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# FLUXES AND IONIZED MASSES OF MAGELLANIC CLOUD PLANETARY NEBULAE

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## ABSTRACT

Absolute Hβ nebular fluxes are presented for a total of 97 planetary nebulae (PN) in the Magellanic Clouds. These new fluxes are compared with all previously published data. Nebular masses are derived for 54 objects and are found to lie mainly in the range 0.01–0.35 $M_\odot$. A relationship between density and ionized mass ($M_{\rm neb} \propto 1/n_e$) for a subset of the nebulae is used to show that these objects are optically thick. Another relationship between Hβ flux and nebular density is examined. The point at which the nebulae become optically thin is seen as a change in the slope of this curve. From these relationships a nebular mass—radius relation of the form $M_{\rm neb} \propto R^{3/2}$ is found to apply to optically thick nebulae, while optically thin nebulae evolve at constant $M_{\rm neb}$.

*Subject headings:* galaxies: Magellanic Clouds — nebulae: planetary

## I. INTRODUCTION

The planetary nebular phase of stellar evolution is one which despite a considerable amount of effort, both theoretical and observational, over the past 20 years, still contains many contentious issues. For example, the evolutionary paths of planetary nebulae nuclei (PNn) have been subject to a large amount of debate. The empirical Harman-Seaton sequence (Harman and Seaton 1964) was generally accepted as being a single evolutionary track. However, this changed after temperatures and luminosities were rederived, and it became interpreted as a superposition of different mass tracks in the range 0.6–1.2 $M_\odot$ (Paczyński 1971; O'Dell 1974). Schonberner (1981) studied the evolution from the AGB phase and concluded it was possible to assign only a very small mass range around 0.58 $M_\odot$ for PNn masses. Wood and Faulkner (1986) carried out a more extensive set of evolutionary sequence calculations for PNn of varying masses (0.6, 0.7, 0.76, and 0.89 $M_\odot$) and conclude there is a large range in possible nuclei masses. They have also found evidence that recent luminosity determinations may have underestimated the stellar luminosities by a factor of up to 3. However, calculation of the absolute luminosity of the PNn relies on a knowledge of its distance, and distance is not a well-known quantity for many Galactic PN. Various authors quote distances to individual nebulae that may differ by factors of up to 2–3 (Cahn and Kaler 1971; Maciel and Pottsch 1980; Daub 1982; Amnuel *et al.* 1984; Phillips and Pottasch 1984). This can be attributed to, among other things, uncertain amounts of extinction within our Galaxy, uncertainty in the optical thickness/thinness of nebulae, and the fact that virtually no nebulae are close enough for independent distance measurements not relying on physical nebular parameters. We believe the Magellanic Clouds hold the solution to many of the unanswered questions relating to PN by furnishing us with a luminosity-limited sample at a common, known distance and with a low line of sight reddening. As a result of this we have been systematically investigating both the kinematics and dynamics of the PN populations in the Large and Small Magellanic Clouds over the past few years (Dopita *et al.* 1985, 1987, 1988; Meatheringham *et al.* 1988; Wood, Bessell, and Dopita 1986; Wood *et al.* 1987, hereafter WMDM).

In this paper we present absolute Hβ fluxes for a total of 23 PN in the Small Magellanic Cloud and 74 in the Large Cloud. Together with WMDM, who obtained Hβ and also [O III] λ5007 flux information for 80 PN we have now covered the majority of known PN in the Magellanic Clouds. These fluxes are being used in conjunction with line intensities measured from spectrophotometry to produce absolute nebular line fluxes for all important emission lines from 3400 Å to 7200 Å. This information will be used further in modeling codes to derive abundances, and physical parameters for a large sample of Magellanic Cloud PN (Meatheringham and Dopita 1988).

The only previously published flux information for Magellanic Cloud PN is from Webster (1969, 1976, 1983), who made photoelectric measurements of absolute emission line fluxes for 25 PN. Osmer (1976) used a spectrophotometric scanner to derive fluxes for selected nebular emission lines from 3700 Å to 6600 Å for six PN, and Aller (1983) derived Hβ fluxes for eight LMC PN from spectrophotometry.

The flux information together with nebular electronic densities ($n_e$) from the [O II] λλ3727, 3729 doublet (Dopita *et al.* 1987; Barlow 1987) allows a determination of the ionized nebular mass. In § III*b* masses are derived for a subset of 54 nebulae in this paper. The density can also be used in conjunction with the flux information and masses to determine at what point a nebula becomes optically thin to hydrogen ionizing radiation, as well as a nebular mass—radius relationship.

## II. OBSERVATIONS AND DATA REDUCTION

### *a) Selection of Objects*

The majority of objects observed in this study come from Sanduleak, McConnell, and Philip (1978, hereafter SMP), who presented a list of 103 PN in the LMC and 28 in the SMC. Many of these had been cataloged as emission nebulae in the Henize (1956) catalog, had also been listed by Lindsay and

Mullen (1963) and had been positively identified as PN by Henize and Westerlund (1963). Throughout this paper we have adopted the numbering system as given by SMP, this being the most comprehensive single listing to date.

The Jacoby (1980, hereafter J) objects present a more difficult group. Many of these are very faint, and only one object (J5) was observed in this study.

### b) *The Observations*

Observations were made in 1982 December, 1983 January, 1984 December, and 1985 November and December using the 1 m telescope operated by the Australian National University at Siding Spring Observatory. A narrow band two-cycle interference filter manufactured by Spectrofilm, Inc., was used to isolate the H$\beta$ nebular line. This filter had a full width at half-maximum (FWHM) of 16 Å centered at the H$\beta$ rest wavelength.

The detector system used was the two-dimensional Photon Counting Array (PCA) (Stapinski, Rodgers, and Ellis 1981). This uses a 25 mm ITT microchannel plate proximity focus intensifier tube with an S20 photocathode coupled to a single-stage electrostatic image tube. The photon events on the output phosphor are read out using an uncooled Fairchild CCD 221 lens coupled to the image tube assembly. After frame subtraction to remove fixed pattern noise in the chip and afterglow from previous photon events, the data are digitized and the centroid of each photon event found to give a resolution (pixel size) in the 512 K pixel external memory of $15 \times 36$ $\mu$m. Calculation to within 0.5 pixel of where the photon landed in one spatial direction (double binning) is the final step. At the *f*/8 focus of the 1 m telescope this gave an image resolution of $\sim 0\farcs5 \times 1''$ on the sky.

Exposure times were varied to give a peak signal in the range 30–100 photons per pixel, giving total counts per exposure approximately in the range 900–3000 photons.

### a) *Reduction Procedure*

In order to remove small-scale variations of sensitivity across the CCD, each observation was divided by a normalized flat field obtained by summing two exposures of the morning and evening twilight sky. The data were then rebinned to give pixels square on the sky.

The Starlink applications program PATCH was used to remove any stars or image defects near the PN that would cause problems later in the reduction, and lead to errors in sky measurements for the photometry. The Starlink aperture photometry program APERASP was then used to derive a magnitude for each object. A circular aperture was centered on the PN to give the total number of counts for objects plus sky. Four separate sky apertures were selected around the PN to find an average sky value. The sky contribution was removed to leave an instrumental magnitude for the planetary nebula. In choosing suitable aperture sizes it had to be ensured that the aperture was large enough to cover the largest PN image for the night, as changes in seeing were frequently encountered throughout a night. In addition, because of different seeing conditions on various nights, appropriately sized apertures were chosen separately for each night.

The instrumental magnitude was corrected for the effect of differential atmospheric extinction, and the final step in the reduction was conversion to absolute H$\beta$ fluxes. Standard fluxes were taken from those objects which had well agreed upon fluxes as determined previously by various authors (Webster 1969, 1976, 1983; Osmer 1976; Aller 1983). [Those PN adopted as standards are denoted by a footnote in column (1) after the object name, in Tables 2 and 3 below.] Standards were measured as every third or fourth object throughout the nights to ensure sufficient coverage.

TABLE 1

Flux Errors Due to Fluctuations in Photon Statistics

| log $F_{H\beta}$ | Error |
|---|---|
| −12.45 | ±0.01 |
| −12.65 | ±0.02 |
| −12.85 | ±0.03 |
| −13.15 | ±0.04 |
| −13.40 | ±0.07 |

### d) *Accuracy*

There are two main sources of error in our measurements. The first is simply a statistical error due to the finite number of photons detected from each planetary nebula. Table 1 shows the error as a function of log $F_{H\beta}$ as determined by repeated measurements of PN of various fluxes.

The second source of error is more difficult to quantify and arises from the fact that we have attempted flux measurements in fields that are frequently extremely crowded. This is especially so in the LMC near the region of the bar. In the most crowded fields it proved difficult to find sky regions not contaminated by faint stars; however, by interactively assigning sky apertures this uncertainty has been minimized. This is borne out by comparing the fluxes determined in this paper with those obtained by WMDM (§ III*a*).

TABLE 2

Flux Data for SMC Planetary Nebulae

| Name (1) | This Study (2) | Previous Studies (3) |
|---|---|---|
| SMP 1 | −12.77 | −12.76 (1) |
| SMP 2 | −12.67 | −12.76 (1); −12.72 (2); −12.78 (3) −12.67 (4) |
| SMP 3 | −13.06 | −13.07 (1) |
| SMP 4 | −12.90 | ... |
| SMP 5[a] | −12.81 | −12.78 (1); −12.86 (2); −12.81 (4) |
| SMP 6 | −12.80 | −12.79 (2) |
| SMP 8 | −12.74 | ... |
| SMP 10 | −12.93 | ... |
| SMP 11 | −12.87 | −12.99 (1) |
| SMP 13 | −12.56 | −12.56 (1); −12.49 (2) |
| SMP 14 | −13.05 | −13.02 (1); −12.86 (2) |
| SMP 15 | −12.43 | −12.44 (2); −12.40 (4) |
| SMP 16 | −12.70 | −12.72 (1); −12.75 (2) |
| SMP 17 | −12.49 | −12.61 (1); −12.54 (2); −12.50 (4) |
| SMP 19 | −12.93 | ... |
| SMP 20[a] | −12.42 | −12.47 (1); 12.42 (3); −12.42 (4) |
| SMP 21 | −13.25 | −13.23 (1) |
| SMP 22[a] | −12.88 | −12.83 (1); −12.88 (3) |
| SMP 23 | −13.06 | ... |
| SMP 24 | −12.68 | −12.69 (1); −12.72 (2); −12.67 (4) |
| SMP 25 | −13.20 | ... |
| SMP 27 | −12.44 | −12.44 (1); −12.48 (2); −12.43 (4) |
| SMP 28 | −13.12 | ... |

[a] Planetary nebulae adopted as standards.

References.—(1) Wood *et al.* 1987. (2) Webster 1969, 1976, 1983. (3) Osmer 1976. (4) Aller 1981.

## III. RESULTS

### a) *Comparison with Previous Flux Measurements*

Tables 2 and 3 present fluxes for the 97 PN we observed. Column (1) is the SMP designation, column (2) gives our flux measurement, while column (3) gives any previously published fluxes.

It is instructive to compare our fluxes with those obtained in previous studies. Figure 1 is a plot of our fluxes as compared with those obtained by previous authors (excluding the measurements from WMDM). The line is of slope unity. We have adopted the mean where more than one value had been published. In general, the agreement is better than 0.03 dex, the only object which differs significantly from previous work is SMC SMP14 (0.19 dex). Our value compares favorably with that from WMDM (0.03 dex difference), and hence we conclude that Webster's measurement is probably incorrect.

WMDM used high time resolution imaging (1/60 s) on the 3.9 m Anglo-Australian Telescope to obtain the sharpest possible images under the prevailing observing conditions by removing the translational component of seeing. Narrow-band filters centered on H$\beta$ and [O III] $\lambda$5007 were used to isolate the nebular lines. This work yielded fluxes for some 80 Magellanic Cloud PN. A comparison of the fluxes obtained in the two studies is shown in Figure 2. The agreement between the two studies for the objects in common is excellent (average of 0.04 difference in the dex), there being only a few objects (SMC SMP 2, SMP 11, SMP 17; LMC SMP 40, and SMP 60) that differ significantly. The fact that the discrepant WMDM fluxes are always lower than the values found in this paper, and that the difference seems independent of brightness probably indicates a slight error. This is most likely to be in the WMDM measurements, for two reasons. First, there is no such difference between our fluxes and those excluding the WMDM measurements. And second, the WMDM fluxes were derived by summing all observation frames except those that may have had cloud contamination. If, however, some cloudy frames did remain then this would give an effect such as we see. Another possibility is that WMDM may have had some faint field stars in their concentric sky aperture, the effect of which would be to lower the flux measured for that nebula.

A total of 39 PN in the SMC and 99 in the LMC have now had their fluxes measured, out of a total known of 62 in the Small Cloud and 170 in the Large Cloud. Those that are still to be measured are the fainter Morgan (1984), Morgan and Good (1985), and Jacoby (1980) objects, or SMP nebulae that could

TABLE 3

FLUX DATA FOR LMC PLANETARY NEBULAE

| Name (1) | This Study (2) | Previous Studies (3) |
|---|---|---|
| SMP 1 | −12.46 | −12.47 (1) |
| SMP 2 | −13.18 | ... |
| SMP 3 | −13.48 | ... |
| SMP 5 | −12.85 | ... |
| SMP 6 | −12.67 | −12.67 (2) |
| SMP 7 | −13.12 | ... |
| SMP 8 | −13.74 | ... |
| SMP 9 | −13.38 | −13.30 (3) |
| SMP 10 | −13.15 | −13.14 (3) |
| SMP 11 | −13.15 | −13.15 (3) |
| SMP 13 | −12.82 | ... |
| SMP 14 | −13.69 | −13.68 (3) |
| SMP 15 | −12.66 | −12.65 (3) |
| SMP 16 | −13.30 | −13.29 (3) |
| SMP 18 | −13.36 | −13.30 (3) |
| SMP 19 | −12.73 | ... |
| SMP 20 | −13.37 | −13.42 (3) |
| SMP 21[a] | −12.76 | −12.69 (1); −12.78 (2); −12.81 (3); −12.78 (4) |
| SMP 23 | −12.68 | ... |
| SMP 27 | −13.40 | ... |
| SMP 29 | −12.71 | −12.70 (1); −12.74 (2) |
| SMP 30 | −13.45 | −13.43 (3) |
| SMP 31 | −12.91 | −12.90 (3) |
| SMP 32 | −12.80 | −12.80 (3) |
| SMP 33 | −12.81 | ... |
| SMP 35 | −12.81 | −12.79 (3) |
| SMP 36 | −12.72 | ... |
| SMP 37[a] | −12.85 | ... |
| SMP 38 | −12.62 | ... |
| SMP 40 | −13.25 | −13.44 (3) |
| SMP 42 | −13.11 | ... |
| SMP 48 | −12.43 | −12.47 (1) |
| SMP 50 | −12.71 | −12.68 (3); −12.70 (1) |
| SMP 52 | −12.52 | −12.53 (3) |
| SMP 53 | −12.62 | ... |
| SMP 55 | −12.66 | ... |
| SMP 56 | −13.13 | ... |
| SMP 57 | −13.41 | ... |
| SMP 58 | −12.48 | ... |
| SMP 60 | −13.50 | −13.63 (3) |
| SMP 61 | −12.48 | −12.41 (1) |
| SMP 62[a] | −12.31 | −12.30 (1); −12.32 (2); −12.32 (3) |
| SMP 63 | −12.48 | −12.45 (1) |
| SMP 64 | −12.70 | ... |
| SMP 65 | −13.31 | ... |
| SMP 66 | −12.95 | ... |
| SMP 67 | −12.81 | ... |
| SMP 69 | −13.17 | ... |
| SMP 71 | −12.86 | ... |
| SMP 73 | −12.54 | −12.52 (1) |
| SMP 74 | −12.66 | ... |
| SMP 76 | −12.54 | −12.53 (1) |
| SMP 77 | −12.78 | ... |
| SMP 78[a] | −12.58 | −12.60 (1); −12.58 (2); −12.57 (3) |
| SMP 79 | −12.63 | ... |
| SMP 81 | −12.61 | ... |
| SMP 83 | −12.65 | −12.65 (1) |
| SMP 84 | −12.63 | ... |
| SMP 85 | −12.42 | ... |
| SMP 86 | −13.68 | ... |
| SMP 87 | −12.91 | −12.90 (3) |
| SMP 88 | −13.26 | ... |
| SMP 89 | −12.61 | −12.65 (1); −12.63 (2) |
| SMP 91 | −13.55 | ... |
| SMP 92 | −12.54 | −12.55 (1) |
| SMP 93 | −13.36 | ... |
| SMP 94 | −12.99 | ... |
| SMP 95 | −13.47 | −13.39 (3) |
| SMP 97 | −12.85 | −12.80 (1); −12.84 (2); −12.79 (4) |
| SMP 100 | −12.86 | ... |
| SMP 101 | −12.89 | ... |
| SMP 102 | −13.22 | ... |
| SMP 103 | −13.53 | ... |
| J5 | −13.25 | ... |

[a] Planetary nebulae adopted as standards.

REFERENCES.—(1) Webster 1969, 1976. (2) Aller 1983. (3) Wood *et al.* 1987. (4) Osmer 1976.

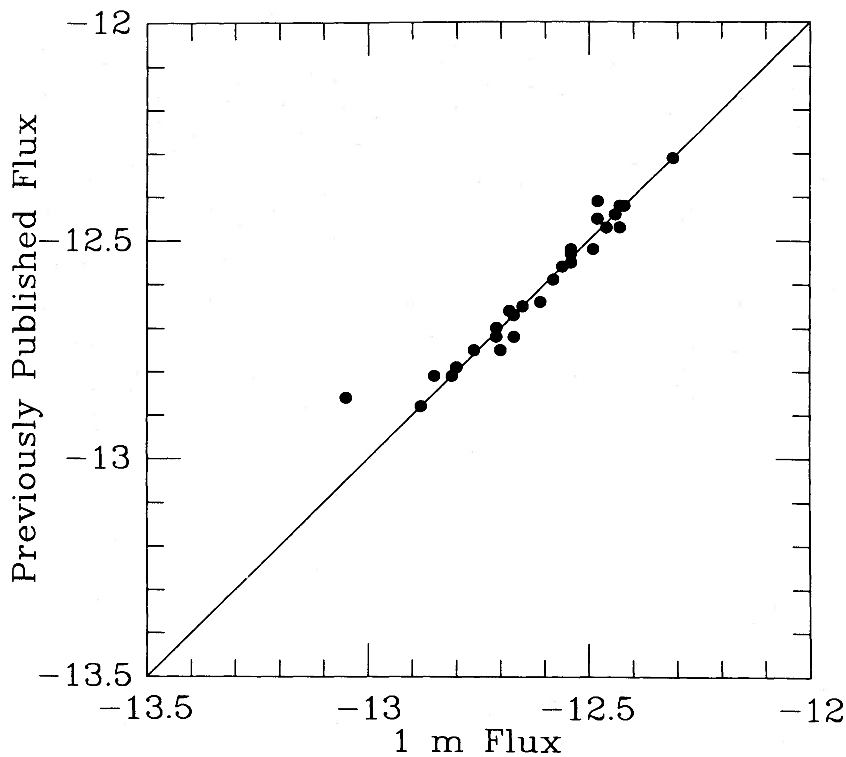


FIG. 1.—Fluxes measured in this study compared with those previously published (excluding the Wood *et al.* 1987 data). The mean was adopted where more than one value was available.

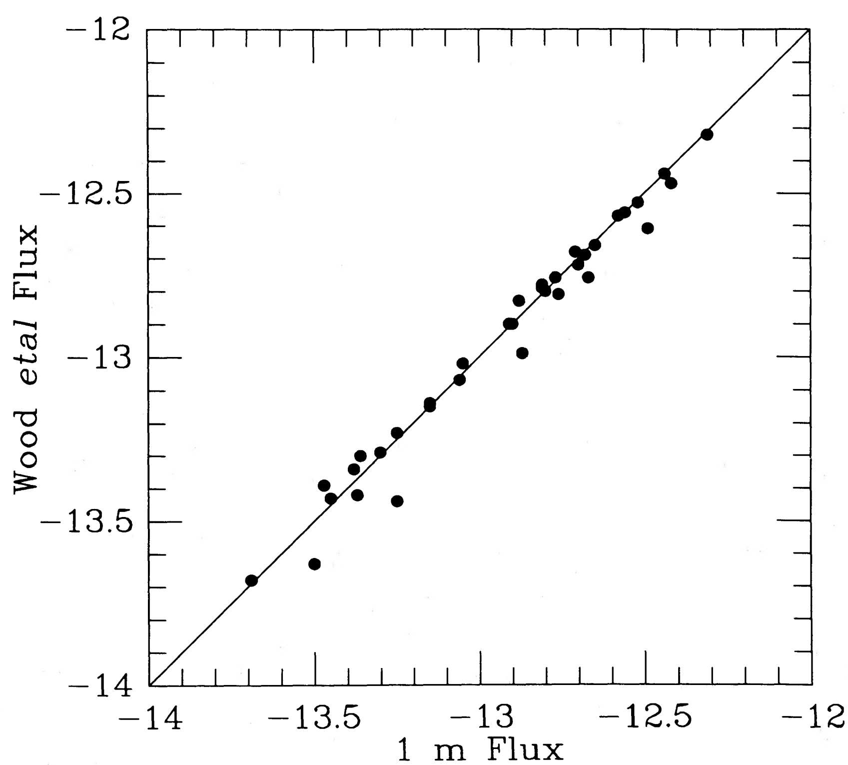


FIG. 2.—Fluxes measured in this paper compared with those in common from Wood *et al.* (1987)

not be found. Those SMP objects that could not be found were assumed to be either too faint for the 1 m telescope or erroneously identified from our objective prism plates.

### *b) Nebular Masses*

We may calculate the approximate ionized mass contained in the nebular shell using the following formula:

$$M_{\rm neb} = 4\pi D^2 F_{\rm H\beta}(1 + 4y)m_{\rm H}/(\alpha_{\rm eff}\, h\nu n_e)\,, \qquad (1)$$

where $D$ is the distance (which we have taken as 53 kpc for the LMC and 66 kpc for the SMC), $y = N(\mathrm{He})/N(\mathrm{H}) = 0.11$, and $\alpha_{\rm eff}$ is the effective recombination coefficient of hydrogen for the emission of H$\beta$ photons of energy $h\nu$ ($\alpha_{\rm eff} h\nu = 1.24 \times 10^{-25}$ ergs cm$^3$ s$^{-1}$ at $T = 10^4$ K and $n_e = 10^4$ cm$^{-3}$).

Substituting numerical values into equation (1) and taking logarithms gives

$$\log M_{\rm neb} = \log F_{\rm H\beta} - \log n_e \begin{array}{ll} +15.52 & (\mathrm{LMC}) \\ +15.71 & (\mathrm{SMC}) \end{array} . \qquad (2)$$

Equation (2) has been used to derive nebular masses for 20 PN in the SMC and 34 in the LMC. The H$\beta$ fluxes used are a mean of all measurements from Tables 2 and 3 (excluding those thought to be erroneous). The densities are from Dopita *et al.* (1988) and Barlow (1987). The masses are given in Tables 4 and 5 for the SMC and LMC PN, respectively. Figure 3 shows a histogram of the distribution of nebular masses, additional masses coming from WMDM (their Table 1). The distribution is strongly peaked around a mass of 0.17 $M_\odot$ but has a wide range from 0.35 $M_\odot$ with a tail extending down to 0.01 $M_\odot$. This may be compared with the results of Maciel and Pottasch (1980) who derived ionized masses for a total of 121 Galactic PN. Their results have a mean mass of 0.14 $M_\odot$, with a range of ionized masses very similar to what we have calculated. This apparent large range in ionized mass has been noted by various authors (Pottasch 1980, 1983; Maciel and Pottasch 1980; Daub 1982; Wood and Faulkner 1986) and must cast serious doubts on the use of the Shklovsky method in its original form (Shklovsky 1956) for determining PN distances.

TABLE 4

NEBULAR MASSES OF SMC PLANETARY NEBULAE

| Name | $\log F_{\rm H\beta}$ | $\log n_e$ (cm$^{-3}$) | $M_{\rm neb}$ ($M_\odot$) |
|---|---|---|---|
| SMP 1 | −12.76 | 4.02 | 0.08 |
| SMP 2 | −12.72 | 3.46 | 0.34 |
| SMP 3 | −13.06 | 3.26 | 0.24 |
| SMP 5 | −12.80 | 3.54 | 0.23 |
| SMP 6 | −12.79 | 4.41 | 0.03 |
| SMP 9 | −13.43 | 2.43 | 0.71 |
| SMP 13 | −12.56 | 3.86 | 0.20 |
| SMP 14 | −13.03 | 3.52 | 0.14 |
| SMP 15 | −12.42 | 4.81 | 0.03 |
| SMP 16 | −12.72 | 4.19 | 0.06 |
| SMP 17 | −12.53 | 3.71 | 0.29 |
| SMP 18 | −12.64 | 3.86 | 0.16 |
| SMP 19 | −12.93 | 3.59 | 0.15 |
| SMP 20 | −12.43 | 4.85 | 0.03 |
| SMP 21 | −13.24 | 3.60 | 0.01 |
| SMP 22 | −12.86 | 3.62 | 0.17 |
| SMP 24 | −12.67 | 3.83 | 0.16 |
| SMP 26 | −13.50 | 3.11 | 0.13 |
| SMP 27 | −12.44 | 3.73 | 0.35 |
| SMP 28 | −13.12 | 3.28 | 0.21 |

TABLE 5

NEBULAR MASSES OF LMC PLANETARY NEBULAE

| Name | $\log F_{\rm H\beta}$ | $\log n_e$ (cm$^{-3}$) | $M_{\rm neb}$ ($M_\odot$) |
|---|---|---|---|
| SMP 1 | −12.47 | 3.56 | 0.32 |
| SMP 5 | −12.85 | 3.30 | 0.23 |
| SMP 6 | −12.67 | 4.15 | 0.05 |
| SMP 8 | −13.74 | 3.80 | 0.10 |
| SMP 15 | −12.66 | 3.73 | 0.14 |
| SMP 20 | −13.40 | 3.11 | 0.10 |
| SMP 21 | −12.76 | 3.89 | 0.07 |
| SMP 23 | −12.68 | 3.77 | 0.12 |
| SMP 29 | −12.72 | 3.88 | 0.10 |
| SMP 31 | −12.91 | 3.94 | 0.05 |
| SMP 32 | −12.80 | 3.45 | 0.19 |
| SMP 37 | −12.85 | 3.86 | 0.06 |
| SMP 38 | −12.62 | 4.11 | 0.06 |
| SMP 40 | −13.34 | 3.08 | 0.13 |
| SMP 45 | −13.10 | 3.15 | 0.19 |
| SMP 46 | −13.60 | 3.60 | 0.02 |
| SMP 47 | −12.52 | 3.71 | 0.20 |
| SMP 50 | −12.70 | 3.70 | 0.13 |
| SMP 52 | −12.52 | 3.46 | 0.34 |
| SMP 55 | −12.66 | 4.60 | 0.02 |
| SMP 58 | −12.48 | 4.82 | 0.02 |
| SMP 61 | −12.45 | 4.60 | 0.03 |
| SMP 62 | −12.31 | 3.79 | 0.26 |
| SMP 63 | −12.47 | 3.99 | 0.12 |
| SMP 67 | −12.81 | 3.57 | 0.14 |
| SMP 76 | −12.53 | 4.16 | 0.07 |
| SMP 77 | −12.78 | 3.54 | 0.16 |
| SMP 78 | −12.58 | 3.63 | 0.20 |
| SMP 83 | −12.65 | 3.36 | 0.32 |
| SMP 87 | −12.91 | 3.26 | 0.23 |
| SMP 89 | −12.63 | 3.64 | 0.16 |
| SMP 92 | −12.54 | 4.00 | 0.09 |
| SMP 96 | −13.34 | 3.43 | 0.06 |
| J5 | −13.25 | 3.04 | 0.17 |

Barlow (1987) derived masses for 32 Magellanic Cloud PN. On the whole the two mass estimates are quite similar, a mean difference of only 0.02 $M_\odot$ existing between the majority of the objects in common. However, a few of the nebular masses are quite different between the two studies, due to differences in adopted density and H$\beta$ flux. For two nebulae in the SMC (SMP 9 and SMP 28) the masses are different as Barlow has used flux measurements which appear to be in error. For those other objects where large variations are found (SMC SMP 15 and SMP 22; LMC SMP 6, SMP 21, and SMP 47) we believe our density measurements to be more accurate (see Dopita *et al.* 1988) and hence our masses more appropriate.

It must be noted that there may be two possible criticisms of our masses. First, the H$\beta$ fluxes are uncorrected for reddening, and hence, our masses will tend to underestimate the actual nebular mass if the reddening should be high. Barlow (1987) gives $C(\mathrm{H}\beta)$ estimates for a number of Magellanic Cloud PN, most of which are found to be of the same order $C(\mathrm{H}\beta) < 0.2$. Second, the density as measured from the [O II] $\lambda\lambda$3727,3727 doublet may not necessarily be representative of the mean density throughout the nebula, and as the objects are not spatially resolved we are unable to determine whether this is the case. However, good agreement is generally found for those Galactic objects with known [O II] densities and densities derived from other means (Aller and Czyzak 1979; Pottasch 1980), which leads us to believe we are justified in using the [O II] densities.

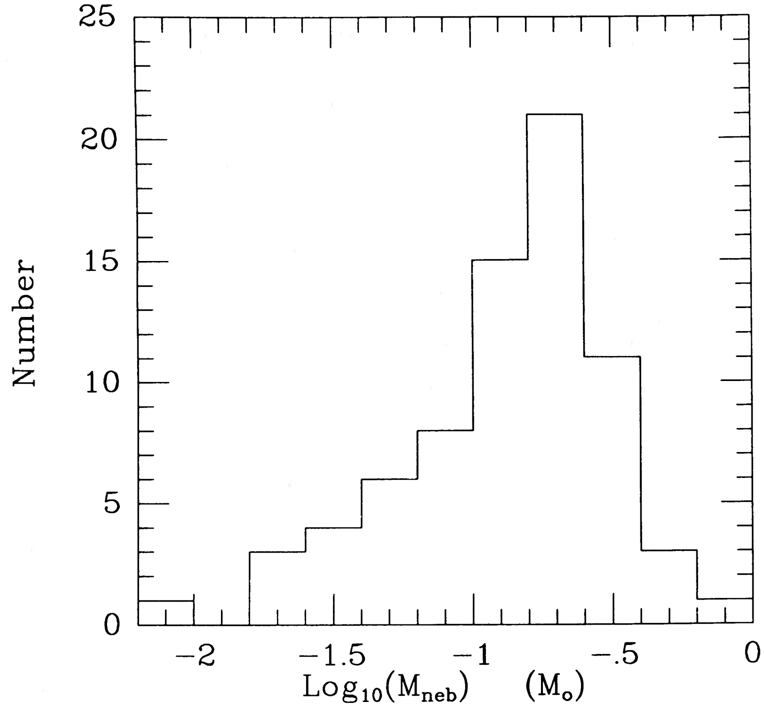


FIG. 3.—Histogram of the relative numbers of nebulae of different masses derived is this paper. The distribution is quite strongly peaked around $M_{\rm neb} \approx 0.17\ M_\odot$.

## IV. DISCUSSION

Dopita *et al.* (1987, 1988) have found a number of tight correlations between various nebular parameters (H$\beta$ flux, expansion velocity, density, excitation class, mass, and dynamical age) leading to tight constraints on models of the pre- and postnebular ejection phase of evolution. In this paper we consider two more possible relationships. The first, between nebular electronic density ($n_e$) and ionized mass, and the second being between density and H$\beta$ flux.

Figure 4 is a diagram of nebular density versus ionized mass. The density information is taken from [O II] $\lambda\lambda$3727, 3729 profiles (Dopita *et al.* 1988; Barlow 1987), while the masses are those derived in this paper (§ III*b*). Much of the scatter at nebular densities greater than log $n_e = 4.4$ is simply due to increased error in the electronic densities from [O II] line ratios. Measurement of the ratio becomes less accurate at high densities and very low densities as the ratio $I(3729)/I(3727)$ tends to finite limits (Osterbrock 1974). For instance, at a nebular temperature of 10,000 K and an electronic density of 30,000 cm$^{-3}$, an uncertainty of $\pm 0.01$ in the ratio introduces a difference of $\pm 6000$ cm$^{-3}$ in the density. However, this reduces to only $\pm 1000$ cm$^{-3}$ at a density of 10,000 cm$^{-3}$. From the Dopita *et al.* study, the errors associated with densities less than $10^4$ cm$^{-3}$ is typically 10%.

The diagram shows that $M_{\rm neb} \propto 1/n_e$, at least for those objects with log $n_e > 3.6$. This is expected, since, as shown in Figure 5, those objects have only a very small range in log $F_{{\rm H}\beta}$, and in conjunction with equation (2), this implies the proportionality. However, we may show that this is what we would expect if these nebulae were optically thick. For an optically thick nebula the number of recombinations is equal to the number of ionizations, i.e., $n_e^2 R^3 = {\rm const}\ F_{\rm ion}$. Where $F_{\rm ion}$ is the flux of ionizing photons from the central star. The ionizing flux is proportional to the stellar luminosity, and is a function of effective temperature. Wood *et al.* (1987) showed that the number of ionizing photons per unit stellar luminosity does not vary by more than $\sim$30% over a large range in PN central star temperatures. Hence, given that the evolutionary tracks of PNn are essentially at constant luminosity early on ($\sim$10,000 yr for a 0.6 $M_\odot$ star; Wood and Faulkner 1987), we may take $F_{\rm ion} = {\rm const}$ over this part of the evolution. As the permissible mass range is also probably small this gives $n_e^2 R^3 = {\rm const}$. A planetary nebula is essentially a Strömgren sphere absorbing a constant flux of ionizing photons ($F_{\rm ion}$) pumped out from the central star. Hence, as the nebula expands the ionized radius must increase in order to dissipate $F_{\rm ion}$, and so the nebular density decreases if we assume an homologous expansion. But as the ionized radius increases so does the ionized mass. The ionized nebular mass is then $M_{\rm neb} \propto n_e R^3 = {\rm const}/n_e$. This is the relation we see in Figure 4 and is as found for Galactic PN (Pottasch 1980). A change in the slope will come about as the nebula begins to become optically thin. There is some indication of this in Figure 4 for those nebulae with densities $n_e < 3.6$; however, as we shall show this is more convincingly seen in Figure 5. The fact that there appears to be an upper limit to the ionized mass also supports the hypothesis that the nebulae in this region are becoming optically thin. Although there is another possible explanation which allows the nebulae to remain optically thick. If the ionizing flux $F_{\rm ion}$ decreases due to the luminosity of the central star dropping, then $M_{\rm neb} \propto F_{\rm ion}/n_e$ will also drop. This could give rise to an apparent upper limit to nebular masses. The limit seems to occur at a maximum ionized mass, $M_{\rm neb} \approx 0.4\ M_\odot$, with only one point ($M_{\rm neb} = 0.7\ M_\odot$) being an exception to this. This upper limit is once again supported by the observations of Pottasch (1980), who finds a similar cutoff in ionized mass of Galactic objects, and Wood *et al.* (1987), who find an upper limit of $\sim 0.5\ M_\odot$ for Magellanic Cloud PN.

We have also constructed a plot of H$\beta$ flux versus nebular

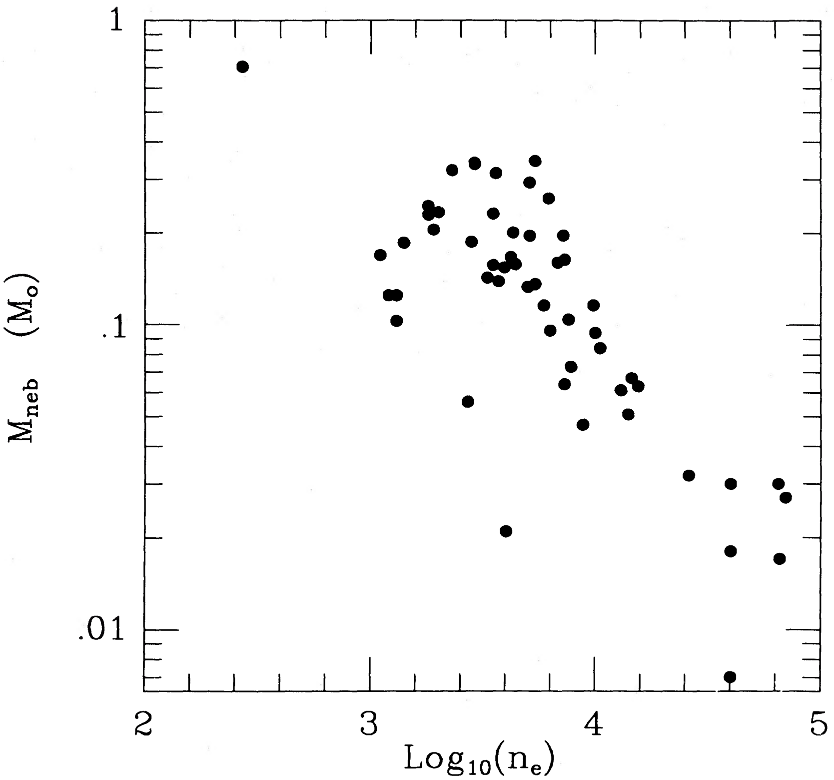


FIG. 4.—Nebular ionized mass plotted against the electronic density ($n_e$). Objects for which log $n_e > 3.6$ are optically thick, while those with lower densities are optically thin. There is an upper limit to the observed mass of $\sim 0.4\ M_{\odot}$.

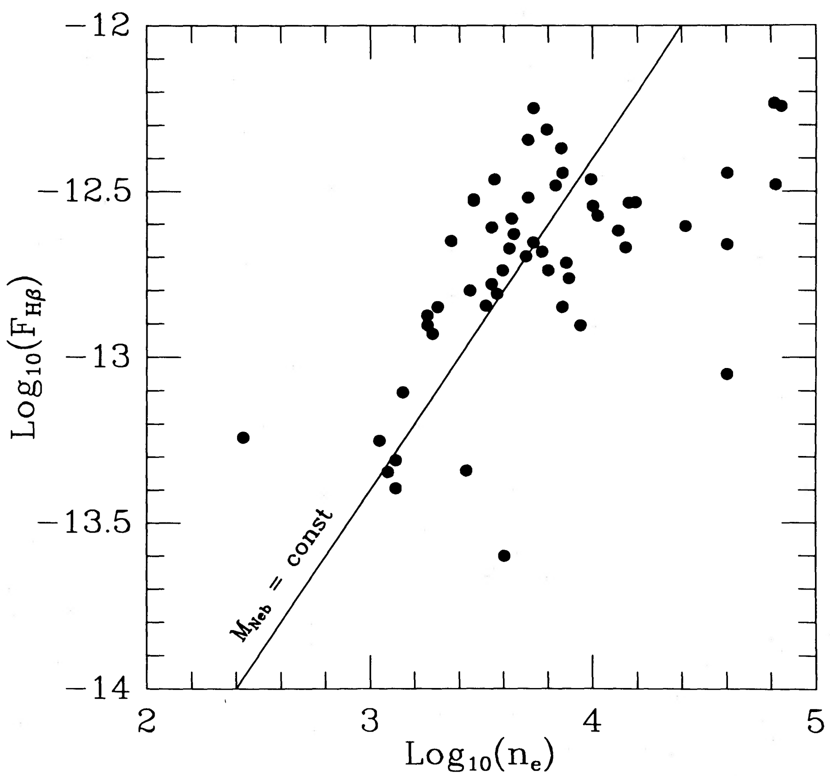


FIG. 5.—Nebular electronic density ($n_e$) as derived from [O II] line ratios vs. H$\beta$ flux. Those fluxes for SMC PN have been corrected to the distance of the LMC. Those nebulae with log $n_e > 3.6$ are evolving at constant luminosity and are optically thick, while those with log $n_e < 3.6$ are evolving at a constant nebular mass and will be becoming progressively optically thinner.

density (Fig. 5). The H$\beta$ fluxes of the SMC PN have been corrected to the distance of the LMC (53 kpc) for this study (a correction of 0.19 in log flux). One possible objection that may be raised is that the observed fluxes have had no reddening corrections applied, and so the actual shape of the diagram may be altered slightly.

This figure is similar to Figure 4, and it shows more clearly a change in slope at the point at which the nebulae begin to become optically thin to hydrogen ionizing radiation. The fact that the slope is greater than a line of constant nebular mass indicates that the ionized mass may be dropping slightly because of the reasons mentioned earlier. Nebulae with densities $\log n_e > 3.6$ form a band of $\sim 0.4$ dex wide in $\log F_{H\beta}$. The nebulae in this part of the diagram are those that we have shown to be optically thick and to be evolving at approximately constant H$\beta$ luminosity. This implies that $M_{\rm neb} \propto R^{3/2}$, as a nebular mass—radius relation, in agreement with Wood, Bessell, and Dopita (1986) and Daub (1982). Sabbadin *et al.* (1984) find $\log n_e \propto -\beta \log R$, where $\beta = -1$, although from their Figure 6 it appears more that $\beta \approx -3/2$, which is in agreement with what we find. The width of the constant luminosity band is proportional to the permitted range in central star masses.

As the nebulae become optically thin they evolve at constant nebular mass. From this we have $n_e \propto R^{-3}$, which is in agreement with Sabbadin *et al.* (1984), who found the same relationship for optically thin nebulae. A representative line of slope unity shows a line of constant nebular mass. We would expect the nebulae to evolve parallel to this line, however, it appears that some of the older and fainter objects fade faster and tend to fall below lines of constant nebular mass. This is supported by the dynamical ages of the group of four nebulae shown in Figure 5 clustered between $-13.4 < \log F_{H\beta} < -13.2$ and lying near the line of constant mass. We may calculate a dynamical age using the observational relationship presented by Dopita *et al.* (1988). The ages are found to be between 3500 and 5000 yr, whereas those clustered around $\log F_{H\beta} = -12.5$ have ages closer to 2000 yr.

The results shown in Figure 5 are consistent with such an evolutionary scheme. The one discrepant point, with $\log n_e = 2.4$, is SMC SMP 9. It is probable that this nebula has evolved from a massive progenitor. However, Barlow (1987) gives a flux measurement fainter than our adopted flux by 0.4 dex. If the value given by Barlow is taken to be correct then this would bring the ionized mass down to 0.27 $M_\odot$. The absence of many nebulae from the optically thin area near SMC SMP 9 is most probably a selection effect, due to the short fading time scale for massive PNn. Hence, Figure 5 shows the nebulae evolving from being optically thick to optically thin, in Figure 4, as well as allowing us to derive a nebular mass—radius relation.

While the density at which the transition from being optically thick to optically thin may appear difficult to tie down accurately from Figure 5, it is worth noting that Barlow (1987) concluded independently at us that the transition occurs at densities between 5000 and 6000 cm$^{-1}$, which is almost exactly the value we derive. Barlow also classifies his sample of nebulae as optically thick or thin on the basis of central star analyses and the presence or absence of nebular He II $\lambda$4686 emission. With the exception of one object (LMC SMP 6) his classification agrees exactly with that obtained from our Figure 5, using density as the discriminant.

## V. SUMMARY

A large sample of PN in the Magellanic Clouds have now had H$\beta$ fluxes measured. These fluxes together with [O II] $\lambda\lambda$3727, 3729 electron densities allow a determination of ionized masses within the nebular shells. A subset of 54 nebulae have had masses derived in this way. These masses together with densities have been used to show at what density the nebulae begin to become optically thin. The H$\beta$ fluxes have been used with the densities to derive a nebular mass—radius relation of the form $M_{\rm neb} \propto R^{3/2}$ for those nebulae that are optically thick have and shown that optically thin nebulae evolve at a constant nebular mass.

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