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OBSERVATIONS OF PLANETARY NEBULAE AT CENTIMETER WAVELENGTHS

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Abstract

Radio frequency observations at 3.75 cm, 10 cm, and 21.4 cm have been made in an attempt to detect planetary nebulae. Fairly definite indications of radio emission were found for five of the eight nebulae studied, IC 418, NGC 6543, NGC 6572, NGC 6853, and NGC 7293. A source was also found within 3 minutes of arc of NGC 7009 and may be associated with that object. The two nebulae not detected were NGC 3242 and NGC 3587. Although the accuracy of the flux determinations is not high there seems to be an indication that, for the observed sources, the radio emission is not as great as one would expect judging by published $H\beta$ flux measurements.

I. INTRODUCTION

The possibility of observing planetary nebulae at radio frequencies has been suggested by L. H. Aller (1959) and by Osterbrock and Stockhausen (1961). Flux measurements in the Balmer lines of hydrogen and at centimeter wavelengths can serve as a useful check on our ideas concerning radiation from an ionized gas. Planetary nebulae offer the advantage that they can be expected to be optically thin in the Balmer radiation and in the high frequency radio continuum. However, the anticipated strength of the radio emission is very low and will make accurate measurementh difficult. This can be seen by computing the emissivity $4\pi j_\nu$ of a plasma in the radio continuum. The emissivity arising from free-free transitions has been calculated by Oster (1959) and Scheuer (1960) and is given by

$$4\pi j_\nu = N_i N_e \; C \ln(A \, B \, \nu^{-1}) \, , \qquad (1)$$

where

$$C = \frac{64\pi Z^2 e^6}{3 c^3 (2\pi m^3 k T_e)^{1/2}} \, ,$$

$$B = \frac{(k T_e)^{3/2}}{Z e^2 \sqrt{m}} \, ,$$

and A is a numerical constant given as 0.425 by Oster and 0.213 by Scheuer. The differing values for A arise apparently from slight differences in the approximations used. We will adopt here the average value 0.319. In the above relation N_i and N_e refer to the number of ions and electrons, respectively, per cm^3 and the other parameters have their usual meanings. Upon substituting numerical values in equation (1), for a pure hydrogen plasma with an electron temperature T_e = 10,000 °K, we find

$$4\pi j_\nu = 3.83 \times 10^{-39} N_e^2 \quad \mathrm{erg\,(cm^3\,sr\,sec\,cps)^{-1}} \tag{2}$$

for the emissivity at 3000 Mc and

$$4\pi j_\nu = 4.12 \times 10^{-39} N_e^2 \quad \mathrm{erg\,(cm^3\,sr\,sec\,cps)^{-1}} \tag{3}$$

at 1400 Mc. These can be compared directly with the Hβ emissivity given by Burgess (1958) (Case B). The resulting ratios of radio continuum emission to Hβ emission are 3.13×10^{-14} and 3.37×10^{-14} per cps for ν = 3000 Mc and ν = 1400 Mc, respectively. These values are somewhat lower than those given by Osterbrock and Stockhausen (1961), principally because we have made no attempt to account for those ions, other than protons, which play a part in the free-free emission but not the Hβ emission.

Let us take as an example the planetary nebula for which Collins, Daub, and O'Dell (1961) find the largest Hβ flux, after correction for interstellar absorption. This nebula, NGC 6572, has an Hβ flux of 1.17×10^{-9} erg$(cm^2 sec)^{-1}$. Applying the flux ratio derived above and changing units we predict a flux density of 3.68×10^{-26} w $(m^2\ cps)^{-1}$ at a frequency of 3000 Mc. For an 85-foot telescope operated at 10 cm this corresponds to a source yielding a peak antenna temperature somewhat greater then 0.3 °K, one which would be easily detectable by averaging drift curves. However, accurate flux measurements at this signal level are quite difficult.

In 1958, F. D. Drake and H. I. Ewen (1958) reported observations of two planetary nebulae at radio frequencies. The planetaries detected were NGC 7293 "Helix" and NGC 6853 "Dumbbell". These observations were made at a frequency of 8000 Mc with a 28-foot paraboloid. The maximum antenna temperatures observed were 0.26 °K and 0.09 °K for NGC 7293 and NGC 6853, respectively. These correspond to flux densities of approximately 30×10^{-26} w $(m^2\ cps)^{-1}$ and 10×10^{-26} w $(m^2\ cps)^{-1}$ if we assume an antenna efficiency of 50 percent. Following the announcement by Drake and Ewen the radio astronomy group at the Naval Research Laboratory attempted to confirm the results and were unable to do so (Mayer 1961). The NRL group, working at a frequency of about 3000 Mc with a 50-foot paraboloid, were able to set an upper limit of 0.1 °K for the maximum antenna temperature yielded by NGC 7293. This limit corresponds to a flux density of approximately 5×10^{-26} w $(m^2\ cps)^{-1}$, again assuming an antenna efficiency of 50 percent. More recently Howard (1961), using the University of Michigan 85-foot paraboloid, has obtained 8000 Mc observations which indicate that NGC 6543 is a source with a maximum antenna temperature of 0.034 °K corresponding to a flux density of 0.4×10^{-26} w $(m^2\ cps)^{-1}$. Finally, it has been reported by Bolton (1961) that Matthews at the California Institute of Technology has obtained positive results on two planetaries, NGC 6543 and NGC 7009. At 960 Mc the flux densities observed were 1.3×10^{-26} w $(m^2\ cps)^{-1}$ for both objects. In addition, upper limits of 3×10^{-26} and 2×10^{-26} w $(m^2\ cps)^{-1}$ were set for NGC 6853 and NGC 7293, respectively. Although the accuracy of the more recent measurements is not high it appears that the early observations of Drake and Ewen are not correct. The observations dealt with in the present report were made in an effort to clarify the situation still further.

II. OBSERVING EQUIPMENT AND PROCEDURES

During the past year an attempt has been made to observe planetary nebulae with the 85-foot Tatel telescope of the National Radio Astronomy Observatory. Observations were made at three frequencies, 8000 Mc, 3000 Mc, and 1400 Mc. Table 1 gives various system characteristics for the three receivers employed. Successive columns in the table give the receiver name, the frequency in Mc, bandwidth in Mc, and the beam width in right ascension and declination in minutes of arc for each frequency. The S and X band receivers employ traveling wave tube front-ends. The L band receiver is a conventional superheterodyne receiver. All three receivers show a peak-to-peak noise deflection of the order of one degree absolute with a one second time constant.

TABLE 1

THE RECEIVERS

Name	Frequency (Mc)	Band Width (Mc)	BW(R.A.)	BW(Dec.)
Ewen-Knight, X Band	8000	1000	6!6	5!7
Ewen-Dae, S Band	3000	200	16.8	15.7
Ewen-Dae, L Band	1400	6	35.0	35.8

Obviously a receiver must exhibit a high order of base line and gain stability to make possible the detection of sources giving antenna temperatures of the order of 0.1 °K. In actual fact the X band receiver proved unreliable in this respect. The few observations taken at 3.75 cm yielded inconclusive results and they will not be referred to further. Although the performance of the L band receiver was quite acceptable another factor limited its effectiveness in detecting weak sources. This factor arises from the poor angular resolution of the telescope at 1400 Mc and the fact that the sky becomes quite "bumpy" at signal levels of the order of a few hundredths of a degree antenna temperature. Because of this the results at 1400 Mc are considered to be of questionable value except for signals stronger than 0.1 °K. The S band receiver has proved the most valuable of the three receivers for this program because of its fairly reliable base line stability and the moderately high angular resolution of the telescope at 10 cm.

All observations reported here were obtained in the form of scans in right ascension and declination. The receiver output was presented in analog form on a Sanborn strip-chart recorder and in digital form on printed tape and on punched teletype tape. All observations on punched tape were reduced and averaged automatically on a Bendix G-15 digital computer. In general, the observing procedure consisted of obtaining, during an observing run of several hours duration, a series of scans in right ascension or declination through the optical center of the planetary nebula. The gate time for the integrator was usually 10 or 20 seconds and the scan speed was made as fast as possible subject to the condition that the gate time of the integrator should correspond to an angle of scan somewhat less than one half the beam width. In almost all cases similar sets of observations for each nebula were obtained on several days. Internal estimates of probable error were made from the consistency of the observations in each observing run and from the repeatability of the observations made on different days. In general a planetary nebula was considered to be "detected" if a signal of about the appropriate width appeared near the optical position in both right ascension and declination and if it had an amplitude greater than or equal to four times the estimated error in the observations. Calibration of the 1400 Mc results depends on observations of 16N0A with an adopted flux density of 44.5×10^{-26} w $(m^2 \text{ cps})^{-1}$ and the calibration of the 3000 Mc results depends on observations of 04N3A with an adopted flux density of 23.7×10^{-26} w $(m^2 \text{ cps})^{-1}$. These fluxes are due to D. S. Heeschen (1961).

III. THE OBSERVATIONS

The planetary nebulae observed in this program are listed in Table 2. Successive columns in the table give the designation, galactic longitude and latitude on the new IAU system, the logarithm of the corrected Hβ flux determined by Collins, Daub, and O'Dell (1961), an apparent photographic magnitude for the nebula, the expected flux density at 3000 Mc and 1400 Mc, and the observed flux density at 3000 Mc and 1400 Mc. The apparent magnitude is the average of the values quoted by Vorontsov-Velyaminov (1934) and Berman (1937) corrected for interstellar extinction using the same procedure and reddening law as that adopted by Collins, et al. The expected radio-frequency flux densities have been computed using the ratios determined in Section I. The observed fluxes given in the table have been determined from the estimated maximum response indicated on the scan profiles. Although the precision of the observations is not high enough to show small amounts of broadening it is reasonable to suppose that all of the planetaries with the exception of NGC 7293 represent nearly point sources. The flux density for NGC 7293 at 10 cm given in the table may have to be revised upward by as much as 30 or 40 percent to account for its probable finite size compared to the telescope beam-width at 10 cm. The parentheses following the fluxes in the table contain

TABLE 2

DATA ON THE PLANETARY NEBULAE

NGC	l^{II}	b^{II}	log F_0(H) (ergs(cm^2 sec)$^{-1}$)	$\bar{m}$	Predicted Flux (w(m^2 cps)$^{-1}$)		Observed Flux (w(m^2 cps)$^{-1}$)	
					$S_{10} \times 10^{26}$	$S_{22} \times 10^{26}$	$S_{10} \times 10^{26}$	$S_{22} \times 10^{26}$
*418	215	-24	- 9.16	10.25	2.17	2.33	1.6 (0.2)	
3242	261	+32	- 9.55	8.61	0.88	0.95	<0.6 (0.3)	
3587	148	+57	-10.17	11.10	0.21	0.23	<0.4 (0.4)	0.5 (0.1)
6543	96	+30	- 9.32	7.95	1.50	1.61	0.9 (0.2)	0.7 (0.2)
6572	35	+12	- 8.93	7.10	3.68	3.96	1.0 (0.1)	<0.3 (0.1)
6853	61	- 4	- 9.60	7.79	1.25	1.34	1.3 (0.1)	0.8 (0.1)
7009	38	-35	- 9.54	7.47	0.71	0.77	0.8 (0.2)	
7293	36	-57	- 9.15‡	7.00	2.22	2.38	1.2 (0.2)	1.2 (0.2)

*IC number.
‡Not a measured value (see text).

estimates of precision in flux units. These estimates of precision are in the form of probable errors and refer only to the precision of the observations and in no way take into account the very large source of error arising from the confusing effect of background radiation. Such effects can become quite serious at low galactic latitudes. A brief discussion of the observations on each nebula follows.

IC 418.— The average of all scans in right ascension and declination are shown in Figures 1 and 2, respectively. The vertical scale is approximate antenna temperature in degrees absolute. The data in Figure 1 were obtained in three observing runs made on three separate dates. The observations represented in Figure 2 were obtained during one long run. A source with maximum $\Delta T_a = 0.14$ °K is clearly shown on both sets of scans but there appears to be a position error of about 7 seconds in right ascension. (The "T" at the top of this and the following illustrations indicate the position of the optical object and the width to the half-power points of the main beam of the antenna). This discrepancy is most likely due to a malfunction of the position indicating system of the telescope which was known to exist at the time these observations were made. From Table 2 it is seen that the observed flux is somewhat lower than the predicted flux. The coordinates of the optical object are $\alpha = 5^h\ 25^m\!.2$, $\delta = -12°\ 44'$ (1950).

NGC 3242.— The observations gave no indication of a source. The scanning center was at $\varphi = 10^h\ 22^m\!.4$, $\delta = -18°\ 23'$ (1950).

NGC 3587.— The flux determination as 1400 Mc is not as good as the probable error would indicate. The reason is that there seems to be a confusion with background sources. This also appears to be an important factor at 10 cm. The scanning center for the observations is at $\alpha = 11^h\ 12^m\!.0$, $\delta = +55°\ 18'$ (1950).

NGC 6543.— The average of all 3000 Mc scans in right ascension and declination appear in Figures 3 and 4, respectively. The right ascension scans were obtained during three separate observing runs on as many days and the declination scans were obtained on four days. It is seen that in both coordinates there is good correspondence between a source and the optical object. The flux density of the source at 10 cm would appear to be significantly less than the predicted value. This is also true for the flux observed at 1400 Mc. The 1400 Mc result depends on declination scans obtained on three separate days. The average of these scans shows, as in the case of the 10 cm observations, a source accurately centered on the optical position of the nebula. The scanning center for NGC 6543 was at $\alpha = 17^h\ 58^m\!.8$, $\delta = +66°\ 38'$ (1950).

NGC 6572.— The 10 cm observations of this object are shown in Figures 5 and 6. Each of the two sets of scans was obtained on two separate days. There is clearly a well defined source corresponding in both right ascension and declination with the optical position of the nebula. The slight discrepancy in the peak intensity for the two cases is within the uncertainty of the observations. It will be noted that the observed flux for this source is far smaller than the predicted value. The 1400 Mc results may shed some light on the situation. The many 1400 Mc declination scans, obtained on a total of ten days, reveal quite clearly that NGC 6572 is situated within a valley between two sources. This condition could cause an underestimate of the flux at 3000 Mc although it is difficult to see how the entire discrepancy can be explained in this way. The scanning center for the observations is at $\alpha = 18^h\ 09^m\!.7$, $\delta = +6°\ 50'$ (1950).

NGC 6853.— The 10 cm observations of this nebula are shown in Figures 7 and 8. Both the right ascension and the declination scan averages were obtained on three separate days. Both sets of data clearly show a source well positioned with respect to the optical object. The apparent difference in response for the right ascension and dec-

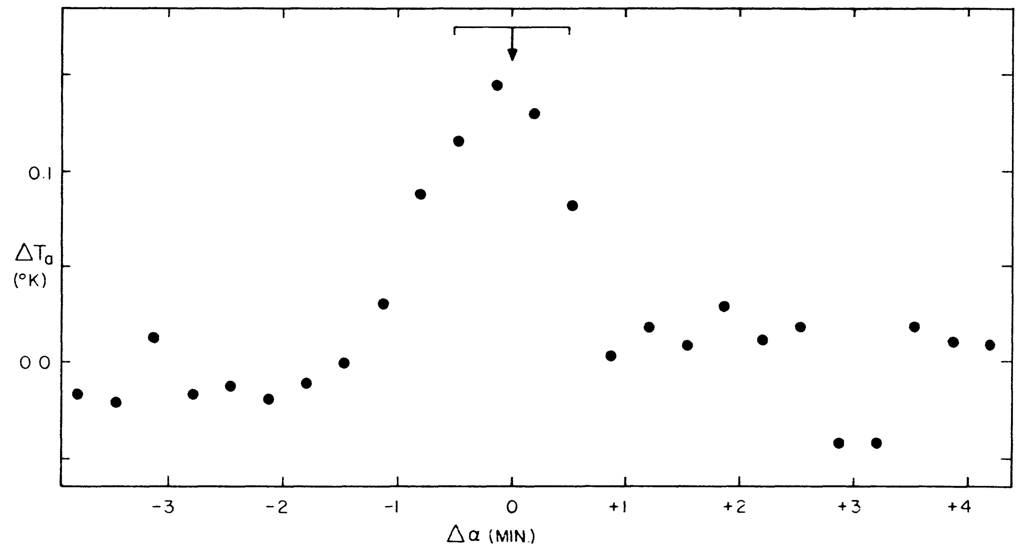

Fig. 1. — The average of all right ascension scans of IC 418 at a frequency of 3000 Mc. The probable error per plotted point is 0.014 °K. The position discrepancy is explained in the text.

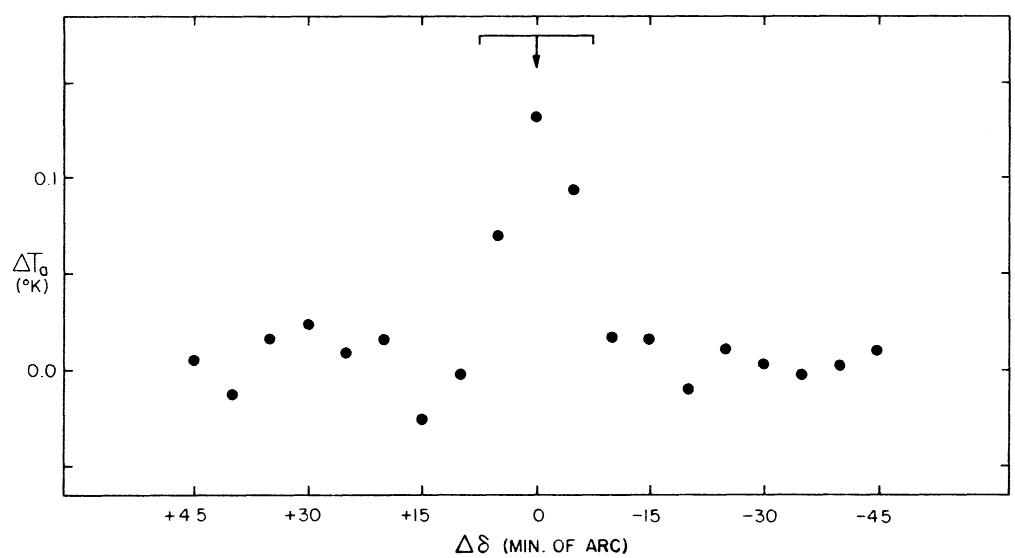

Fig. 2. — The average of all declination scans of IC 418 at a frequency of 3000 Mc. The probable error per plotted point is 0.017 °K.

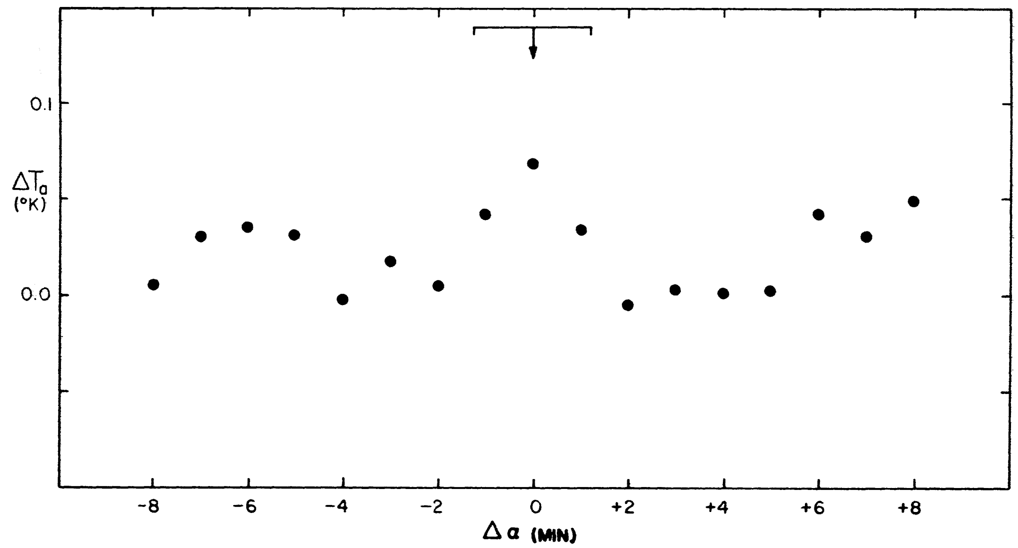

Fig. 3. — The average of all right ascension scans of NGC 6543 at a frequency of 3000 Mc. The probable error per plotted point is 0.015 °K.

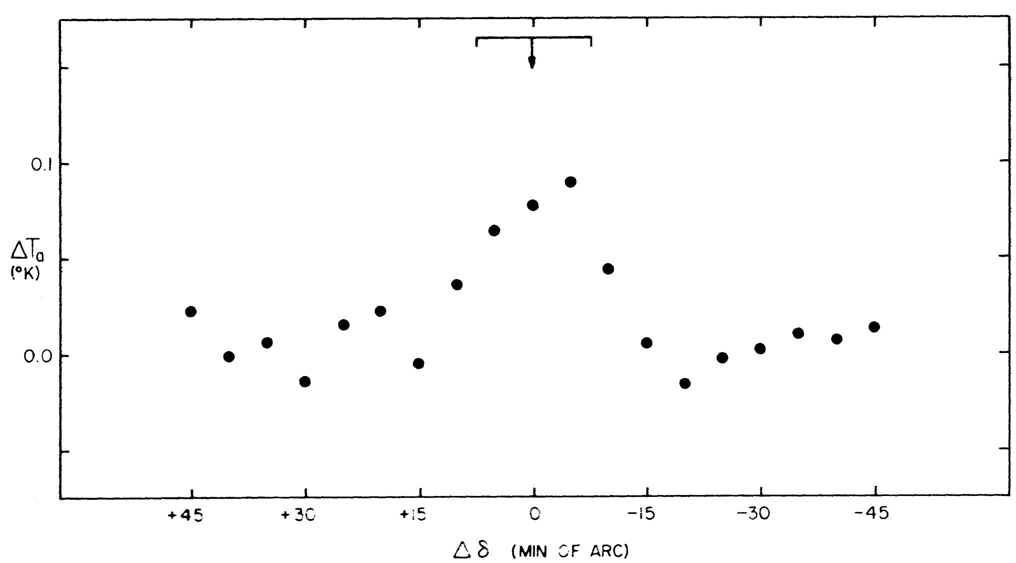

Fig. 4. — The average of all declination scans of NGC 6543 at a frequency of 3000 Mc. The probable error per plotted point is 0.008 °K.

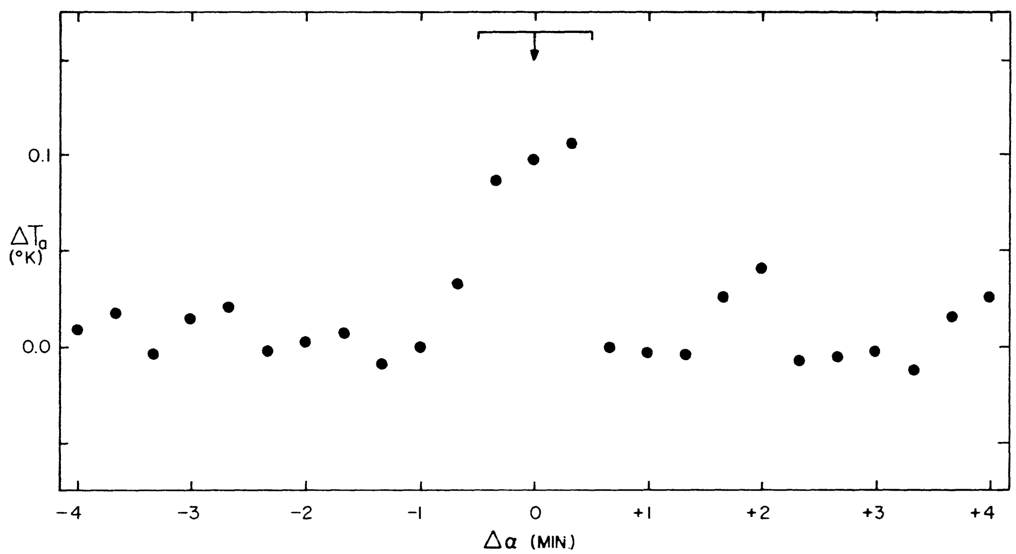

Fig. 5. — The average of all right ascension scans of NGC 6572 at a frequency of 3000 Mc. The probable error per plotted point is 0.015 °K.

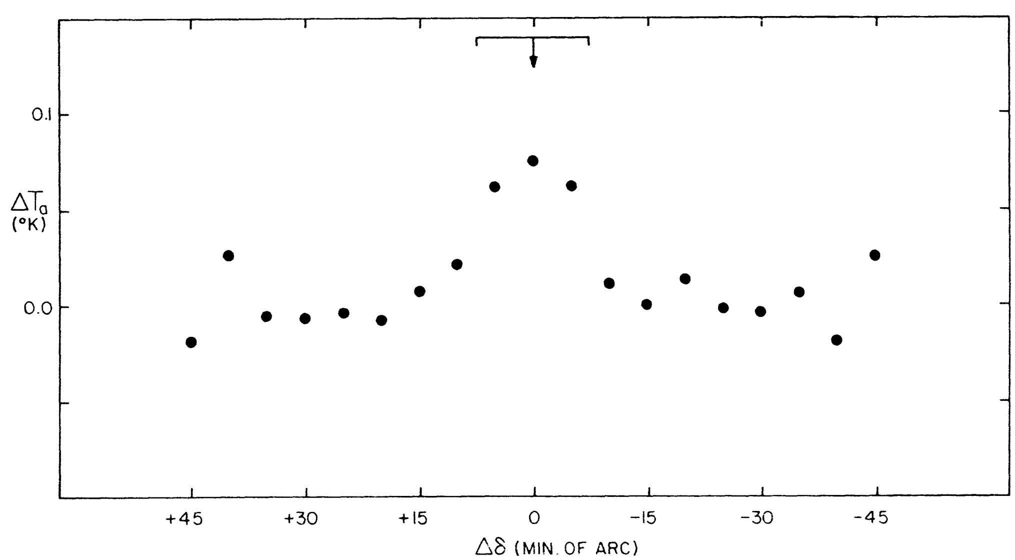

Fig. 6. — The average of all declination scans of NGC 6572 at a frequency of 3000 Mc. The probable error per plotted point is 0.015 °K.

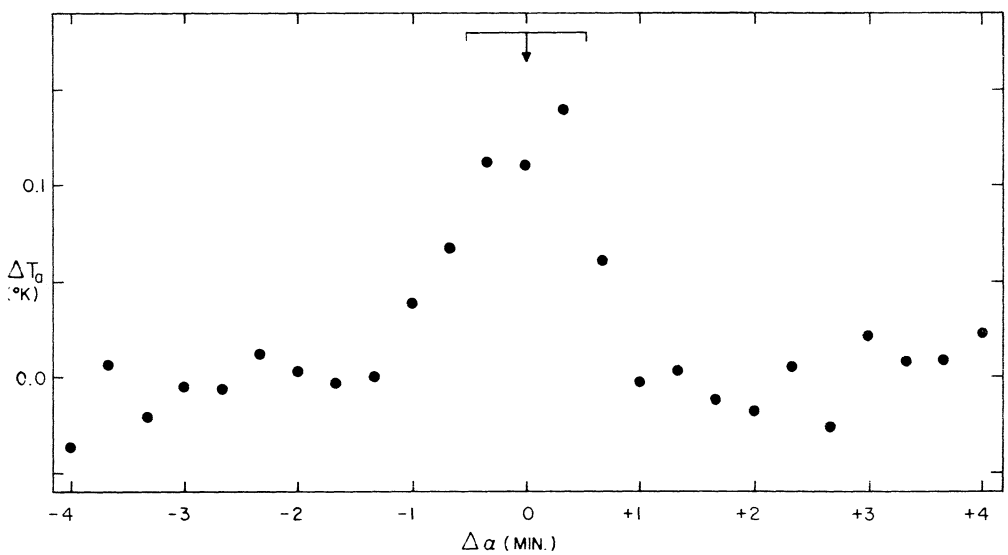

Fig. 7. — The average of all right ascension scans of NGC 6853 at a frequency 3000 Mc. The probable error per plotted point is 0.012 °K.

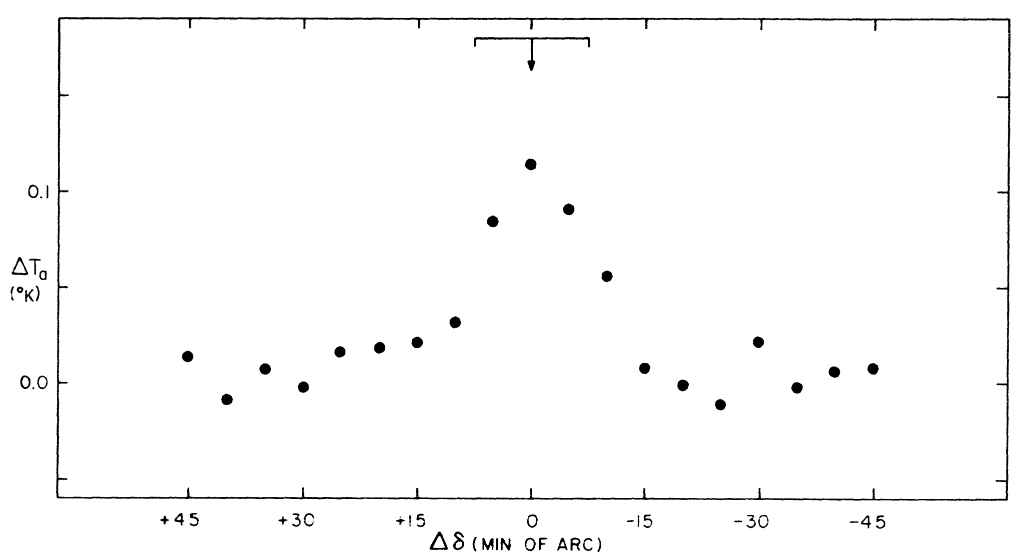

Fig. 8. — The average of all declination scans of NGC 6853 at a frequency of 3000 Mc. The probable error per plotted point is 0.012 °K.

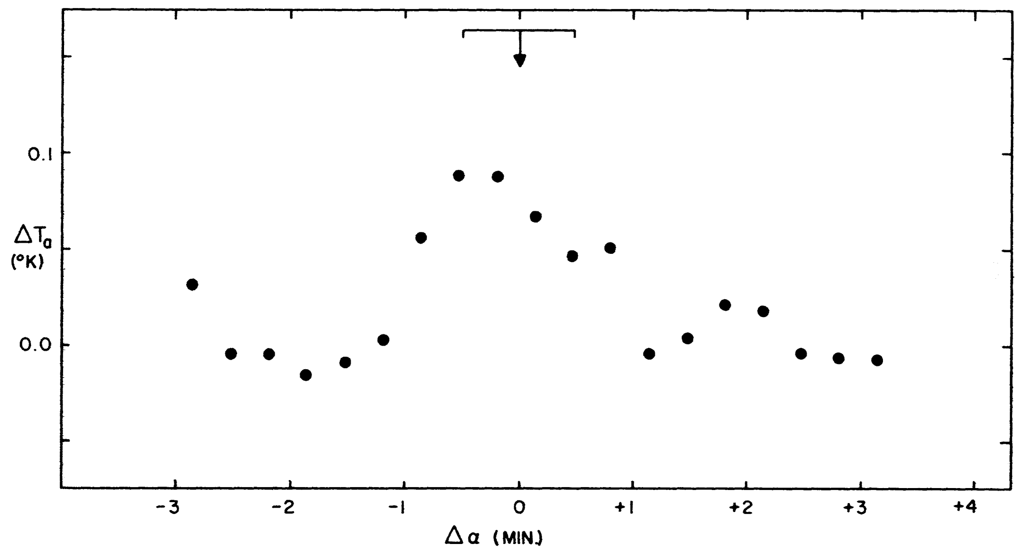

Fig. 9. — The average of all right ascension scans of NGC 7293 at a frequency of 3000 Mc. The probable error per plotted point is 0. 015 °K. The position is explained in the text.

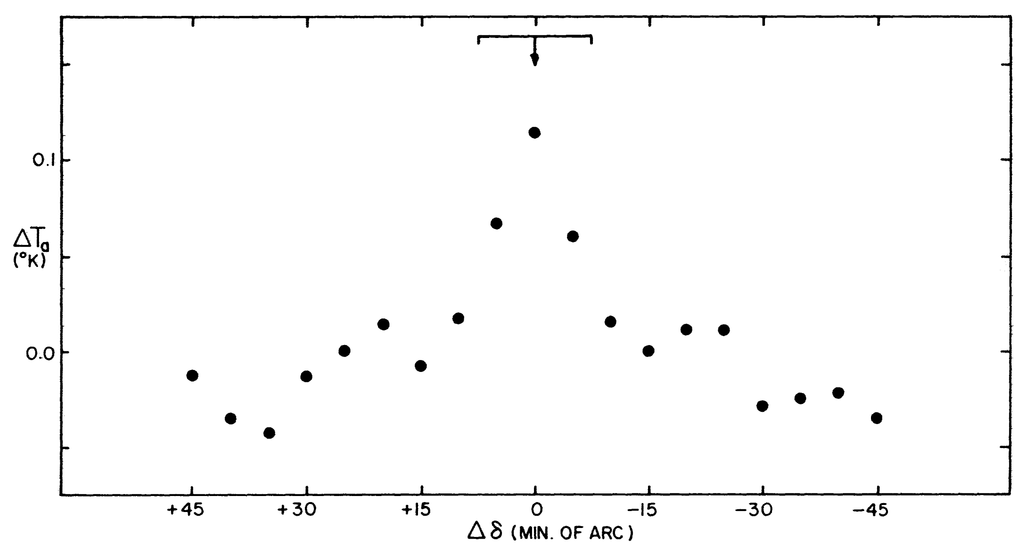

Fig. 10. — The average of all declination scans of NGC 7293 at a frequency of 3000 Mc. The probable error per plotted point is 0. 016 °K.

lination scans can be accounted for by the errors of the observations. The flux density indicated is about the same as that predicted from the Hβ fluxes. The 1400 Mc observations of this object are somewhat less reliable because of the influence of background radiation; NGC 6853 is very near the galactic plane. The scanning center is at α = 19^h $57^m.4$, δ = +22° 35' (1950).

NGC 7009.— The right ascension scans of this object indicate a source corresponding fairly well with the optical position. The declination observations likewise indicate a source but in this case the source is displaced about three minutes of arc south of the optical object. A check of the optical position used and the observing procedure have yielded no clue to the source of such a discrepancy. For this position in the sky the telescope pointing accuracy is normally of the order of one minute of arc. Obviously more observations are needed on this object. However, in view of the reported measurement of this planetary by Matthews, it seems possible that the source shown by the present observations is associated with NGC 7009. The scanning center for these observations is α = 21^h $01^m.4$, δ = -11° 34' (1950).

NGC 7293.— The averages of the right ascension and declination scans at 10 cm are shown in Figures 9 and 10. The declination scans were obtained during one long observing run and the right ascension observations were obtained during two runs on as many days. The declination scans show a source accurately centered on the optical position of the nebula but the source shown by the right ascension observations is displaced somewhat to the west. The reason for the position discrepancy is that one of the declination observing runs was made during the time of the telescope pointing difficulty mentioned above in the case of IC 418. This accounts for the apparent position shift and some of the excessive width of the source shown in Figure 9. The position of the optical object is at α = 22^h $26^m.8$, δ = -21° 06' (1950). The 1400 Mc observations of NGC 7293 consisted of declination scans on four days. These scans show a source properly centered with respect to the nebula. At each frequency the flux density for this source is about half the value predicted. This discrepancy can be lessened somewhat for the 10 cm measurements by considering the source to be extended. The 10 cm flux can be revised upward by as much as 30 or 40 percent if we assume the radio source to be as large as the brightest parts of the optical object (12' x 15'). In addition, the predicted flux density for NGC 7293 is somewhat uncertain. This value is not based on an Hβ flux measurement but rather on the corrected mean apparent photographic magnitude $\overline{m}$, and was derived in the following way. If we plot log F_o (Hβ) against $\overline{m}$ for all of the planetary nebulae listed by Collins, et al. (1961) we obtain the correlation shown in Figure 11. Although the scatter in the points is quite large the correlation seems well defined and it is possible to make a fair estimate of the Hβ flux for NGC 7293. The predicted fluxes for this nebula given in Table 2 were arrived at in this manner.

IV. CONCLUSIONS

In general the observations have shown six planetary nebulae, IC 418, NGC 6543, NGC 6572, NGC 6853, NGC 7009, and NGC 7293, to be weak radio sources. As pointed out above the case for NGC 7009 is somewhat less than certain. The failure to detect NGC 3587 is reasonable in view of the small predicted flux density. The failure to detect NGC 3242 is more difficult to understand and the object certainly needs more work. For NGC 6543 and NGC 7009 the present flux determinations seem low by comparison with those of Matthews; the flux densities found for NGC 6853 and NGC 7293 are well

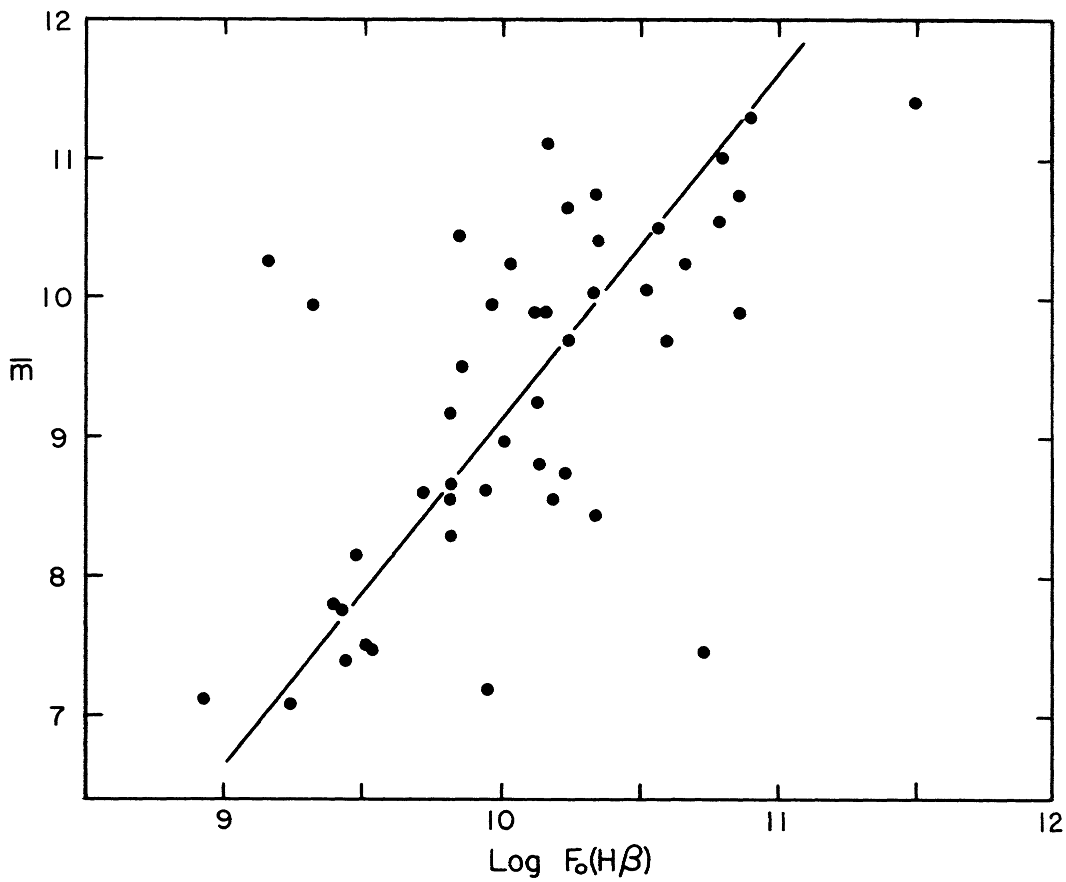

Fig. 11. — The correlation, for several planetary nebulae, between the corrected apparent photographic magnitudes and the corrected Hβ fluxes given by Collins, Daub, and O'Dell.

below the upper limits set by Matthews. The flux densities at 1400 Mc and 3000 Mc for NGC 6543 are intermediate between those of Matthews and Howard at frequencies of 960 Mc and 8000 Mc, respectively. However, it should not be supposed that these differences represent any real information concerning the radio spectrum of the object. It is more likely that the differences indicate the magnitude of the errors involved in the measurement of such weak sources.

It will be noted that the declination scans for IC 418 and NGC 7293 indicate a source response which is somewhat narrower than the beam-width of the telescope. Likewise there are several indicated sources broader than the telescope beam. Both occurrences may reasonably be attributed to the errors of the observations.

It appears that there is a general tendency for the radio flux determinations to be about 50 percent lower than those predicted from the Hβ measurements. However, in view of the size of the errors in the radio flux determinations and the possibility of systematic errors in the extinction corrections which have been applied to the Hβ measurements, it is clear that we are not yet prepared to make a meaningful test on the theory of free-free radiation from ionized media.

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