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THE KINEMATICS OF PLANETARY NEBULAE IN THE OUTER FIELDS OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present echelle observations of 16 planetary nebulae (PNs) in the [O III] λ5007 emission line, originally detected in a UK-Schmidt objective prism survey of the outer fields of the Large Magellanic Cloud (LMC). Of these 16 objects, 11 have had no velocity information published previously. Expansion and radial velocities have been derived by a simple Gaussian fitting technique. These results have been used in conjunction with previous data presented to test whether the position angle of the kinematic line of nodes, θ_0, and the systemic Galactocentric velocity, V_0, of the LMC remain unchanged with the inclusion of this additional outer field information. After analysis of the combined sample, and also for those objects greater than 4° from the optical center of the LMC, we find that our results confirm previous values, where $\theta_0 \sim 170°$ and $V_0 \sim 40$ km s^{-1}. The LMC is confirmed to consist of a single disk, and not a dual disk structure as originally proposed by Freeman, Illingworth, and Oemler.

Subject headings: galaxies: kinematics and dynamics — Magellanic Clouds — planetary nebulae: general

1. INTRODUCTION

Planetary nebulae (PNs) are believed to form from low- to intermediate-mass stars which undergo a mass-loss process as they evolve up, and off, the asymptotic giant branch (AGB). As such a star evolves to higher temperatures after leaving the AGB, it becomes hot enough to ionize the expanding shell of material surrounding it. The emission-like nature of the resultant PNs makes them excellent test objects for studying far-off systems, such as the Galactic Center and other galaxies.

Although the study of their precise behavior is an ongoing process, substantial progress has been made in the past decade in trying to understand these objects (see, for example, IAU Symposium 131, 1989). Observations of Galactic PNs have been hampered by reddening and distance scale problems. The Magellanic Clouds offer an ideal opportunity to observe a group of PNs which form a large luminosity-limited sample at a common and externally determined distance.

Naturally, a major concern is that the Magellanic Clouds are not an isolated, dynamically undisturbed system. There has been considerable research into the area of tidal interaction between the Magellanic Clouds and with the Galaxy. Simulations by Murai & Fujimoto (1980) suggest that a major event may have occurred as late as $\sim 10^8$ yr ago. Various kinematical studies have lent support to this theme. H I surveys of the region clearly show some complex form of interaction (Mathewson & Ford 1984 & references therein; Rohlfs et al. 1984; Mathewson, Ford, & Visvanathan 1986).

The Small Magellanic Cloud (SMC) has a rather confusing radial velocity field as seen in the 21 cm line of H I, characterized by a double peak structure with a velocity splitting of 30–40 km s^{-1} (Hindman 1967; McGee & Newton 1981; Bajaja & Loiseau 1982; Mathewson & Ford 1984). The PNs in the SMC, which offer an older subsystem to study than the gas, seem to indicate that the SMC was subject to some tidal interaction, and that the stellar and gaseous components differed in response to the event (Dopita et al. 1985).

The situation in the LMC is not so clear and has consequently earned a much more intense investigation (see Westerlund 1991 for an overview). Recent kinematical studies have been carried out using the H I gas (Rohlfs et al. 1984; Rohlfs & Luks 1991), CO molecular clouds (Cohen et al. 1988), PNs (Meatheringham et al. 1988, hereafter MDFW; Meatheringham 1991), CH stars (Hartwick & Cowley 1988, 1991; Cowley & Hartwick 1991), young and old clusters (Freeman, Illingworth, & Oemler 1983 (hereafter, FIO); Freeman 1984; Olszewski et al. 1988; Schommer 1991), and long-period variables (Hughes, Wood, & Reid 1991a, b).

To summarize the above work: The oldest long period variables (periods = 100–225 days) have flattened-spheroidal kinematics; and, the old FIO clusters and CH stars yield a different rotation solution to the other remaining studies—the difference in position angle of the line of nodes being 49°, and systemic velocity being lower by ~ 18 km s^{-1}.

The original cluster data of FIO has been recently reanalyzed, yielding new ages and velocities, rectifying the discrepancy in systemic velocity, but not position angle of the line of nodes (Olszewski et al. 1988; Schommer 1991). With regards to the CH stars, these objects may be younger than originally proposed (Hughes, Wood, & Reid 1991a, b).

Early studies of PNs in the LMC have yielded radial velocities for a total of 35 PNs (Feast 1968; Webster 1969; Smith & Weedman 1972). Recently MDFW carried out an extensive kinematical study of the LMC using new data for 94 PNs. They found the PN population forms a flattened disk with an almost identical rotation solution to that of the H I. Following the reasoning used by Schommer (1991), it may be instructive to study the kinematics of a sample of PNs in the outer fields of the LMC. Our sample, which consists of 11 new objects, offers no better statistics than the old cluster group used by FIO and Schommer (1991). Consequently, we have combined the observations presented here with those of MDFW to see whether their rotation solution still holds in the outer disk.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Selection of Objects*

Our sample consists of 16 objects recorded by Morgan (1992) on an UK Schmidt telescope objective prism survey of the outer fields of the LMC. The extensive identification procedure used to find PN candidates is described in Morgan & Good (1992). Of these 16 objects, 5 have been identified as belonging to the list of Sanduleak, MacConnell, & Philips (1978, hereafter SMP). One other object, listed as A4 in MDFW, is object No. 47 in Table 2 of Morgan & Good (1992). The remaining 10 objects are classified as new. Optical spectroscopy exists for these objects and is published elsewhere (Vassiliadis, Dopita, & Morgan 1992).

The spatial distribution of this sample is depicted in Figure 1. The original MDFW sample, totaling 94 PNs, is also shown.

2.2. *The Observations*

The observations were obtained in 1990 November using the 2.3 m Advanced Technology Telescope at Siding Spring Observatory, operated by the Australian National University. The spectrograph was a Perkin-Elmer echelle with a 79 line mm^{-1} echelle grating, and a 316 line mm^{-1} cross disperser blazed at 7500 Å. The detector used was an uncoated, 416 × 578 pixel, GEC CCD. In conjunction with a slit width of 150 μm, the whole system gave a resolution (FWHM) of 11.5 km s^{-1} at the [O III] λ5007 line. In comparison to the Photon Counting Array (PCA) detector system used by MDFW, which gave a sampling rate of 0.083 Å pixel^{-1}, the CCD offered a poorer sampling rate of 0.116 Å pixel^{-1}. Exposure times varied from 400 to 2000 s. The raw detections are presented in Figure 2.

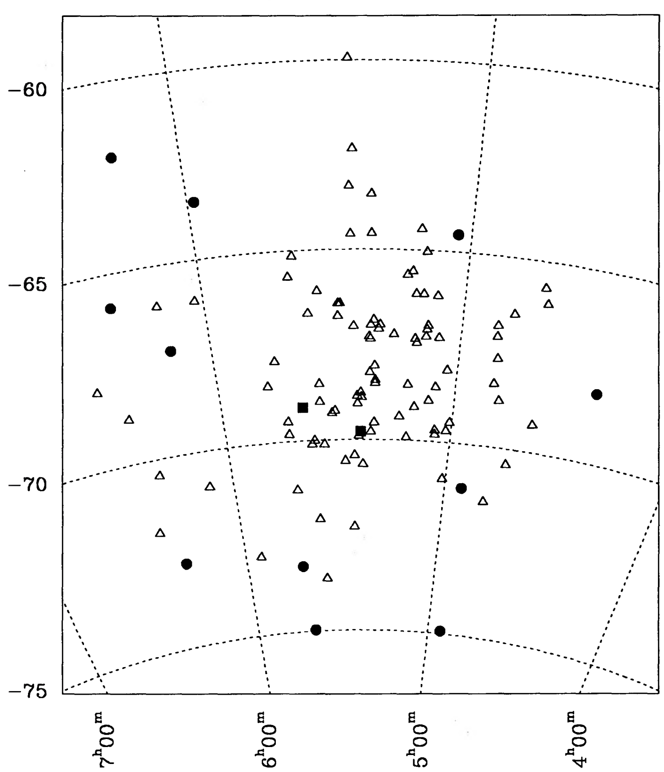

FIG. 1.—The spatial distribution of PNs. Filled circles represent the new PNs presented in this paper and the open triangles represent the MDFW sample. The filled box at the center represents the optical center of the LMC, with the position of 30 Dor indicated to the left of it.

2.3. *Reduction Procedure*

The data were reduced using version 2.9.1 of the Image Reduction Analysis Facility (IRAF). The standard CCD reduction techniques of dividing through by a mean flat-field and a median bias frame were carried out. Nebular observations were interspersed with thorium-argon arc lamp exposures throughout the observing schedule to record any instrumental drifts. In general, every three nebular observations were bracketed with arc lamp exposures.

The CCD was oriented such that the dispersion axis coincided with the long axis of the detector. The resultant spectral lines from test arc exposures were thus parallel to the short axis of the CCD. The exact orientation of the detector was accomplished by trial and error using arc exposures, until the FWHM of the spectral lines were minimized in the region where [O III] λ5007 was expected to be observed. No further straightening of the orders was attempted in the reduction procedure.

The echelle order to be used covered $\sim$65 Å: from 4975 to 5042 Å. Because of the slanting pattern of the echelle orders across the face of the CCD, the central, uncontaminated portion of the order required was extracted, being 200 pixels in length. All spatial increments having appreciable signal were reduced to one-dimensional form.

Treating this reduced portion of the CCD as essentially being linear, the standard deviation of the wavelength fitting procedure averaged 0.09 pixels ($\sim$0.01 Å), which transforms to a velocity error of 0.7 km s^{-1}. The dispersion solutions were calculated and applied to each nebular observation. The pixel shift between successive arc exposures was found to average 0.04 pixels ($\sim$0.005 Å), corresponding to a velocity error of 0.3 km s^{-1}.

The [O III] profiles were fitted by a single Gaussian. The resulting fits are overlaid on the corresponding spectra displayed in Figure 2. Because of the relatively poor signal-to-noise ratio in some spectra, the application of multiple Gaussian fits does not appear to be justified.

2.4. *Accuracy*

Combining the errors from our reduction procedure, the estimated uncertainty in the radial velocity measurements is 1.0 km s^{-1}. Of course, there is also the added uncertainty due to photon shot noise. In MDFW, this error is represented as $\pm\sigma/N^{1/2}$, where σ is the e-folding width of the Gaussian fit and N is the number of photons in the profile (Bevington 1969). Individual errors are calculated and recorded accordingly in Table 1. These error measurements range from 0.5 to 5.4 km s^{-1}. The average shot noise error is 2.5 km s^{-1}. Hence the total error in the radial velocity measurements is the tabulated shot noise error plus the inherent uncertainty in the reduction procedure of 1 km s^{-1}.

3. RESULTS

3.1. *Radial Velocities*

Using the time of observation, the observed radial velocity measurements were converted to velocities in the local standard of rest (LSR) frame. These velocities were then, in turn, converted to the Galactic standard of rest (GSR) frame, assuming a canonical LSR motion of 250 km s^{-1} about the

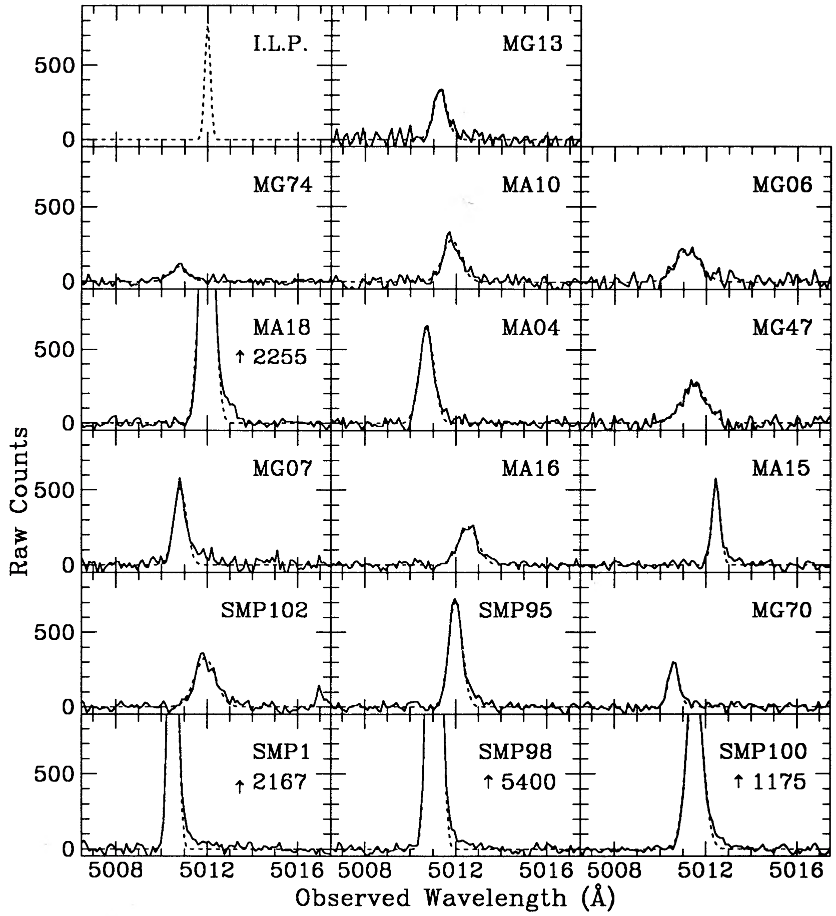

FIG. 2.—Observed profiles in solid lines. Gaussian fits superposed as dotted lines. The identification of each object is indicated in the top right corner of each panel. For those profiles which do not fit on the scale used, the peak number of counts is indicated below the name of the object. The instrumental line profile (ILP) is shown in the top-left panel.

Galactic center:

$$V_{GSR} = V_{LSR} = 250.0 \sin (l^{II}) \cos (b^{II}) . \quad (1)$$

Since the sample of objects presented in this paper are at a relatively large distance from the LMC center (i.e., $\gtrsim 5°$), a correction must be made for the transverse motion of the LMC (Feitzinger et al. 1977; Prevot, Rousseau, & Martin 1989). To be as consistent as possible with the work of MDFW, we have adopted a value of 275 ± 65 km s^{-1}. The corrected velocities, V_c, and all of the velocities mentioned above, are presented in Table 1.

Comparing measurements of V_{LSR} between this study and that of MDFW, we find a mean absolute difference of 4.7 km s^{-1} for the five coincident objects listed in Table 2.

TABLE 1

SAMPLE DATA[a]

Object	R.A. (1950.0)	Decl. (1950.0)	log $F(H\beta)$	E.C.	V_{exp}	V_{LSR}	V_{GCR}	V_c
SMP 98	06^{h}18^{m}42^s.2	− 73°11′15″.6	− 12.52	5.5	24.4	236.8 ± 0.5	23.3	− 2.8
MA 04	04 24 49.7	− 69 49 07.7	− 13.27	9.0	36.2	211.7 ± 1.8	18.6	40.2
MA 10	06 09 34.5	− 68 43 12.9	− 13.63	8.4	47.4	280.6 ± 3.2	64.5	36.4
MA 15	06 13 23.7	− 63 59 47.4	− 12.65	0.9	17.4	320.0 ± 1.2	100.3	84.5
MA 16	05 58 32.3	− 64 30 52.2	− 13.24	9.6	52.2	324.7 ± 3.5	108.6	99.1
MA 18	06 21 01.2	− 66 06 29.5	− 12.65	7.0	32.6	292.8 ± 0.9	72.7	52.2
MG 70	05 39 47.8	− 75 01 55.0	...	...	25.3	207.9 ± 2.1	1.9	− 12.7
MG 07	04 55 34.7	− 75 04 31.0	...	5.1	32.1	219.3 ± 1.9	20.4	18.8
MG 74	05 42 24.7	− 74 42 38.0	...	0.9	49.7	217.2 ± 5.4	10.6	− 4.4
MG 13	05 02 51.3	− 65 27 10.0	...	...	32.8	247.4 ± 2.4	45.4	60.5
MG 06	04 55 06.5	− 72 51 05.0	...	...	67.5	241.2 ± 4.3	41.6	45.0

[a] $H\beta$ flux and excitation class (E.C.) information from Vassiliadis, Dopita, & Morgan 1992.
Objects with MA prefix from Morgan 1992.
Objects with MG prefix from Morgan & Good 1992.

TABLE 2

LSR VELOCITY COMPARISON[a, b]

Object	V_{LSR} (MDFW)	V_{LSR} (this study)
SMP 1	209.1	200.1
SMP 95	290.9	292.2
SMP 100	270.1	264.6
SMP 102	286.5	288.8
A 4	254.2	259.3

[a] All measurements in km s^{-1}.
[b] Mean absolute difference = 4.7.

3.2. *Expansion Velocities*

Expansion velocities for the PNs are derived from the widths of the Gaussian fits to the spectral profiles. The velocity dispersion is corrected for the instrumental half-width, assuming it adds in quadrature.

It is fortunate that all of the fits to the spectral profiles appear to be satisfied by single-component Gaussians as this simplifies the definition of what is meant by expansion velocity. We have defined the expansion velocity, V_{exp}, as half the full width at one-tenth maximum intensity. Thus V_{exp} is equivalent to 0.911 times the measured velocity dispersion corrected for the instrumental half-width (see Dopita et al. 1985). The resultant expansion velocities for this sample of PNs are presented in Table 1.

As a comparison between the expansion velocities obtained in this study and that of MDFW, we find a mean absolute difference of 2.6 km s^{-1} (Table 3).

The object SMP 102 has been excluded from the calculation of the mean absolute difference. Upon closer inspection, the [O III] λ5007 profile of this object may be treated as having two components. Assuming the FWHM for each component is equal, we derive $V_{exp} = 42.3$ km s^{-1}, a value more in agreement with the MDFW measurement. Meatheringham has confirmed the two-component structure for the profile of this object: The components are separated by 30 km s^{-1} and have an amplitude ratio of 5:1.

We must stress that this two-component identification was only accomplished in hindsight, as our resolution is too low to be definitive in such cases. The possibility remains that some of the broad, low signal-to-noise profiles may, in fact, be made up of two components.

3.3. *Rotation Solution*

With this information in hand, it remains to derive the rotation solution as given by equation (2) of MDFW. The procedure is to minimize the residuals in this equation using a nonlinear χ^2-minimization routine from the software package MINUIT (James & Roos 1975). Two free parameters need to be minimized with respect to the velocity residuals: The position angle of the kinematic line of nodes, θ_0, and the Galactocentric velocity of the LMC, V_0.

Three rotation solutions were calculated: The first corresponds to the 11 new PNs; The second uses the whole of the combined sample, and the third corresponds to all the PNs in the combined sample greater than 4° from the LMC center. The results are presented in Table 4, together with the original solution from MDFW. All results are identical within the errors.

TABLE 3

EXPANSION VELOCITY COMPARISON[a, b]

Object	V_{exp} (MDFW)	V_{exp} (this study)
SMP 1	17.2	17.0
SMP 95	31.2	34.1
SMP 100	46.4	41.8
SMP 102	41.2	56.9[c]
A 4	68.8	66.0

[a] All measurements in km s^{-1}.
[b] Mean absolute difference = 2.6.
[c] Not included in calculation. See text for discussion.

TABLE 4

ROTATION SOLUTIONS

Sample	N[a]	V_0[b]	θ_0[c]
New PNs	11	40	164
New + MDFW PNs	106	42	168
New + MDFW PNs ($R \geq 4°$)	30	46	170
MDFW PNs	95	42	170

[a] Number of objects.
[b] In km s^{-1}.
[c] In degrees.

4. DISCUSSION

The question of whether the second, old, disk (FIO) exists still has no definitive answer. However, the results presented here, and the results of other kinematical studies in recent years appear to be making the existence of such a structure dubious. As stated by FIO, a two-disk structure is dynamically unstable and could be no older than ~1 Gyr.

Based on the work of Wielen (1977), relating the observed velocity dispersion of various disk populations in the Galaxy and their age, it is believed that the PNs, CH stars, intermediate age (225–450 days) long-period variables, and old cluster populations in the LMC have ages of the order of ~4 Gyr (Hughes, Wood, & Reid 1991). If this is the case, then this intermediate-age population precludes the possibility that any twisting has taken place due to the tidal torques initiated by a recent (~0.2 Gyr ago) close encounter of the LMC with the SMC. Any change in kinematics must have taken place at least 4 Gyr ago.

Our data appear to support the rotation solution derived by MDFW. Our sample of 11 objects is an effective increase in the MDFW sample of ~11%. More importantly, since our sample predominantly falls at distances greater than ~5° from the optical center of the LMC, we are essentially adding weight to the outer fields of the LMC when deriving our rotation solution. Ignoring the velocity dispersions, we can state that no significant difference exists between the H I PNs kinematics, following from the analysis made by MDFW for their sample.

Referring to the results in Table 4, it is obvious there are no significant difference exists between the H I PN kinematics, First, the solution based on only the 11 new PNs should be treated with caution because the sample is so small. The other two solutions show that the same rotation solution is stable from the center of the LMC to ~8° radius (the maximum extent of the combined sample).

Our results seem to yield no support for the findings of FIO, Schommer (1991), and Cowley & Hartwick (1991), that there exists an old age component ($\gtrsim$1 Gyr) with a rotation axis inclined ~50° to the young and intermediate populations.

Since the work of FIO, several of the old clusters have had their ages redetermined to $\lesssim 4$ Gyr (Jensen, Mould, & Reid 1988; Frantsman 1988; Mould & da Costa 1988; da Costa 1991). The reanalysis by Schommer (1991) has also shown that some published velocities suffer from systematic errors (~ 18 km s^{-1}). With this correction, the systemic velocities agree for all clusters but the line of nodes is still rotated for the oldest clusters ($\gtrsim 10$ Gyr). This constitutes such a small sample (~ 10 objects) that little can be said conclusively with this data. It should also be pointed out that the new clusters found by Olszewski et al. (1988), beyond the boundary defined by the Hodge & Wright atlas (1967), are heavily concentrated north and south of the bar (see Figure 2 of Olszewski et al. 1988). The spatial distribution of the PNs studied in this paper give a relatively more uniform spatial distribution across the face of the LMC.

The similarity in the CH star rotation solution (Hartwick & Cowley 1988, 1991; Cowley & Hartwick 1991) with the FIO cluster result suggests that the ages of the two populations are comparable. That is, the CH star population in the LMC is younger than its analogous Galactic counterpart. The reanalysis by Hughes, Wood, & Reid (1991a, b) proposed that the CH stars in the LMC could be similar to the young, CH-like stars, observed by Yamashita (1975) to have disk kinematics. For the inner 2° field, these authors find that the only disagreement between the populations is in the lower systemic velocities of the CH stars and also the FIO clusters. However, the uncertainty introduced by small sample statistics cannot be avoided. Also, as stated before, the reanalysis by Schommer (1991) found that several of the FIO cluster velocities suffered from systematic errors.

A main factor in studies of this nature, which is clearly evident from the literature, is that a definitive statement cannot be made about the outer-field kinematics when the samples considered only consist of ~ 10 objects. The work presented here has been combined with previous PN observations to yield an important result which has proved to be allusive in the past.

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