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THE IDENTIFICATION OF FAINT PLANETARY NEBULAE IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

Faint planetary nebulae in four fields of the SMC have been identified to a plate limit of $V \sim 21.5$, using on-band/off-band filter photography at [O III] λ5077 and Hα. In those fields where seven planetary nebulae were previously known, 11 new and nine possible planetary nebulae have been identified. The total number of planetaries in the SMC is estimated to be 100 and the number of planetaries in the Galaxy is discussed. One planetary is clearly resolved at both Hα and λ5007 and the shell mass is estimated to be 0.69 $M_\odot$. The contribution by planetary nebulae to the chemical enrichment of galaxies is found to be small.

Subject headings: galaxies: Magellanic Clouds — nebulae: planetary

I. INTRODUCTION

The identification of planetary nebulae in nearby galaxies provides a means of studying the older stellar populations. The determination of chemical abundances in these planetary nebulae allows a comparison of the abundances with the young populations (e.g., H II regions) and with galactic planetary nebulae. Kinematical studies of planetary nebulae provide further understanding of their progenitors and are especially interesting in the Small Magellanic Cloud, where two distinct velocity groups exist (Feast 1968). The number of planetary nebulae in a galaxy is a direct measure of the stellar death rate and the rate at which the interstellar medium is being enriched. The nitrogen abundance in the SMC has been shown to be deficient relative to the LMC and Orion (Osmer 1976). This must be reconciled with the observations by Torres-Peimbert and Peimbert (1971) which show that planetary nebulae are the dominant source of nitrogen enrichment in our Galaxy and the estimate by Westerlund (1968) that the occurrence of SMC planetaries is similar to that in the Galaxy.

At the distance of the Magellanic Clouds, the large planetary nebulae of the class discovered by Abell (1966) would be just resolvable with diameters of 2″ to 3″. Because all the planetary nebulae in either of the Clouds are at essentially the same distance, which is well known from independent methods (van den Bergh 1975), the diameters, along with an estimated expansion velocity, allow the ages to be calculated. The evolutionary track of the nebulae and central stars can then be determined. Resolved planetary nebulae at a known distance also provide a means for computing the nebular shell mass (for an assumed filling factor) if the flux in the Balmer lines can be measured.

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The importance of identifying planetary nebulae in the Clouds is reflected in the number of previous surveys as summarized by Westerlund (1968). More recently, Sanduleak, MacConnell, and Philip (1978) have completed an objective-prism survey of the Clouds in which they are able to distinguish emission-line stars and compact H II regions from planetary nebulae. Because their survey extends to fainter objects than earlier surveys, new planetary nebulae were identified, bringing the total in the SMC to 27. This is not very different from the earlier value of 30 given by Henize and Westerlund (1963); although the limiting magnitude has been increased, several objects have been discarded.

All but one of the previous surveys used the objective-prism technique. Koelbloed (1956) successfully identified planetary nebulae in the SMC by using on-band/off-band filter photography. This method was also used by Baade (1955) to identify five planetary nebulae in M31. The technique was later refined, using narrow-band interference filters combined with image-tube photography. Ford, Jenner, and Epps (1973) and Ford and Jacoby (1978) identified over 300 planetary nebulae in M31 and its companion elliptical galaxies in this way. The success of this method led to its choice for the present study, although no image tube was used because a large field was desirable. With the recent availability of large southern telescopes, it has become possible to extend the identifications of planetary nebulae in the Clouds to significantly fainter limits and to resolve those with diameters greater than 0.5 pc (1″.5).

II. IDENTIFICATIONS

Four fields in the SMC were photographed during 1977 September at the prime focus of the Cerro Tololo 4 m telescope. The on-band and off-band plate and filter combinations and exposure times are

TABLE 1

FILTER AND PLATE COMBINATIONS

PARAMETER	[O III] On-Band	[O III] Off-Band	Hα On-Band	Hα Off-Band
Filter central wavelength (Å)	5013*	5900 (OG5)	6560	6300 (RG1)
Bandpass (FWHM) (Å)	35*	1000	130	300
Transmission (%)	50*	90	57	90
Plate	IIIa-J	IIa-D	IIIa-F	IIa-D
Exposure time (min)	120	1.5	120	12
Filter size (inches)	6	8	4.5	8

* Includes the effects of the f/2.8 convergent prime focus beam and an ambient temperature of 8° C.

listed in Table 1. The off-band exposure times were chosen to provide a fainter limiting magnitude than the on-band plates to avoid confusion at the plate limit, especially from blue stars.

The criteria for identification of planetary nebulae have been discussed by Lindsay (1961), but the requirement for stellar appearance must be relaxed if the object is very small (i.e., less than 3″) and very faint, so that old, extended planetary nebulae are not excluded. When the plate pairs were blinked, Lindsay's criteria were satisfied by 16 objects. Two additional faint objects were found to be resolved at diameters less than 3″ and must be considered planetary nebulae. Seven of the 18 objects are listed by Sanduleak, MacConnell, and Philip (1978) as confirmed planetary nebulae and three of the 11 new planetary nebulae were identified on two plates. Nine additional objects were found but cannot be considered definite planetary nebulae because they exhibit a weak but detectable continuum.

The equatorial coordinates (see § III*b*) of the 27 identified objects were compared with the coordinates in Lindsay's (1961) catalog of SMC emission-line stars. In addition to confirmed planetary nebulae, two objects identified here as definite planetary nebulae were found to be close (2′) to emission-line stars L136 and L162. These objects were carefully reviewed, but no trace of continuum could be seen. Either these objects are variable or the proximity is coincidental. A third object considered here to be a possible planetary is close to emission-line star L102. This object is very faint and exhibits a weak continuum about 2–3 mag fainter than that listed by Lindsay. Again, the proximity may be a coincidence. As a comparison, the positions of the confirmed planetary nebulae agree to within 0′.5, that is, within the precision of Lindsay's values.

A summary of the fields surveyed and the number of planetary nebulae found is presented in Table 2. Columns (1) and (2) are the equatorial coordinates of the field centers for the date of observation. Column (3) is the number of confirmed planetaries in the field as listed by Sanduleak, MacConnell, and Philip (1978). Columns (4) and (5) list the number of new objects found in [O III] and Hα as a pair of numbers; the first element of the pair refers to definite identifications and the second element is the number of possible identifications. Column (6) lists the number of objects which coincide with both columns (4) and (5).

The limiting magnitude of the plates can be estimated from the standard star sequences of Martin (1977) appearing on most plates. Martin's sequences extend to $V \sim 17$, corresponding to $m(5007) \sim 17.5$ for the red stars generally used at the faint end of the sequences. Because of the narrow bandpass at λ5007, a planetary nebula as bright as Martin's standard having $m(5007) = 17.5$ corresponds to $V = 21$. Since the plates clearly extend somewhat fainter than Martin's faintest standards, the limiting magnitude of the λ5007 plates is estimated at $V = 21.5$. This extends the identifications 2 to 3 mag fainter than previous surveys.

TABLE 2

SUMMARY OF RESULTS

R.A. (1)	DECL. (2)	NO. KNOWN (3)	NEW PN [O III] (4)	NEW PN Hα (5)	OVERLAP (6)	NOTES (7)
0^h56^m	−73°02′	2	1, 2	3, 2	1, 1	a
0 48	−72 33	1	3, 2	...	...	
0 49	−73 16	2	...	3, 4	1, 1	a,b
0 45	−73 37	2	2, 1	3, 1	2, 1	b
Totals		7	6, 5	9, 7	4, 3	

[a] These fields share one possible identification.

[b] These fields share one definite identification.

Because fainter planetary nebulae are more difficult to detect during the plate-blinking process, a selection effect exists which discriminates against the very faint nebulae. One can estimate the reliability of detecting the faint objects by blinking all plate pairs twice. Memorization of fields can be effectively eliminated by waiting several days after the first blinking session and rotating the plates. For the SMC, only three of the 18 planetary nebulae were not identified in both sessions, indicating that the rate of return for a third session would be small. These highly reproducible results indicate at a high confidence level that all the identifiable planetary nebulae were found, and that no correction for omitted objects is necessary.

III. DISCUSSION

a) The Number of Planetary Nebulae in the SMC

The total number of planetary nebulae in the SMC can be estimated subject to the following assumptions. (1) The survey by Sanduleak, MacConnell, and Philip (1978) is limited by luminosity only and is not subject to crowding confusion problems (see Webster 1977, for a discussion of crowding in the LMC). (2) The planetary nebulae sampled by Sanduleak, MacConnell, and Philip (1978) and those of this survey belong to the same disk population as suggested by Henize and Westerlund (1963). (3) A negligible number of SMC planetary nebulae are obscured by dust. The relative rarity of stars obscured by dust is apparent from blue photographs of the SMC. (4) The present survey identifies the faintest planetary nebulae, since planetary nebulae nearly as large as 1.2 pc have been identified. This size has generally been accepted as the maximum diameter at which a planetary can still be recognized. Some of the planetary nebulae in the list presented by Abell (1966), however, have even larger diameters.

The total number of planetary nebulae is simply the total given by Sanduleak, MacConnell, and Philip (1978) multiplied by the ratio of the new total in the surveyed fields to the previous total in the same fields. If only the definite identifications are considered, the total number of planetary nebulae in the SMC is 70. If the nine possible candidates are included, the total could be as high as 104. These values are smaller than the estimate given by Henize and Westerlund (1963) by a factor of 3, and smaller than the more recent estimate given by Alloin, Cruz-Gonzalez, and Peimbert (1976) by a factor of 2. This apparent discrepancy can be understood in the context of the then available data, which have been shown to have overestimated the number of planetary nebulae known to the limits of the earlier surveys (Sanduleak, MacConnell, and Philip 1978).

A test of the completeness of this survey can be made by computing the apparent flux received at the Earth from the faintest known planetary nebula if placed at the distance of the SMC. The planetary A7 is the least luminous object in Abell's (1966) list of faint galactic planetary nebulae. At the distance of the SMC its $M_{\rm pr}$ of $+3.3$ corresponds to an $m_{\rm pr}$ of 22.5 or about 1 mag below the Hα limit reported here. A similar argument can be made for this object at [O III]. Thus A7 would not have been detected if placed in the SMC, nor would a total of 10 out of the 56 planetary nebulae listed by Abell for which absolute photo-red magnitudes are available. Hence a correction of less than 18% can be applied in the following discussions.

The true correction to the total number of planetary nebulae in the SMC will actually be less than 18% because the sample of Abell nebulae is already a faint subset of galactic nebulae. Because of its uncertainty and its relatively small value, this correction factor is not considered in the subsequent discussion.

The mass of the SMC can be taken as $1.5 \times 10^9 M_\odot$ (Hindman 1967). The specific number (per unit mass) of planetary nebulae for the SMC then is $4.6 \times 10^{-8} M_\odot^{-1}$ or $6.9 \times 10^{-8} M_\odot^{-1}$ if the possible candidates are included. For a comparison with M31, Ford and Jacoby (1978) find the specific number between $1.7 \times 10^{-8} M_\odot^{-1}$ and $8.7 \times 10^{-8} M_\odot^{-1}$, in general agreement with the SMC (assuming the mass of M31 is $3.1 \times 10^{11} M_\odot$; Roberts 1966). Ford (1978) estimates the number of planetary nebulae in M32 to be 64 to 88, and Ford, Jacoby, and Jenner (1979) find the mass of M32 to be $5 \times 10^8 M_\odot$. The specific number for M32 is then $13 \times 10^{-8} M_\odot^{-1}$ to $17 \times 10^{-8} M_\odot^{-1}$. Estimates for our Galaxy, however, range from $7.7 \times 10^{-8} M_\odot^{-1}$ (Alloin *et al.*) using Cudworth's (1974) distance scale to $29 \times 10^{-8} M_\odot^{-1}$ (Cahn and Wyatt 1976) using Seaton's (1968) distance scale. The predicted deficiency of planetary nebulae in the LMC (Westerlund 1968) will be discussed in a later paper.

b) The Resolved Planetary Nebulae

Two small resolved objects have been identified as planetary nebulae in the SMC. One nebula is shown in Figure 1 (Plate 4) at Hα and λ5007. Unfortunately, an optical problem in the guider system caused severe guiding difficulties, so no reliable diameter measurement can be made for the second resolved nebula. The following relation is used to remove the effects of seeing from the diameter measurement:

$$d(\text{neb})^2 = d(\text{meas})^2 - d(\text{star})^2 ,$$

where d(meas) and d(star) are the actual measured diameters of the nebula and a nearby star of similar photographic density. The resolved planetary nebula is found to have a diameter of 2".8 at Hα and 1".5 at λ5007. At a distance of 69 kpc (van den Bergh 1975), this Hα angular diameter represents a linear diameter of 0.93 pc, corresponding to an age of 15,000 yr for an assumed expansion velocity of 30 km s^{-1} (Smith 1976).

By inverting the Shklovskii method for distance determination (Aller and Liller 1968), one can compute the shell mass of this planetary nebula if the flux at Hα is known. Although no photoelectric data are available, the flux has been measured from the plate, using the KPNO PDS to digitize the sensitometer spots, the resolved planetary, and a nearby sequence of photoelectric standards (Martin 1977) on the same plate. Using the photo-red system of Abell (1966), and a foreground reddening of $E(B-V) = 0.02$ (Gascoigne 1969), $\log F(\text{red}) = -13.6$. The mass of the ionized shell is calculated as $0.87K^{1/2}\,M_\odot$, where K is defined as

$$e/[1 + F(\text{N II})/F(\text{H}\alpha)]\,,$$

e is the volume filling factor, and $F(\text{N II})/F(\text{H}\alpha)$ is the ratio of the flux in the two [N II] lines ($\lambda\lambda$6548, 6584) to the flux in Hα. A value of 0.1 will be used for this flux ratio, since the SMC planetary nebulae exhibit almost undetectable [N II] emission relative to Hα (Sanduleak, MacConnell, and Hoover 1972). However, a small value for these resolved nebulae may be inappropriate because low-surface-brightness galactic planetary nebulae often exhibit strong [N II] emission. It should be noted that the shell mass is insensitive to this ratio until it approaches unity. Aller and Liller (1968) suggest an average value of $e = 0.7$, but this is also uncertain. Using these values, we have $K^{1/2} = 0.80$ and the shell mass is $0.69\,M_\odot$. This rough estimate suggests that this planetary nebula was expelled from a star of about $1.5\,M_\odot$ (Osterbrock 1974), which would indicate an intermediate age population. The uncertainty in e is significant; a value as low as 0.1 cannot be excluded, yet the mass would be $0.26\,M_\odot$ and the progenitor would be derived from an old population. The measurement of the diameter also introduces a major error as the shell mass $\propto d(\text{neb})^{3/2}$. For diameters only slightly larger than the seeing disk, the uncertainty is large and the definition of diameter becomes important. A more accurate shell mass value can be determined when photoelectric fluxes and deep image-tube photographs of this object are obtained.

Equatorial coordinates for the planetary nebulae have been determined on the basis of 18 nearby SAO stars. A plate of the SMC taken with the CTIO 24/36 inch (61/91 cm) Schmidt telescope was used to generate coordinates for fainter stars in the immediate vicinity of the resolved planetary on both 4 m plates. The coordinate transformations follow the procedure outlined by Ford and Jenner (1975). The average 1975.0 epoch position is given in Figure 1 and is accurate to 0".75 (1 σ) in both right ascension and declination. This error is generated principally in the primary transformation of the Schmidt plate and is probably due to inaccuracies in the positions of the SAO stars. The measuring error is relatively small (0".2). Positions and finding charts for the remaining planetary nebulae in the SMC and LMC will be presented in a future paper.

IV. CONCLUSIONS

The filter photography technique allows identifications of considerably fainter planetary nebulae than the objective-prism method. When these faint planetaries are counted, the total number of planetary nebulae in the SMC is about 100, or half that of previous estimates, and the specific number is 4 times smaller than some estimates for the Galaxy. Either the Galaxy is overabundant in planetary nebulae relative to M31, M32, and the Magellanic Clouds, or the Cudworth (1974) distance scale for planetary nebulae must be invoked to reduce the specific number in the Galaxy. Nevertheless, the observationally determined values given here for the SMC are in essential agreement with previous investigators.

Dufour and Killen (1977) suggest that planetary nebulae in the SMC do not contribute significantly to its nitrogen enrichment. The small number of planetaries in the SMC would support this conclusion. If the specific number of planetaries in the Galaxy is similar to that in the SMC, it may be necessary to reexamine the conclusion of Torres-Peimbert and Peimbert (1971) that planetary nebulae are the dominant source of nitrogen enrichment in the Galaxy. Their statement is based on a planetary nebula production rate of 40 yr^{-1} (Cahn and Kaler 1971), but this has since been shown to be a considerable overestimate (Cahn and Wyatt 1976). If we assume (1) a specific number of planetary nebulae for the Galaxy of $7 \times 10^{-8}\,M_\odot^{-1}$, (2) a galactic mass of $1.3 \times 10^{11}\,M_\odot$ (Innanen 1966), (3) a typical upper limit to the radius of a planetary of 0.6 pc, and (4) a mean expansion velocity of 30 km s^{-1}, then the birthrate of planetary nebulae in the Galaxy is 0.45 yr^{-1}. This would produce a mass return rate similar to that for supernovae and suggests that planetary nebulae may not be the dominant source of nitrogen in the Galaxy.

Osmer (1976), Webster (1977), and Dufour and Killen (1977) have begun the detailed study of the chemical composition of a few Magellanic Cloud planetary nebulae. Observations of the remaining planetaries, especially the fainter and resolved ones, would be extremely useful to the understanding of the chemical enrichment processes and ages of these stellar systems. Additional kinematical studies would be desirable to confirm Feast's (1968) observations of 11 SMC planetary nebulae which fall into two distinct velocity groups. The identification of more planetary nebulae in the SMC provides the basis for these future studies.

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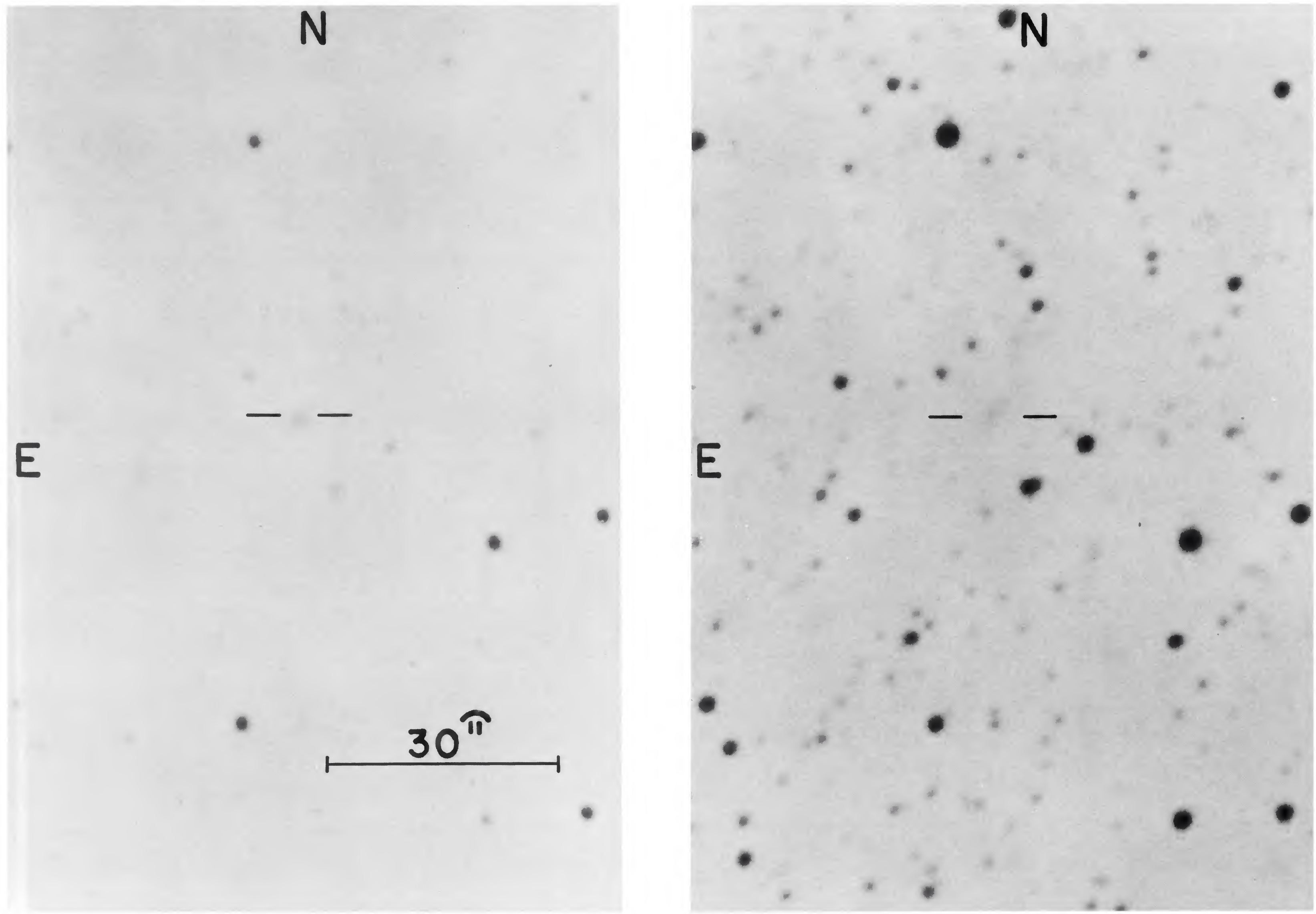

(a) (b)

FIG. 1.—An enlargement of the on-band photographs of the resolved planetary nebulae taken in (*a*) [O III] and (*b*) Hα. The planetary nebula is marked and has 1975.0 coordinates R.A. = $0^h44^m14^s.7$, decl. = $-73°28'43''.9$. Note the effectiveness of the narrower [O III] filter in suppressing the stellar continua.

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