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# PHOTOELECTRIC FILTER PHOTOMETRY OF PLANETARY NEBULAE

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## ABSTRACT

Twenty-five planetary nebulae have been observed photoelectrically with a variety of interference filters. New absolute Hβ fluxes are presented here for 22 of these nebulae. Fluxes relative to Hβ are given for 23 nebulae in one or more of the following lines: λ4959 [O III], λ4740 [Ar IV], λ4686 He II, λ4471 He I, λ3868 [Ne III], and λ3727 [O II]. *B* and *V* apparent magnitudes are given for the central stars of most of the nebulae. Helium-to-hydrogen ratios are derived for 10 nebulae, and upper limits are set on two more.

*Subject heading:* nebulae: planetary

### I. INTRODUCTION AND OBSERVATIONAL PROCEDURE

In 1971 a program of photoelectric interference filter photometry of planetary nebulae was begun at the Prairie Observatory of the University of Illinois. The primary purposes of this program are the precise measurement of helium-to-hydrogen ratios and the photometry of large nebulae of low surface brightness. The observatory site has a very dark sky, and is well suited to the measurement of weak line fluxes from extended objects. The photometer has a maximum aperture of 7′, so that absolute fluxes can be measured for almost any planetary without the need for drift scans.

The instrument used is a single channel photometer with a cooled EMI 6256-S photomultiplier coupled to the 40 inch (102 cm) Cassegrain telescope which can operate at either f/7.6 or f/13.5 depending upon the aperture requirements. Until June of 1974 the system used a d.c. integrating device with digital display; after this date, pulse-counting was employed. The photometer and original amplifier were built by E. C. Olson, and the pulse-counting equipment by M. A. Nelson.

The interference filters were made by Baird Atomic, Inc. Their transmission wavelengths, lines transmitted, equivalent widths, and transmissions at the emission line wavelengths are presented in successive columns in Table 1. Eight filters pass nebular emission lines, and three, which are essentially free of lines, are used to observe the continuum. The λ5500 filter is the Strömgren *y* four-color filter. Those at λ4880 and λ4861 are standard wide and narrow Hβ filters.

Let $D'(\lambda)$ be the deflection, or number of counts, observed through the photometer system for a given filter. Then

$$D'(\lambda) = \mathscr{F}(\lambda_0)T(\lambda_0)S(\lambda_0)A(\lambda_0) + \int_0^\infty \mathscr{F}_c(\lambda)T(\lambda)S(\lambda)A(\lambda)d\lambda + D(\text{Sky})\,, \quad (1)$$

where $T(\lambda)$, $S(\lambda)$, and $A(\lambda)$ represent the filter transmission function, telescope-photometer sensitivity function, and atmospheric extinction function, respectively. $\mathscr{F}(\lambda_0)$ and $\mathscr{F}_c(\lambda)$ are the flux in the line and the flux density in the continuum as would be observed above the atmosphere. The sky is observed with the nebula by an ON-OFF technique, usually several (3–6) 30 second integrations ON, followed by the same number OFF. The sky is then subtracted during reduction to give $D(\lambda) = D'(\lambda) - D(\text{Sky})$ where $D(\lambda)$ is the nebular deflection alone.

The filters are all sufficiently narrow to assume that $T(\lambda)$, $S(\lambda)$, $A(\lambda)$, and $\mathscr{F}_c(\lambda)$ are constant across the filter bandpass. $A(\lambda)$ is represented by $A(\lambda) = \text{dex}\,[-a(\lambda)M]$ where $M$ is the air mass of the observation. The atmospheric transmission function $a(\lambda)$ is determined for each night by four-color photometry of several stars from the standard list of Crawford and Barnes (1970). These atmospheric standards are observed over the course of a night so that variations with time in $a(\lambda)$ can be taken into account. The air mass of an object of course changes continuously during observation. During reduction it is computed for the center point of each individual observation, which rarely lasts for more than 3 minutes (see above).

TABLE 1

INTERFERENCE FILTERS

| λ | Line Observed | *W* | *T* (line) |
|---|---|---|---|
| 5500..... | Continuum | 208 | ... |
| 4880..... | Hβ, λ4959 [O III],<br>λ5007 [O III] | 134 | 0.765, 0.395,<br>0.12 |
| 4861..... | Hβ | 17.1 | 0.59 |
| 4740..... | [Ar IV] | 6.29 | 0.485 |
| 4686..... | He II | 5.83 | 0.46 |
| 4471..... | He I | 16.0 | 0.585 |
| 4428..... | Continuum | 19.73 | ... |
| 4363..... | [O III] | 4.74 | 0.475 |
| 3868..... | [Ne III] | 6.46 | 0.25 |
| 3727..... | [O II] | 15.0 | 0.435 |
| 3552..... | Continuum | 37.04 | ... |

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After correction for atmospheric extinction, we can then write

$$D(\lambda) = \left[\mathcal{F}(\lambda_0)T(\lambda_0) + \mathcal{F}_c(\lambda_0)\int_0^\infty T(\lambda)d\lambda\right]S(\lambda_0)$$

$$= \left[\frac{\mathcal{F}(\lambda_0)T(\lambda_0)}{\int_0^\infty T(\lambda)d\lambda} + \mathcal{F}_c(\lambda_0)\right]S(\lambda_0)\int_0^\infty T(\lambda)d\lambda\,. \quad (2)$$

We want the flux in the line, $\mathcal{F}(\lambda_0)$, and solve equation (2) to find

$$\mathcal{F}(\lambda_0) = \frac{\int_0^\infty T(\lambda)d\lambda}{T(\lambda_0)}\left[\frac{D_\lambda}{S(\lambda_0)\int_0^\infty T(\lambda)d\lambda} - \mathcal{F}_c(\lambda_0)\right]. \quad (3)$$

Thus we must determine three quantities above: (1) $\int_0^\infty T(\lambda)d\lambda/T(\lambda_0) = Q(\lambda)$, the ratio of the integrated filter transmission to the transmission at the line wavelength, (2) the function $S(\lambda_0)\int_0^\infty T(\lambda)d\lambda = Y(\lambda)$, and (3) the flux density in the continuum underlying the nebular line.

The values of $Q(\lambda)$ were determined for each filter from transmission curves supplied by the manufacturer. The values of $Y(\lambda)$ are determined for each filter by observing one or more standard stars over the course of a night. We write the deflection for a standard star reduced to the same integration time as the nebula, and corrected for atmospheric extinction, as

$$D^*(\lambda) = \mathcal{F}_c^*(\lambda_0)S(\lambda_0)\int_0^\infty T(\lambda)d\lambda = \mathcal{F}_c^*(\lambda_0)Y(\lambda)\,. \quad (4)$$

If we know $\mathcal{F}_c^*(\lambda_0)$, we can determine $Y(\lambda)$ for each filter. Three standard stars have been chosen for this work: $\eta$ UMa, 55 Cyg, and $\pi^3$ Ori. The primary standard is $\eta$ UMa. Except for λ3868 and λ3727 (see below), the relative energy distribution adopted for it is an average of that measured by Wolff, Kuhi, and Hayes (1968) and an energy distribution measured at Prairie Observatory by comparison with BD +28°4211 where Stone's (1974) fluxes were used for the latter star. The two energy distributions are within ±4 percent of one another. The energy distributions for 55 Cyg and $\pi^3$ Ori were first taken from Code (1960) modified to the Hayes (1970) system. Further small adjustments were made to the fluxes of these two stars by comparing each of them with $\eta$ UMa on several nights.

One of the major problems with this kind of filter photometry is that the standard stars have absorption lines, often strong ones, within the passbands of the filters. This problem is particularly evident for H$\beta$. In addition, the λ4471 filter is affected by λ4471 He I and λ4481 Mg I, the λ3727 and λ3868 filters by hydrogen lines, and the λ4428 filter by the λ4430 interstellar band present toward 55 Cyg. Line blanketing coefficients, which include convolution with the filter passband, were determined for each filter-star combination by a combination of methods. Measurements were made from a spectrogram of 55 Cyg taken at Kitt Peak, and equivalent widths of lines were supplied by E. C. Olson for $\eta$ UMa and $\pi^3$ Ori. Comparison of wide and narrow H$\beta$ filter measurements allowed the computation of the effective equivalent width of H$\beta$. The three stars all have different coefficients, so that intercomparison also allowed their computation. Finally, the λ3868 and λ3727 filters are in badly blanketed regions. The effective fluxes of the three standards were determined by comparing 55 Cyg and $\eta$ UMa with BD +28°4211 which is free of significant lines in this region.

With $Q(\lambda)$ and $Y(\lambda)$ known, all that is left is to determine the flux density of the underlying continuum $\mathcal{F}_c(\lambda_0)$. The observed continuum is a combination of the nebular continuum and the continuum of the central star. Especially for the larger nebulae, field stars occasionally produce an additional component. The flux density in the continuum is found from measurements made at λ5500, λ4428, and λ3552. The fluxes are easily measured at these points, since $D(\lambda) = \mathcal{F}_c(\lambda)Y(\lambda)$, and $Y(\lambda)$ has been found from standard star observations. The λ3552 point is observed usually only in conjunction with λ3868 and λ3727. In order to find the continuum under these lines it is necessary first to remove the Balmer continuum contribution from the λ3552 observation. The strength of the Balmer continuum can be estimated with respect to the observed H$\beta$ flux by using the continuum tables of Brown and Mathews (1970), Brocklehurst's (1971) effective recombination coefficients, and by adopting a reddening constant (see below). Once the Balmer continuum component is removed from the λ3552 observations, a smooth continuum can be drawn through the three points. These continuum points have proven to be entirely satisfactory for accurate measurement of the line fluxes. The continuum is usually weak with respect to the stronger lines (so that errors in the interpolated continuum are of little consequence), and one of the observed continuum points is very close in wavelength to the weakest line commonly observed, λ4471 He I.

The λ4880 (H$\beta$-wide) filter passes three lines: H$\beta$, and λ4959 and λ5007 of [O III]. The flux in H$\beta$ alone is known from the λ4861 (H$\beta$-narrow) filter, and it can then be removed from the λ4881 observations. If we use the known ratio of $\mathcal{F}(\lambda 5007)/\mathcal{F}(\lambda 4959) = 2.9$ (Nussbaumer 1971), we can then determine the flux in either of these lines; the results are expressed here in terms of $\mathcal{F}(\lambda 4959)$.

The positions of the continuum points and the filter bandwidths were chosen to minimize contamination from other emission lines; some such contamination is inevitable, however, and must be removed from the observations. The λ5500 filter passes λ5411 He II (Pickering 7), λ3727 includes several weak H lines, and λ3868 includes λ3889 H and He I. The contaminants are easily removed if their fluxes relative to H$\beta$ are known. These were generally computed by using Brocklehurst's (1971, 1972) tables, where interstellar reddening was taken into account. Reddening constants were taken from Cahn (1976) or Kaler (1976*a*). Other minor contaminants include [Cl III] and [N II] lines for the λ5500 filter and He I and [Ne V] lines for

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the λ3552 filter. The observational errors were such that it was unnecessary to consider these except for NGC 7027 (see below).

So far, the fluxes have been derived on an arbitrary scale, since only relative energy distributions are given in the literature cited. Calibration to an absolute scale is made by adopting the absolute flux density at λ5480 for a star of $V = 0.00$, as measured by Oke and Schild (1970). Visual magnitudes of the standard stars were taken from Blanco *et al.* (1968), as follows: $\eta$ UMa, 1.86 ± 0.02; 55 Cyg, 4.83 ± 0.03; $\pi^3$ Ori, 3.19 ± 0.01.

The principal source of error lies in the evaluation of the $Q(\lambda)$'s, either in $Q(\mathrm{H}\beta)$, since H$\beta$ is expressed as an absolute flux, or in the ratios $Q(\lambda)/Q(\mathrm{H}\beta)$, as the other lines are expressed relative to H$\beta$. The measurements of $Q(\lambda)$ were made from transmission curves made by a Carey Spectrometer working at f/6, whereas the observations are made at f/7.6 and f/13.5. Errors also enter purely from the measurement of the transmission curves themselves. Adjustment of the nebular fluxes is made by observing NGC 7027 at both f-ratios with the system as so far described, and by determining the correction factors necessary to bring the observed fluxes of NGC 7027 into agreement with the following adopted set of fluxes. The value of $\mathscr{F}(\mathrm{H}\beta)$ (which includes He II Pickering 8) for NGC 7027 is $6.41 \times 10^{-4} \pm 0.32$ ergs cm$^{-2}$ s$^{-1}$ from Miller and Mathews (1972). Fluxes relative to H$\beta$ are taken from the compilation of photoelectric fluxes presented by Kaler *et al.* (1976), except for that of λ4740 [Ar IV] which was taken from their photographic measurement. The adopted relative fluxes, with mean error, are given in Table 2. (The last column is discussed in the next section.) The corrections to NGC 7027 are generally 10 percent or less, except for λ4959 for which it is ~20 percent, not surprising since the line is offset to the wing of the transmission curve.

In effect, the $Q(\lambda)$ are determined by the NGC 7027 observations. The underlying continuum of NGC 7027 is measured directly by comparison with standard stars. These measurements are discussed elsewhere (Kaler 1976*b*). In principle, the observations of the nebulae could have been reduced by direct comparison to NGC 7027. This procedure would be impractical, however, because of its inaccessibility during part of the year and the more time-consuming integration required.

TABLE 2

ADOPTED RELATIVE FLUXES FOR NGC 7027

| λ | ID | $\mathscr{F}(\lambda)$ (rel.) | Correction Error (%) |
|---|---|---|---|
| 4959...... | [O III] | 512 ± 2 | ±0.7 |
| 4861...... | Hβ | 100 | ±4* |
| 4740...... | [Ar IV] | 6.4 ± 0.4 | ±8 |
| 4686...... | He II | 41.2 ± 0.9 | ±4 |
| 4471...... | He I | 2.64 ± 0.10 | ±8 |
| 4363...... | [O III] | 18.5 ± 0.4 | ±7 |
| 3868...... | [Ne III] | 53.1 ± 0.6 | ±3 |
| 3727...... | [O II] | 14.3 ± 1.2 | ±10 |

* Error for absolute flux. Other errors are for corrections relative to Hβ.

The use of the filters involves two other problems. First, the fluxes must be corrected for shifts of the lines within the filter passbands due to radial velocity effects. These corrections, which are never more than a few percent, are derived from the radial velocities given in the Perek-Kohoutek (1967) catalog, or made by Bohuski and Smith (1974), and the filter transmission curves. Of the nebulae considered in this study only IC 972 and A39 have no measured radial velocities. Nebular expansion will also cause shifts of the lines within the filter passbands. No correction is made for this effect. The expansion shifts are not generally known for the lines of the nebulae observed. Generally, however, the expansion velocities are small enough that the correction required would be substantially less than the error of measurement.

Second, the problem of filter drift must be considered. Drift in wavelength can occur from temperature variations, since the temperature of the filters was uncontrolled in the photometer, and from aging effects. With one exception, drift does not appear to be significant. The standard NGC 7027 was observed on 11 nights over 3 years under a variety of observing conditions, as were a number of other nebulae, and no systematic effects can be seen, at least to within the errors quoted (see Table 3). The exception is for the λ4686 filter. This narrowest filter was very stable until 1975 April when it suddenly shifted by several angstroms. Only one measurement was made using it after that date, and the shift was taken into account.

One final correction must be made, for the photometer "beam pattern." Some of the nebulae observed are quite large, up to 5′ in diameter. The photometer response is not flat over this large a diameter, and drops to about 1/2 of the maximum near the edge of the field. The beam has been mapped at both f-ratios by positioning a bright star at various points within the field of view. Corrections were derived for nebulae of various diameters by convolving the beam pattern with circles of uniform surface brightness. Errors will be introduced if the nebula does not have uniform surface brightness. This correction is necessary only for objects larger than 2′ in diameter. Stratification of ions will introduce a small error; for example, the correction factors will be different for H$\beta$ and He II λ4686. The effect would be to increase slightly $\mathscr{F}(\lambda4686)$ over that presented in this paper. This error is not computed or accounted for but it is expected to be small, almost certainly less than 10 percent.

## II. LINE FLUXES AND ERRORS

The results of the observations are presented in Table 3. Columns (1) and (2) give the common name of the nebula and the Perek-Kohoutek (1967) designation, respectively. Column (3) gives the value of $\log \mathscr{F}(\mathrm{H}\beta)$ in ergs cm$^{-2}$ s$^{-1}$. For nebulae with λ4686 present, the flux of He II Pickering 8 is included in the measurement. Columns (4) through (9) give the relative line fluxes for the various lines on the scale $\mathscr{F}(\mathrm{H}\beta) = 100$. Improved and additional fluxes for

## TABLE 3

### Observed Line Fluxes and Central Star Magnitudes

| | | | Relative Line Fluxes, $I(\mathrm{H}\beta) = 100$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nebula (1) | PK (2) | $-\log \mathscr{F}(\mathrm{H}\beta)$ (ergs cm$^{-2}$ s$^{-1}$) (3) | λ4959 [O III] (4) | λ4740 [Ar IV] (5) | λ4686 He II (6) | λ4471 He I (7) | λ3868 [Ne III] (8) | λ3727 [O II] (9) | *B* (10) | *V* (11) | Notes (12) |
| NGC 246 W | ... | ... | 172 ± 2 | ... | ... | ... | ... | ... | | ... | |
| C | 118−74°1 | ... | ... | ... | (121 ± 14) | ... | ... | ... | (12.0 ± 0.1) | ... | |
| N | | ... | ... | ... | (90 ± 15) | ... | ... | ... | | ... | |
| NGC 1514 | 165−15°1 | (11.05 ± 0.03)* | 385 ± 25 | ... | ... | ... | ... | ... | (10.03 ± 0.05) | (9.44 ± 0.04) | 1 |
| NGC 2346 | 215+3°1 | ... | ... | ... | ... | ... | ... | ... | 11.43 ± 0.06 | 11.2 ± 0.1 | 2 |
| NGC 2438 | 231+4°2 | 11.23 ± 0.03 | (460 ± 13) | ... | 41 ± 3 | (< 3) | (87 ± 9) | (390 ± 45) | (15.0 [+0.7, −0.4]) | ... | 3 |
| NGC 2440 | 234+2°1 | (10.54 ± 0.02) | (505 ± 10) | ... | (71 ± 4) | ... | ... | ... | ... | ... | 4 |
| NGC 2474−5 | 164+31°1 | (11.34 ± 0.06) | 202 ± 43 | ... | 21 ± 9 | ... | (110 ± 26) | ... | ... | ... | 5 |
| NGC 2610 | 239+13°1 | 11.42 ± 0.02 | 170 ± 10 | ... | (95 ± 10) | (< 2.3) | (28 ± 8) | (30 ± 15) | ... | ... | |
| NGC 3242 W | 261+32°1 | 9.83 ± 0.03 | 410 ± 20 | ... | 27 ± 3 | ... | ... | (21 ± 2) | 11.7 ± 0.1 | 11.9 ± 0.1 | |
| C | | ... | ... | ... | (36 ± 1) | ... | ... | (17 ± 3) | | | |
| NGC 3587 W | 148+57°1 | 10.49 ± 0.02* | 253 ± 9 | (2.8 ± 1.2) | 10.3 ± 0.9 | 3.7 ± 1.4 | (73 ± 20) | ... | ... | ... | |
| C | | | (280 ± 15) | ... | (21 ± 2) | ... | ... | ... | ... | ... | |
| NGC 4361 | 294+43°1 | (10.63 ± 0.05) | (99 ± 23) | (6.1 ± 0.6) | (115 ± 5) | 1.0 ± 0.4 | ... | ... | 12.93 ± 0.07 | (13.6 [+∞, −3)] | |
| NGC 6833 | 82+11°1 | 11.33 ± 0.02 | 250 ± 4 | ... | ... | 4.7 ± 0.7 | ... | ... | 14.95 ± 0.07 | 15.1 ± 0.1 | |
| NGC 7026 | 89+0°1 | (10.97 ± 0.02) | (332 ± 5) | ... | (10.1 ± 0.7) | 3.8 ± 0.5 | ... | ... | 15.6 ± 0.2 | 14.2 ± 0.1 | 6 |
| IC 289 | 138+2°1 | ... | ... | ... | ... | ... | ... | ... | (15.5 [+0.7, −0.5]) | ... | 2 |
| IC 972 | 326+42°1 | 12.09 ± 0.03 | 270 ± 35 | ... | 10 ± 10 | ... | ... | 400 ± 100 | 15 ± 1: | >16 | 8 |
| IC 2165 | 221−12°1 | 10.99 ± 0.03 | ... | ... | (38 ± 3) | 2.6 ± 0.4 | ... | ... | 14.8 ± 0.3 | 15.1 ± 0.2: | 7 |
| IC 3568 | 123+34°1 | 10.87 ± 0.02 | 350 ± 20 | (3.9 ± 1.8) | ... | 4.4 ± 0.6 | (54 ± 6) | ... | 12.3 ± 0.2 | 12.4 ± 0.2 | |
| A33 | 238+34°1 | 11.4 ± 0.3 | 265 ± 65 | ... | (62 ± 25) | ... | ... | ... | ... | ... | 8, 9 |
| A36 | 318+41°1 | 10.93 ± 0.03* | 100 ± 20 | ... | (118 ± 10) | ... | (17 ± 11) | ... | 11.2 ± 0.1 | 11.3 ± 0.1 | 10 |
| A39 | 47±42°1 | 11.85 ± 0.05* | 300 ± 50 | ... | (90 [+10, −40]) | ... | ... | 33 ± 22 | ... | ... | 11 |
| Hu 1–1 | 119−6°1 | 11.70 ± 0.02 | 485 ± 18 | ... | (9.3 ± 1) | 3.0 ± 0.6 | ... | ... | >18.3 | 16.5 ± 0.3 | |
| Hu 1–2 | 84−8°1 | 11.27 ± 0.02 | 268 ± 6 | (7.8 ± 1.8) | (95 ± 5) | 2.9 ± 0.5 | (35 ± 6) | ... | 15.8 (+0.7, −0.4) | (15.1 ± 0.1:) | 12 |
| M1–64 | 64+15°1 | (11.96 ± 0.05) | (261 ± 42) | ... | ... | ... | ... | ... | ... | ... | |
| Me 2–1 | 342+27°1 | 11.39 ± 0.03 | (525 ± 21) | ... | (90 ± 8) | ... | ... | ... | 14.2 (+1, −0.5) | (13.9 ± 0.2) | |
| Me 2–2 | 100−8°1 | 11.27 ± 0.03 | (242 ± 16) | ... | ... | 8.1 ± 0.8 | (53 ± 5) | ... | 15.0 ± 0.5 | (160 ± 0.2) | 12 |
| Vy 1–1 | 118−8°9 | (11.60 ± 0.03) | (300 ± 30) | ... | ... | (4.6 ± 2.4) | (35 ± 15) | ... | (14.2 ± 0.2) | ... | |

### NOTES TO TABLE 3

1. NGC 1514: Continuum dominated by a bright A-star (Greenstein 1972) with strong Hβ absorption. Effect of the absorption line was accounted for by observing the star with a small diaphragm.
2. NGC 2346, IC 289: Fluxes given by Kaler, Aller, and Czyzak (1976).
3. NGC 2438: Flux significantly lower than earlier reported; see text. Some of NGC 2438 may not have been included in the diaphragm.
4. NGC 2440: Continuum, as for NGC 7027, appears to be all nebular. No central star is detected.
5. NGC 2474–NGC 2475: This nebula is larger than the 4′ aperture used to observe it. The two lobes (NGC 2474 and NGC 2475) were observed separately and their fluxes summed. Some of nebula was missed, so that the true flux is somewhat greater than presented here.
6. NGC 7026: Flux of λ4471 less than half that reported by Czyzak and Aller (1970), and more in line with that measured by Aller (1951).
7. IC 2165: Flux of λ4471 half that reported by Kaler, Czyzak, and Aller (1968). The central star cannot be seen, but the continuum appears clearly above the nebular level.
8. IC 972 and A39, no radial velocity available.
9. A33: A very bright field star makes the measurement of total flux very difficult. The flux given here is derived from a measurement of the surface brightness of a 76″ diameter section of the brightest part of the nebula, multiplied by 2.6.
10. A36: Note the very high flux of λ4686 He II; this planetary, like NGC 246 and NGC 4361, is of very high excitation.
11. λ4686 filter had shifted, resulting in very high error. Value presented represents little more than a significant detection.
12. Hu 1–2 and Me 2–2: See also Kaler (1974); the fluxes are modified somewhat from the earlier paper.

W: Whole nebula.
C: Central region (circular apertures of 40″, 27″, 76″ for NGC 246, 3242, 3587, respectively).
N: 40″ circular aperture 50″ N of central star.
* Correction for photometer beam applied.

two nebulae (He 2–1 and Me 2–2) reported on in an earlier paper (Kaler 1974) are included in Table 3.

Mean errors are given for each line flux in the table. Errors are derived during reduction from the residuals in the individual deflections as compared with a mean deflection computed for an entire series of observations with a filter. Most nebulae were observed on two or more nights, and an error can also be computed by comparison of results of individual nights. Generally, each night was treated independently of others. In some instances, however, one of the continuum points had to be adapted from one night to another because of weather or equipment problems. The errors in Table 3 are the larger of the two errors so computed. Errors in atmospheric extinction and in standard star observations are not expressly included, although they are naturally included in errors derived from observations made on more than one night. The standard stars are bright and random error in their measurement is almost vanishingly small. Errors in atmospheric extinction, which are usually small anyway, enter into the reductions only through the differential air mass between the nebula and the standard star, and will ordinarily be small compared with the random error. Observations derived from only one night's observation are enclosed in parentheses.

There are also errors in the correction factors derived for the $Q(\lambda)$ from the NGC 7027 observations. These errors are a compound of the mean errors of the adopted NGC 7027 fluxes (col. [3], Table 2), and the errors in the filter observations of NGC 7027. The percentage of errors in the correction factors are given in column (4) of Table 2. The error for H$\beta$ is for the absolute flux, the others are for fluxes relative to H$\beta$. The errors presented in Table 3 include the errors in the correction factors. An effort has been made to make these errors as realistic as possible.

Of the 22 nebulae for which absolute fluxes are presented in Table 3, 13 have been observed previously by O'Dell (1962, 1963), Collins, Daub, and O'Dell (1961), Capriotti and Daub (1960), and Perek (1971). The logs of the fluxes observed here are compared with those observed by the above authors in Figure 1. Also included are IC 289 and Hb 12 whose fluxes were measured by the same system and are given by Kaler, Aller, and Czyzak (1976). The present fluxes are tied to Miller and Mathews's (1972) flux of NGC 7027, which is 0.07 in the log fainter than the value given by Capriotti and Daub (1960) because of changes in the absolute stellar standards. We would expect then that the correlation between the two sets of fluxes would be displaced upward by about 0.07, which fits the run of points very well.

The most discrepant point in Figure 1 is NGC 2438 which, after the calibration change of $-0.07$ is applied to O'Dell's (1963) measurement, is still low by 0.14 in the log. The value given in Table 1 may be an underestimate, as the main body of the nebula just barely fits into the largest aperture used, and the weak outer envelope is missed (see Perek and Kohoutek 1967). The flux of this object is difficult to measure because of its setting on the periphery of a galactic cluster.

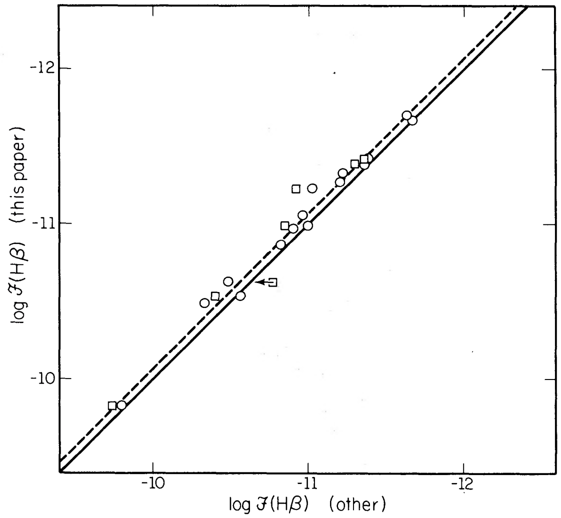

FIG. 1.—The log of $\mathscr{F}$(H$\beta$) observed here plotted against that observed by others. The circles represent comparison with observations of O'Dell (1962, 1963), Collins, Daub, and O'Dell (1961), and Capriotti and Daub (1960). The boxes represent comparison with Perek (1971). The solid line is the 1:1 line; the dotted line is the solid line shifted upward by $-0.07$ in log $\mathscr{F}$(H$\beta$) to account for the different absolute calibration used by the above authors and the present work.

### III. MAGNITUDES OF THE CENTRAL STARS

As a consequence of the measurement of the line fluxes, continuum flux densities at λ5500 and λ4428 are also available for most of the planetaries listed in Table 3. The measured values will be combinations of the atomic continua of the nebulae and continua from central stars and field stars. The nebulae with significant field star contributions can be excluded readily by inspection of photographs. If the contribution of the nebular continuum can be evaluated, magnitudes of the planetary nuclei can be determined. The λ5500 (Strömgren $y$) filter readily yields a $V$ magnitude, and λ4428 is close to the effective wavelength of the $B$ magnitude, so that $B$ can be determined with a small correction.

For each nebula, the expected nebular atomic continua at λ4428 and λ5500 were calculated from the tables of Brown and Mathews (1970) and Brocklehurst (1971) and the measured H$\beta$ flux of the object. The appropriate values of electron temperature, $T_e$, reddening constant, $c$ (with the Whitford 1958 curve), ratios of singly and doubly ionized helium to hydrogen were used, and $X$ (see Brown and Mathews 1970) was set to 0.3 for the 2-photon calculations. Values of $T_e$ and $c$ were taken from Cahn (1976) or calculated from data in Kaler's (1976*a*) catalog, and the He$^+$/H$^+$, He$^{2+}$/H$^+$ ratios are from this paper, or calculated from data in the preceding reference.

With the nebular continuum removed, magnitudes at $y$ and λ4428 were simply calculated by taking the ratios of photon-counting rates measured for the nebula and standard star after correction for atmospheric extinction. The magnitudes adopted for the standards are given in the previous section. The effective wavelengths of the *V* and *y* filters are not very dependent upon the object being observed so that the magnitude of the planetary nucleus derived from the *y* deflections is called *V*. The effective wavelength for the *B* filter, however, changes as a function of $B - V$, so that the correction of the natural magnitude at λ4428 to *B* depends upon which standard star was used, and upon reddening constant to the nebula. This correction was applied to the λ4428 magnitude by assuming that the planetary was a reddened blackbody at $T_{\text{eff}} \approx 10^5$ K, to yield *B*. NGC 1514 and NGC 2346 are exceptions in that the apparent nuclei are of roughly spectral class A (see Greenstein 1972 and Kohoutek and Senkbeil 1973), for which the appropriate effective wavelength was used. The correction to *B* is small, never exceeding 0.14 mag.

This simple magnitude transformation is allowable because of the relatively high errors in the magnitudes derived. Not only are the counting rates quite low, which leads to fairly large random errors, but the nebular continuum is usually competitive with the stellar, and occasionally it dominates, which further increases the error.

The *B* and *V* magnitudes are presented in columns (10) and (11) of Table 3. As for the nebular line fluxes, the error presented is the larger of those computed from the random errors on the given nights, or computed by comparison of magnitudes derived on different nights.

The errors are such that in general the value of $B - V$ derived from the magnitudes is not significant. Special note should be made however of Hu 1–1 (VV 3) for which the radiation appears to be all nebular at λ4428, suggesting that this star is cooler than normal and is similar to those in NGC 1514 and NGC 2346. Other notable objects are IC 2165 and Hu 1–2 (VV 267) for which stars are not directly visible in the centers. The continua are clearly above the expected nebular values, and it seems very likely that the star is being detected.

## IV. HELIUM-TO-HYDROGEN RATIOS

Of the nebulae presented in Table 3, there are sufficient data to calculate He/H for 10 nebulae, and to set upper limits on this quantity for two more. The flux ratios $\mathscr{F}(\lambda4471\ \text{He I})/\mathscr{F}(\text{H}\beta)$ and $\mathscr{F}(\lambda4686\ \text{He II})/\mathscr{F}(\text{H}\beta)$ were first corrected for interstellar reddening by using the references cited earlier. The adopted values of *c* are shown in column (2) of Table 4.

The theoretical calculations required to derive He/H come from Brocklehurst (1971, 1972). The flux of λ4471 was corrected for $2\,^3S$–$4\,^3D$ collisional excitation. If we follow Peimbert and Torres-Peimbert (1971), this correction is applied with $\frac{1}{3}$ the rate initially predicted by Cox and Daltabuit (1971). The electron temperatures ($t = 10^{-4}T_e$) and densities ($x = 10^{-4}N_e/\sqrt{t}$) required to make these calculations are given in columns (3) and (4) of Table 4. $T_e$ is derived from [O III] and is taken from Cahn (1976) or calculated from data in Kaler's (1976*a*) catalog and Seaton's (1975) formula. Values of *x* are derived from the [O II] and [Cl III] lines. Line intensities come from references listed by Kaler (1976*a*), Aller and Epps (1976), and *x* is derived from the tables presented by Saraph and Seaton (1970) and by Krueger, Aller, and Czyzak (1970).

The results, with errors, are presented in Table 4. Columns (5), (6), and (7) give the values of $\text{He}^+/\text{H}^+$, $\text{He}^{2+}/\text{H}^+$, and their sum He/H. The values are all close to 0.1 except for He 1–2 and Me 2–2 reported on earlier (Kaler 1974) and NGC 4361, for which they are significantly greater than 0.1 and for Hu 1–1 for which the value appears significantly less. For Hu 1–1, λ4686 was observed on only one night. Aller (1951) found $I(\lambda4686)$ to be 2.8 times the strength as reported in Table 3, which would increase He/H to 0.089.

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TABLE 4

HELIUM-TO-HYDROGEN RATIOS

| Nebula (1) | *c* (2) | *t* (3) | *x** (4) | $\text{He}^+/\text{H}^+$ (5) | $\text{He}^{2+}/\text{H}^+$ (6) | He/H (7) |
|---|---|---|---|---|---|---|
| NGC 2438 | 0.58 | 1.0 | (0.1) | < 0.07 | 0.037 ± 0.002 | < 0.11 |
| NGC 2610 | 0.41 | 1.5 | (0.1) | < 0.05 | 0.084 ± 0.009 | < 0.14 |
| NGC 3587 | 0.01 | 1.0 | 0.1 | 0.076 ± 0.028 | 0.008 ± 0.001 | 0.084 ± 0.028 |
| NGC 4361 | 0.19 | 2.0 | (0.1) | 0.022 ± 0.009 | 0.108 ± 0.005 | 0.130 ± 0.010 |
| NGC 6833 | 0.78 | 1.5 | 1.0 | 0.108 ± 0.016 | ... | 0.108 ± 0.016 |
| NGC 7026 | 0.86 | 1.0 | 0.5 | 0.095 ± 0.012 | 0.009 ± 0.001 | 0.104 ± 0.012 |
| IC 2165 | 0.74 | 1.0 | 0.5 | 0.062 ± 0.010 | 0.034 ± 0.002 | 0.096 ± 0.010 |
| IC 3568 | 0.18 | 1.1 | 0.5 | 0.091 ± 0.013 | ... | 0.091 ± 0.013 |
| Hu 1–1 | 0.32 | 1.1 | 0.1 | 0.067 ± 0.013 | 0.008 ± 0.001 | 0.075 ± 0.013 |
| Hu 1–2 | 0.59 | 1.9 | 1.0 | 0.061 ± 0.011 | 0.092 ± 0.005 | 0.153 ± 0.013 |
| Me 2–2 | 0.00 | 1.1 | 0.8 | 0.160 ± 0.015 | ... | 0.160 ± 0.015 |
| Vy 1–1 | 0.96 | 1.1 | (1.0) | 0.114 ± 0.061 | ... | 0.114 ± 0.061 |

* Numbers in parentheses are rough estimates; no measurements are available.

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