RADIO MEASUREMENTS OF PLANETARY NEBULAE

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ABSTRACT

Sixty-eight planetary nebulae have been investigated in a series of observations at 10-cm wavelength using the two 90-ft diameter antennas of the Owens Valley Radio Observatory. Of these, 52 were found to have flux densities greater than a minimum detectable level of approximately 10^{-27} $Wm^{-2}\ Hz^{-1}$. To indicate cases of possible confusion in the radio observations, the measured radio position of each nebula was compared with an accurate optical position. For a number of the stronger nebulae angular widths in the East–West direction and flux densities at 21 cm were also measured. The results lead to the conclusion that the radio emission is thermal, and on this basis the expected flux densities in Hβ have been calculated. A comparison with optical data shows values of the Hβ extinction $\Delta \log F_{H\beta}$, ranging from zero to approximately 2·0 for NGC 6537 and NGC 6369.

A small number of nebulae show prominently the effects of self-absorption in their radio spectra. For two of these, IC 418 and NGC 6572, an attempt has been made to derive accurate optical depths and electron temperatures using models based on Balmer-line isophotes. The temperature values have large uncertainties, but appear to be less than the values derived from forbidden-line ratios by a factor of at least 1·5. A possible explanation of this difference in terms of temperature variations within the nebulae is discussed.

Preliminary results of observations to detect absorption features at the wavelength of the 21-cm hydrogen line are described for 6 nebulae with high radio-flux densities. Two nebulae, NGC 6369 and NGC 6857 show absorption which is probably attributable to hydrogen clouds within the galaxy. No definite evidence of absorption at frequencies near the radial velocities of the nebulae was found, and an upper limit on the mass of neutral hydrogen in two nebulae is briefly discussed.

1. Flux Densities

The observations of planetary nebulae reviewed in this paper were made at the Owens Valley Radio Observatory in a program commenced in August 1965 (Thompson *et al.*, 1967; Thompson and Colvin, 1967). Flux densities of 68 planetary nebulae have been measured at 10-cm wavelength (2840 MHz and 2890 MHz) using the two 90-ft diameter antennas and interferometer receiving system. Fifty-two of these nebulae were found to have flux densities greater than the minimum detectable limit of approximately 10^{-27} $Wm^{-2}\ Hz^{-1}$. A list of the nebulae and their flux densities is given in Table 1, in which column 2 gives the designations of the nebulae in the new galactic number system of Perek and Kohoutek (1967). The list of nebulae includes almost all of those north of declination $-40°$ for which a value of $F_{H\beta}$, the integrated flux density in Hβ, greater than 10^{-11} erg cm^{-2} sec^{-1} has been measured, and should contain most of the stronger radio emitters observable from Northern latitudes.

The flux-density measurements were made with antenna spacings of 100 feet or

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200 feet East–West, and the values of right ascension deduced from the phases of the observed fringe patterns were compared with optical positions measured from the National Geographic Society – Palomar Observatory Sky Survey. Significant discrepancies between the radio and optical positions, which are taken as evidence of probable confusion in the radio measurements, were found for a small number of nebulae as indicated in Table 1. The 3 nebulae with the highest flux densities at 10-cm wavelength are NGC 6857, NGC 7027, and NGC 6302. NGC 6857 coincides with a broad thermal source, NRAO 621, and the Sky Survey plates show an overlapping diffuse nebula. A small planetary nebula, K 3-50, lies about 1′ North of NGC 6857 (Perek and Kohoutek, 1967). A detailed radio survey is required to determine the possible contributions of these other objects to the flux density of NGC 6857 given in Table 1. NGC 7027 is a well-known bright planetary nebula, and NGC 6302 is a nebula which contains unusually high expansion velocities and has been suggested as a possible X-ray source (Johnson, 1966; Minkowski and Johnson, 1967).

For 22 of the stronger nebulae, measurements of the flux density were also made at a wavelength of 21 cm (Thompson *et al.*, 1967). A comparison of the 10-cm and 21-cm results, together with measurements at other wavelengths by various observers, leads to the conclusion that the observed spectra are compatible with thermal emission for almost all nebulae. The exceptional cases usually show evidence of confusion from the position measurements, and there is no clear evidence of non-thermal emission from any of the nebulae investigated. For example NGC 6781 showed a significant deviation between the radio and optical positions at 21 cm, and the presence of a nearby confusing source was later confirmed by Terzian (1967). The broad confusing source near NGC 3242 (Kaftan-Kassim, 1966) was resolved by the interferometer, and had no significant effect on the observations.

2. Hβ Extinction

On the assumptions that the radio emission is thermal and that the nebulae are optically thin at 10-cm wavelength, it is possible to calculate the expected Hβ emission and hence to determine the extinction in Hβ between the nebula and the observer. Column 4 of Table 1 gives the logarithm of the observed value of $F_{\mathrm{H}\beta}$ (Collins *et al.*, 1961; O'Dell, 1962, 1963; Vorontsov-Velyaminov *et al.*, 1964) and Column 5 gives the logarithm of the extinction, $\Delta \log F_{\mathrm{H}\beta}$. The extinction was obtained using $F(\nu)/F_{\mathrm{H}\beta} = 3{\cdot}38 \times 10^{-14}$ sec, $F(\nu)$ being the radio-flux density as given in Column 3 of Table 1. This value of $F(\nu)/F_{\mathrm{H}\beta}$ was calculated for the following conditions; electron temperature, T_e, $= 10000\,°\mathrm{K}$, the ratio of the total ion density to the proton density $= 1{\cdot}15$, the mean ionic charge $= 1{\cdot}0$ and $\nu = 3$ GHz. $F(\nu)/F_{\mathrm{H}\beta}$ is proportional to $T_e^{0{\cdot}56}$, and a change in T_e by a factor of $1{\cdot}5$ would produce a change of only $0{\cdot}10$ in $\Delta \log F_{\mathrm{H}\beta}$. Delmer *et al.* (1967) point out that for some nebulae the contribution of He^{++} ions to the radio emission may be significant. For a nebula in which the ratio

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Table 1

Values of flux density at 10-cm wavelength and calculated Hβ extinction

Nebula	Perek and Kohoutek Designation	Flux Density at 10 cm Wavelength (10^{-26} $Wm^{-2}Hz^{-1}$)	Log $F_{H\beta}$ Observed (erg cm^{-2} sec^{-1})	Δ log $F_{H\beta}$	Nebula	Perek and Kohoutek Designation	Flux Density at 10 cm Wavelength (10^{-26} $Wm^{-2}Hz^{-1}$)	Log $F_{H\beta}$ Observed (erg cm^{-2} sec^{-1})	Δ log $F_{H\beta}$
NGC 40[a]	120 + 9°1	0·34 ± 0·05	−10·64		NGC 6309	9 + 14°1	0·15 ± 0·06	−11·29	0·94
NGC 246	118 − 74°1	0·15 ± 0·02			NGC 6369	2 + 5°1	1·56 ± 0·17	−11·34	2·01
NGC 650-1	130 − 10°1	0·16 ± 0·02	−10·67	0·35	NGC 6445	8 + 3°1	0·27 ± 0·06	−11·20	1·10
IC 2003	161 − 14°1	< 0·14	−11·18		H 1-40	359 − 2°3	< 0·16		
NGC 1501	144 + 6°1	0·19 ± 0·04	−11·26	1·01	NGC 6543	96 + 29°1	0·84 ± 0·11	− 9·60	0·0
NGC 1514	165 − 15°1	0·29 ± 0·04			NGC 6537[a]	10 + 0°1	0·54 ± 0·06	−11·78	1.99
NGC 1535	206 − 40°1	< 0·10	−10·36		NGC 6563	358 − 7°1	0·13 ± 0·06	−10·96	0·54
J 320	190 − 17°1	< 0·09	−11·37		NGC 6572	34 + 11°1	0·92 ± 0·1	− 9·74	0·33
IC 2120	169 − 0°1	0·17 ± 0·05			NGC 6629	9 − 5°1	0·32 ± 0·06	−10·94	0·92
IC 418	215 − 24°1	1·4 ± 0·1	− 9·53	0·21	IC 4732	10 − 6°1	< 0·10	−11·54	
NGC 2022	196 − 10°1	< 0·13	−11·15		M 1-64[a]	64 + 15°1	0·16 ± 0·06		
IC 2149	166 + 10°1	0·14 ± 0·05	−10·50	0·12	NGC 6720	63 + 13°1	0·42 ± 0·05	−10·06	0·16
SH-2-267	196 − 1°1	< 0·3	−10·50		NGC 6741	33 − 2°1	0·26 ± 0·06	−11·49	1·38
SH-2-266[a]	195 − 0°1	0·18 ± 0·05			K 1-17	51 + 6°1	< 0·14		
IC 2165	221 − 12°1	0·22 ± 0·05	−10·99	0·80	NGC 6781[a]	41 − 2°1	0·37 ± 0·05	−11·19	1·23
NGC 2346	215 + 3°1	< 0·11			A 48	53 + 3°1	0·13 ± 0·05		
NGC 2371-2	189 + 19°1	< 0·13	−10·96		NGC 6790	37 − 6°1	< 0·14	−10·75	
NGC 2392	197 + 17°1	0·23 ± 0·03	−10·39	0·23	BD 30°3639	64 + 5°1	0·44 ± 0·11	−11·50	1·62

Table 1 (continued)

NGC 2438[a]	231 + 4°2	0·12 ± 0·04	−11·02	
NGC 2440	234 + 2°1	0·31 ± 0·04	−10·56	0·53
M 3-4	241 + 2°1	0·13 ± 0·06		
NGC 3132	272 + 12°1	0·22 ± 0·03		
NGC 3242	261 + 32°1	0·72 ± 0·1	− 9·81	0·14
NGC 3587	148 + 57°1	0·10 ± 0·03	−10·33	(−0·19)
NGC 4361	294 + 43°1	0·22 ± 0·03	−10·48	0·30
IC 3568	123 + 34°1	< 0·12	−10·82	
NGC 5882[a]	327 + 10°1	0·34 ± 0·05		
NGC 6058	64 + 48°1	< 0·14	−11·70	
IC 4593	25 + 40°1	0·12 ± 0·04	−10·55	0·10
NGC 6072	342 + 10°1	0·11 ± 0·04	−11·37	0·88
NGC 6153	341 + 5°1	0·51 ± 0·04		
NGC 6210	43 + 37°1	0·32 ± 0·04	−10·06	0·04
IC 4634	0 + 12°1	0·15 ± 0·05	−10·07	0·62
NGC 6302	349 + 1°1	2·3 ± 0·1		
NGC 6818	25 − 17°1	0·34 ± 0·14	−10·13	0·14
NGC 6826	83 + 12°1	0·42 ± 0·05	− 9·92	0·02
NGC 6853	60 − 3°1	1·3 ± 0·2	− 9·44	0·03
NGC 6857[b]	70 + 1°2	6·4 ± 0·5		
NGC 6891	54 − 12°1	0·20 ± 0·08	−10·60	0·37
IC 4997	58 − 10°1	< 0·09	−10·49	
NGC 6905[a]	61 − 9°1	0·11 ± 0·06	−10·90	
NGC 7008	93 + 5°2	0·18 ± 0·05	−10·86	0·59
NGC 7009	37 − 34°1	0·62 ± 0·09	− 9·78	0·05
NGC 7026	89 + 0°1	0·27 ± 0·06	−10·90	0·80
NGC 7027	84 − 3°1	3·53 ± 0·3	−10·12	1·43
NGC 7048	88 − 1°1	< 0·1	−11·39	
NGC 7139	104 + 7°1	< 0·16	−11·78	
IC 5217	100 − 5°1	0·15 ± 0·08	−11·18	0·83
NGC 7354	107 + 2°1	0·66 ± 0·06	−11·55	1·85
NGC 7662	106 − 17°1	0·66 ± 0·05	− 9·98	0·28

[a] Radio measurements probably confused.
[b] See text.

of the He^{++} ion density to the proton density is 0·05, which is near the maximum value observed, the calculated value of $F(\nu)/F_{H\beta}$ should be increased by a factor of 1·13, and $\Delta \log F_{H\beta}$ in Table 1 decreased by 0·05. The r.m.s. error in $\log F_{H\beta}$ is 0·07 (O'Dell, 1962) and the r.m.s. errors in $F(\nu)$ are given in Table 1. The r.m.s. error in $\Delta \log F_{H\beta}$ resulting from the uncertainties mentioned above should therefore not be more than 0·15 if the accuracy of $F(\nu)$ is better than 20%. For IC 418, NGC 6572 and NGC 7027 the values of $F(\nu)$ were corrected for self-absorption of the radio emission (Thompson *et al.*, 1967), but for any other nebulae with high optical depths at 3 GHz the Hβ extinction is probably underestimated. The values of $\Delta \log F_{H\beta}$ in Table 1 range up to 2·0 for NGC 6369 and NGC 6537, corresponding to transmission of only 1% of the radiation.

3. Angular Widths

An attempt was made to compare radio and optical angular widths of 27 of the nebulae using observations of the fringe visibility at 10 cm made with spacings of 2351 and 4701 wavelengths East-West (Thompson *et al.*, 1967). High accuracy in the radio dimensions could not be achieved in most cases, since the change in the effective flux density from the shortest to the longest spacings was only a few times greater than the limiting accuracy of measurements. Further, the optical data on angular widths are not precisely defined and, except for those nebulae for which isophotes in one of the emission lines of hydrogen have been published, depend on the responses and exposure times of photographic plates. Taking into account these limitations, the agreement between the radio and optical widths was found to be generally satisfactory.

4. Optical Depths and Electron Temperatures of Two Optically Thick Nebulae

A small number of planetary nebulae show clearly the effect of self-absorption in their spectra, and in these cases an estimate of the optical depth and electron temperature can be made by fitting to the observed flux densities a calculated spectrum based on a model of the nebula which represents the variation of optical depth with solid angle. Such an analysis has been performed (Thompson, 1967) for IC 418 and NGC 6572, two nebulae for which profiles or isophotes of brightness in Hβ and other emission lines of hydrogen have been published (Berman, 1930; Wilson and Aller, 1951; Aller, 1956). The Hβ brightness at any point on the surface of a nebula is proportional to the integral along the line of sight of $N_e N_i T_e^{-0 \cdot 91}$ (Peimbert, 1967) and the radio frequency optical depth is proportional to $N_e N_i T_e^{-1 \cdot 35}$, where N_e and N_i are the electron and proton densities. Thus, if the temperature variations within a nebula are not too large, the isophotes of Hβ brightness should accurately represent the variation of relative optical depth with solid angle. On this basis a computer program was used to calculate the expected spectrum and the r.m.s. deviation from it of the measured values of flux density, for a series of values of T_e and of τ_1, the optical depth at 1GHz along a line of sight through the centre of the nebula. The measured flux densities were taken from work by Lynds (1961), Menon and Terzian (1965), Slee and Orchiston (1965), Hughes (1967), Thompson *et al.* (1967), and Kaftan-Kassim (1967). The best fit to the observed data, as indicated by the minimum value of the r.m.s. deviation, was obtained with $T_e = 7100\,°K$ and $\tau_1 = 3{\cdot}5$ for IC 418 and $T_e = 6500\,°K$ and $\tau_1 = 19{\cdot}2$ for NGC 6572. These temperatures are much lower than those derived from forbidden-line ratios, which are approximately 19000 °K for IC 418 and 13000 °K for NGC 6572 (Seaton, 1954; Liller and Aller, 1954). The temperatures derived from the radio data depend almost entirely upon the flux-density values at frequencies of 1420 MHz and lower, where the observations show appreciable self-absorption. Taking into account the errors assigned to the measured flux densities, the uncertainties in the resulting values of electron temperatures are large, and in the case of IC 418 a temperature of 10000 °K or a little higher cannot be excluded. The optical data used were corrected for the increase in angular dimensions introduced by seeing fluctuations, which would have the effect of decreasing T_e, but it is difficult to be sure that all such systematic errors were eliminated. As a general conclusion it appears, however, that this analysis indicates values of T_e which are lower than those derived from the forbidden-line ratios by a factor of at least 1·5. The emission measures obtained from the best fit values of τ_1 and T_e given above are $6{\cdot}7 \times 10^6$ cm^{-6} parsec for IC 418 and $3{\cdot}3 \times 10^7$cm^{-6} parsec for NGC 6572, and correspond to the line of sight through the centre of each nebula.

A most probable explanation of at least part of the discrepancy between the radio and forbidden-line values of T_e is that the temperature is not constant but varies significantly within each nebula. Peimbert (1967) has shown that under these circumstances the value of electron temperature determined by any particular method will be weighted towards the cooler or hotter parts of the nebula, depending upon the way in which the strengths of the measured parameters are related to T_e. A factor of 1·5 between the radio and forbidden-line values of T_e would be explained if the r.m.s. deviation of T_e, weighted in proportion to $N_e N_i$, is 0·31 of the mean value. In the case of IC 418 the isophotes of the λ5007 line of [O III], on which the forbidden-line temperature values in part depend, show a much greater concentration towards the central part of the nebula than do the Hβ isophotes (Aller, 1956). The forbidden-line temperature should thus be more strongly weighted towards the central region of the nebula than the radio value, and on this basis the present results suggest a decrease in temperature from the centre to the outer parts of IC 418.

5. The 21-cm Hydrogen Line in Absorption

At the frequency of the 21-cm hydrogen line, absorption features are to be expected in the spectra of the planetary nebulae. These would result from the presence of

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neutral hydrogen between the nebula and the observer, which could be either part of the galactic population of hydrogen clouds, or the neutral outer part of a planetary nebula in which the ionization boundary does not enclose the whole mass of gas. The following is a description of preliminary observations made during May 1967 by Thompson and Colvin in an investigation to detect such absorption features, again using the interferometer at the Owens Valley Radio Observatory.

For observations of hydrogen-line absorption the interferometer offers a great advantage over a single antenna, since galactic hydrogen clouds which lie within the antenna beam are highly resolved, and the response of the interferometer to the background emission can therefore be ignored. A receiver bandwidth comparable to the expected Doppler width of the absorption features is required, which limits the maximum usable bandwidth to about 100 kHz. With this bandwidth the sensitivity of the interferometer is reduced by a factor of 10 relative to that obtained with the bandwidth of 10 MHz used for continuum observations. The present investigation therefore included only the 6 nebulae listed in Table 2, which were chosen for their high

Table 2

Nebulae observed for hydrogen-line absorption

Nebula	Flux Density at 21-cm Wavelength (10^{-26} Wm^{-2} Hz^{-1})	Galactic Coordinates l^{II}	b^{II}	Total Observing Time (Hours)
IC 418	1·14 ± 0·06	215°2	−24°3	15·1
NGC 6302	2·02 ± 0·16	349·5	1·0	4·75
NGC 6369	1·63 ± 0·1	2·4	5·8	11·25
NGC 6543	1·13 ± 0·16	96·5	29·9	12·25
NGC 6857	5·0 ± 0·4	70·3	1·6	2·5
NGC 7027	1·30 ± 0·07	84·9	−3·5	12·0

flux densities and also for their small diameters, since nebulae in the early stages of their expansion are most likely to be incompletely ionized.

The observations were made using an interferometer system with 23 channels, each of 100-kHz bandwidth. The antenna spacing used was 400 feet East–West, and the total observation time for each nebula is given in Table 2. The results of these observations are shown in Figure 1, in which the relative amplitudes are plotted against the velocity with respect to the local standard of rest corresponding to the centre frequency of each channel. The radial velocities of the nebulae, as measured optically by Campbell and Moore (1918) or Wilson (1950), are indicated by V_R. The features of definite significance are the absorption dip near zero velocity for NGC 6369 and the broad dip near −40 km/sec for NGC 6857. The dip for NGC 6369 is well removed from V_R and is therefore attributable to galactic hydrogen clouds. The absorption for NGC 6857 is more difficult to interpret since V_R has not been measured and the effect of the

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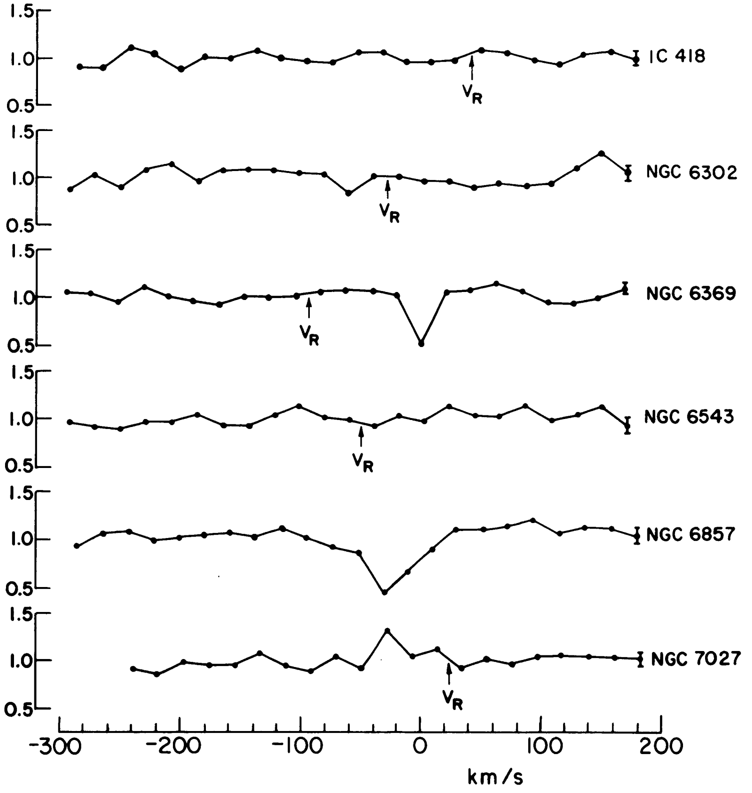

FIG. 1. *Preliminary results of a program to detect the 21-cm line in absorption. The relative signal strengths in 23 channels of width 100 kHz are plotted against velocity with respect to the local standard of rest. The radial velocities of the nebulae, determined optically, are indicated by* V_R. *The rms deviation of a single point is indicated by the error bar at the right-hand end of each curve.*

diffuse nebula mentioned in Section 1 is not known. It is interesting to note that NGC 6369 is also one of the nebulae for which the Hβ absorption is very large (Table 1). Absorption dips resulting from galactic hydrogen may provide information on the distances of the nebulae when examined with a narrower receiver bandwidth, so that details of the profile can be determined. Positive peaks such as those at -30 km/sec for NGC 7027 are probably caused by the residual response to galactic emission features within the antenna beam.

The absorption resulting from a neutral-hydrogen envelope around a planetary nebula would be expected to occur within a range of velocities from V_R to $V_R - V_E$, where V_E is the expansion velocity measured relative to the centre of the nebula. An expansion velocity of 21·35 km/sec has been measured for NGC 7027 and a velocity near zero for IC 418 (Wilson, 1950). The record of NGC 6302 shows a small dip near

-60 km/sec, but this cannot be regarded as significant on the basis of the present data alone. For IC 418, NGC 6369, NGC 6543 and NGC 7027 it is possible to put an upper limit of 0·1 on the fraction of power absorbed in a 100-kHz channel in the vicinity of V_R. If we assume that the width of an absorption feature is not greater than 200 kHz, which corresponds to a Doppler spread of 42 km/sec, then at least half of the absorbed power must fall within one receiving channel. Using a simple spherical model it is found that $\int \tau(v)\, dv < 2{\cdot}8$ km/sec, where $\tau(v)$ is the optical depth in the neutral-hydrogen envelope corresponding to the radial velocity v. For IC 418 and NGC 7027 the radius is approximately $1{\cdot}6 \times 10^{17}$ cm (Aller, 1956), from which one finds that the mass of neutral gas is not greater than $1{\cdot}4 \times 10^{-3} T$ solar masses, where T is the temperature of the neutral hydrogen. For $T = 100\,°$K the upper limit on the neutral hydrogen is therefore 0·14 solar masses and for $T = 1000\,°$K, 1·4 solar masses. Since the total mass of a planetary nebula is about 0·14 solar masses (O'Dell, 1962), the upper limit is of significance only if we take a low value for the gas temperature. It is planned to make further observations to attempt to improve this limit.

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DISCUSSION

Terzian: Using your method of determining electron temperatures I find that H II regions also have lower indicated average temperatures compared with the temperatures determined by optical methods.

Aller: Walker and Kron are obtaining improved isophotes of a number of planetaries using an electronic camera. A long focal length and exquisite seeing are required. Berman's pioneer isophotometry carried out 40 years ago, was affected by the small scale of the only telescope available for his program at that time.