wavelengths. Curtis (1918) describes this nebula as "stellar-like with bright nebulous nucleus." No visible structural details exist, and no central star has been identified for NGC 6572. The present high-resolution 8085-MHz radio map shows only slight effects of some structure in the central part of NGC 6572. In general, however, this source seems compact with a uniform brightness distribution. There is almost no indication of an outer faint envelope in the radio observations, although the *U*, *V* coverage possible at the declination of NGC 6572 makes studies of large-scale structure difficult. The optical position of this nebula reported by Milne (1973) lies ~20″ northeast of the radio source! Excess infrared radiation has been detected from NGC 6572 by Woolf (1969) and Gillett *et al.* (1972).

BD 30−3639 (*see* fig. 10).—This nebula has a very small apparent size of ~5″. It is a symmetrical nebula of high surface brightness and low excitation with weak [O III] lines, but with strong [O II] and [N II] lines. BD 30−3639 has been studied in detail by O'Dell and Terzian (1970). The radio maps clearly suggest a small and compact source. The high-resolution 8085-MHz map shows BD 30−3639 resolved into two central components separated by 2″–3″. This nebula has a very large infrared excess radiation (Woolf 1969; and Gillett *et al.* 1972), similar to NGC 6572 and NGC 7027.

IC 4997 (*see* fig. 11).—This nebula has a very small apparent size on the order of 2″, and it is indistinguishable from a star. The radio maps presented here show that it is totally unresolved and must have a very small angular size. Gillett *et al.* (1972) have reported some infrared excess radiation for IC 4997. The optical position given by Milne (1973) falls outside the radio contours and is ~7″ west-northwest of the radio position.

NGC 7027 (*see* fig. 12).—This nebula was recently discussed in detail by Balick *et al.* (1973) and Scott (1973). The optical appearance of NGC 7027 is irregular with bright condensations. Its maximum optical size is 18″ × 11″. The radio results clearly show the double-source structure at 8085 MHz, which is a characteristic of planetary nebulae. Optically local obscuration makes the northeast major radio component very faint. The high-resolution radio results are suggestive of a central-intensity depression in NGC 7027. Although no central star is optically visible, it may be totally obscured by dust as suggested by Miller and Mathews (1972). A bright and very small radio source located near the southwest component has been reported by Miley, Webster, and Fullmer (1970). NGC 7027 shows a very large infrared excess radiation (Woolf 1969; Gillett *et al.* 1972). Recently Knacke and Dressler (1973) observed the brightness distribution of NGC 7027 at 11.7 μ with an angular resolution of ~4″. Although such a resolution is not enough to resolve the source into distinct components, there are indications that with higher resolution the infrared brightness distribution may resemble the radio structure.

NGC 7354 (*see* fig. 13).—Curtis (1918) describes this nebula as an irregular oval ring 22″ × 18″ in size. This ring is surrounded by an outer fainter one about 32″ in size. The radio maps presented here clearly show a double-peak structure at 2695 MHz, and the high-resolution 8085-MHz map shows a detailed fine structure to a scale of ~2″. This map, and that for NGC 6543, have the highest resolution in this study, e.g., effective half-power source to beam ratios ≳10. The main double radio structure is in the east-west direction. It is interesting to note that two very small intensity peaks appear closer to the map center and in the same direction as the main components. A central intensity depression is apparent from the 8085-MHz map. The two main radio peaks have a good correspondence with the optical maxima of the oval ring structure.

NGC 7662 (*see* fig. 14).—At optical wavelengths this nebula shows two very thin rings. The inner one, which peaks at ~8″ from the center of the nebula, has a prolate shape. The outer one, which is fainter and peaks at 14″ from the nebula center, has a more circular appearance. The radio maps presented here show the general double structure of the nebula with a central-intensity depression (somewhat displaced to the west of the map center). The high-resolution 8085-MHz map also shows fine structure with a scale of ~2″. The outer optically visible ring structure does not show much radio emission. Aller (1971) has given optical intensity contours superposed on a photograph of NGC 7662. Our 8085-MHz radio map is very similar to these results, indicating no large changes in obscuration across the nebula.

b) *Class II Sources*

IC 2003.—From the present observations we have determined that the radio size of this nebula is ~7″ in the northeast direction.

VV 29 (*J320*).—The radio size of VV 29 is ~15″ in the northeast direction. The present 8085-MHz observations indicate that this source may have a complex structure. The position given by Milne (1973) is 10″ east of the radio position.

M1-5.—We have been able to establish an upper limit of ⩽4″ for the size of this source in the northeast direction.

IC 2165.—An approximate size of 6″ is indicated from the present work in the east direction, and a size of ~15″ in the northwest direction. Unlike most other planetary nebulae no significant radio fine structure is seen from this extended source.

M1-6.—A somewhat irregular radio source with a mean size ~5″ in the east and northeast directions.

M1-9.—A size upper limit of ⩽8″ has been determined for this nebula.

M1-11.—This nebula shows a complex structure. Two small radio components are resolved close to the center of the source. Such a feature as we have seen above is common to planetary nebulae. The flux density of the individual components seems to be twice as large at 8085 MHz than at 2695 MHz, probably indicating that the central part of M1-11 is optically thick at frequencies ⩾2695 MHz. The optical position given by Milne (1973) is ~10″ west-southwest of the radio position.

M1-16.—We have determined an upper limit for the size of M1-16 in the northeast direction of ⩽5″. The optical position given by Milne (1973) is 16″ west-southwest of the radio position.

V. CONCLUSION

The results presented above indicate clearly that aperture-synthesis techniques can be used profitably in the study of planetary nebulae. More synthesis observations are needed to study the nebulae which were not included in this study. Optical positions should be obtained at least for class I objects to the accuracy of the radio positions in order to make detailed superpositions of the radio and optical intensity distributions. The available optical positions of planetary nebulae are just not good enough for radio synthesis observations. (Milne 1973, private communication, has remeasured several optical positions of planetary nebulae and indicates better agreement with the radio positions, compared with previous publications.)

The distribution of the radio emission from planetary nebulae reflects the spatial distribution of matter in these objects. Such studies, together with the investigations of the velocity fields in the nebulae, can be used to study comprehensively the dynamics of planetary nebulae. It is hoped that the observed morphological forms will help us understand the mechanisms which produce planetary nebulae initially. (This will be the topic of a subsequent paper.)

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