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THE VELOCITY DISPERSION OF OLD STARS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Radial velocities have been obtained for a group of the oldest long-period variables (LPVs) in the Large Magellanic Cloud. The LPVs have periods in the range $150 < P(\text{days}) < 250$, and they are similar to the Mira variables in 47 Tuc and the Galactic center; in particular, they have ages $\gtrsim 10^{10}$ yr. The old LPVs belong to a kinematic system which has a systemic velocity that is indistinguishable from that of the H I gas. The intrinsic line-of-sight dispersion of the LPV velocities about their systemic velocity mean is 30 km s^{-1}. Such a velocity dispersion is consistent with that expected for stars belonging to a flattened disk with a scale height of ~0.3 kpc. There is marginal evidence that the kinematic system to which the old LPVs belong rotates.

Subject headings: galaxies: internal motions — galaxies: Magellanic Clouds — stars: long-period variables — stars: stellar dynamics

I. INTRODUCTION

An analysis of the kinematics of star clusters in the LMC by Freeman, Illingworth, and Oemler (1983, hereafter FIO) led these authors to conclude that the old (age $\gtrsim 10^9$ yr) clusters and stars in the LMC belonged to a flattened, rotating disk system. Two notable features of the kinematical/dynamical picture of the LMC presented by FIO are (1) the rotating disk formed by the old clusters differs from the rotating disk defined by young objects, H I gas, and H II regions; the young and old disk systems have different systemic velocities (40 ± 3 km s^{-1} and 26 ± 2 km s^{-1} galactocentric, respectively) and different lines of nodes (at position angles $1° \pm 5°$ and $41° \pm 5°$, respectively), and (2) there is no evidence that the oldest clusters in the LMC belong to a kinematic halo population as would be the case in our Galaxy. However, the case for the absence of a kinematic halo in the LMC is not strong as it is based on a sample of only nine clusters. The aim of the present study is to see if the above conclusions of FIO apply to a larger sample of old objects where, in the present case, the objects studied are individual stars rather than star clusters.

Because of the large distance to the LMC and the low intrinsic luminosity of most old stellar objects, the relatively high-dispersion spectra needed to obtain radial velocities accurate to better than ~15 km s^{-1} (as required here) are very difficult to obtain. However, low-mass stars do become intrinsically bright during their second ascent of the giant branch and, at their brightest, they are the long-period variables (LPVs) of large amplitude, i.e., Mira variables. Three such variables are known in 47 Tuc, and many other examples are known in globular clusters (Clements and Sawyer-Hogg 1977).

A characteristic feature of the oldest LPVs is that their periods tend to concentrate around a value of ~200 days. For example, in globular clusters in the Galaxy, the Mira variables mostly have periods in the range ~190 to ~230 days, although some shorter and longer period examples exist (Clements and Sawyer-Hogg 1977; Feast 1981). In addition, the kinematics of Mira variables in the solar vicinity shows that those stars with $150 \lesssim P(\text{days}) \lesssim 200$ have Population II kinematics (Feast 1963), while Mira variables with $200 \lesssim P(\text{days}) \lesssim 250$ belong kinematically to an old disk population. Finally, direct pulsation theory estimates of masses for M-type LPVs with $P \lesssim 250$ days (Wood, Bessell, and Fox 1983; Wood, Bessell, and Paltoglou 1985) indicate masses of $\lesssim 1.0$ $M_\odot$ for these stars. We have therefore chosen LPVs in the LMC with $150 < P(\text{days}) < 250$ to form a sample of stars which should have ages similar to the globular clusters and halo stars in our Galaxy. The sources for our sample, which consists of 18 stars, are Wood, Bessell, and Paltoglou (1985), Lloyd Evans (1971, and private communication), Butler (1971, and private communication), and Hodge and Wright (1969). For most of the stars in the sample, Wood, Bessell, and Paltoglou (1985) and Glass and Lloyd Evans (1981) have obtained bolometric magnitudes which are consistent with those expected for Mira variables in globular clusters. We have obtained infrared photometry of the remaining four stars in the sample and derived bolometric magnitudes using the prescriptions in Wood, Bessell, and Fox (1983). The magnitudes so obtained (see Table 1) confirm that these stars also have luminosities typical of globular cluster Miras.

II. TiO BANDHEADS AS SOURCES OF RADIAL VELOCITIES IN LONG-PERIOD VARIABLES

As TiO bandheads are very prominent features in the spectra of LPVs, they should be ideal for the determination of radial velocities provided their positions are stable throughout the pulsation cycle of the star. The bandheads are formed far out in the atmosphere of the star because of their great strength. At these large radii, pulsation velocities are relatively small (e.g., Wood 1979) so that we might not expect the bandheads to move by more than a few km s^{-1} as the star pulsates. In order to test this hypothesis, we have determined the radial

TABLE 1
JHK Photometry

Star	JD	*J*	*H*	*K*	M_{bol}
DV 140	6049	13.24	12.53	12.12	−3.73
DV 197	6050	12.99	12.21	11.91	−3.99
DV 206	6050	12.72	11.66	11.39	−4.24
HV 12990	6043	13.17	12.54	12.23	−3.86

Note.—JD is Julian Date −2,440,000. *JHK* values are on the AAO system.

TABLE 2

STANDARD STARS

Star	v_*[a]	v_{obs}[b]	Notes[c]
RR Aql	12.5	9.0	1, 2
V Mic	0.0	−6.5	1, 3
S Scl	22.0	7.5	4
HR 9082	2.3	−4.5	5
HR 9030	−8.6	−15.5	5
HR 46	−2.4	−0.5	5
R Car	17.0	25.5	4
R Leo	7.0	19.5	6, 7
RR Sgr	89.5	93.0	1, 8
U Mic	−63.0	−58.5	1, 9
o Cet	56.5	53.5	6
HR 8991	−33.5	−28.5	5
HR 8089	−11.8	−11.5	5
T Col	59.0	67.0	4
W Vel	4.0	9.5	1, 9

[a] v_* is the adopted heliocentric velocity.

[b] v_{obs} is the heliocentric velocity in km s^{-1} obtained from the present observations.

[c] NOTES.—(1) v_* is taken at the midpoint of the twin OH maser peaks. (2) OH velocity from Wilson and Barrett 1972. (3) OH velocity from Caswell, Robinson, and Dickel 1971. (4) v_* from Balmer emission-line spectra (Fox, Wood, and Dopita 1984). (5) v_* from the radial velocity catalogue of Wilson 1953. (6) v_* from the midpoint of circumstellar CO emission (Knapp *et al.* 1982). (7) v_* from the midpoint of circumstellar SiO thermal emission (Reid and Dickinson 1976). (8) OH velocity from Fillet, Foy, and Gheudin 1973. (9) OH velocity from Bowers and Kerr 1977.

velocity of a sample of local LPVs of known velocity using TiO bandheads in the wavelength interval 6900–7280 Å. The observations were made on 1984 November 12 at the AAT using the RGO spectrograph with the 25 cm camera and CCD (GEC chip) as detector. The dispersion of the system used was 0.727 Å per pixel (31 km s^{-1} per pixel).

The only LPVs for which accurate stellar center-of-mass velocities can be measured directly are those for which the mean velocity of the circumstellar gas around these stars can be obtained. There are two sources of such velocities: (1) the midpoint of the twin OH maser peaks found in some LPVs; the two peaks correspond to the velocities of the approaching and receding gas in a stellar wind produced by the LPV (Elitzer, Goldreich, and Scoville 1976), and (2) the midpoint of the thermally excited microwave emission of CO and SiO molecules (Reid and Dickinson 1976); once again this emission comes from the gas in the stellar wind produced by the central star. A group of LPVs for which accurate radial velocities are known from the above two features is listed in Table 2. We have also included some extra objects for which Fox, Wood, and Dopita (1984) obtained radial velocities from high-dispersion Balmer emission-line observations over a large fraction of the pulsation cycle. Fox, Wood, and Dopita were able to make the conversion from Balmer line velocity to stellar center-of-mass velocity for these objects by noting the relation between Balmer emission-line velocities and the central velocities of the circumstellar microwave emission in those objects where both types of emission occurred together. Radial velocities were also obtained for five nonvariable early M stars in order to have a good range in spectral type.

Some examples of the spectra of the velocity standards are shown in the top row of Figure 1. The spectra were cross-correlated using the spectrum of HR 9089 as a template and the velocities so obtained are given in Table 2. The zero point of the velocity scale was adjusted so that the mean of the derived velocities was equal to the mean of the adopted velocities (the sources of these velocities are listed in the footnote to Table 2). The dispersion of the observed velocities v_{obs} about the given velocities v_* for the whole sample is $\sigma_{TiO} = 7$ km s^{-1}. This value represents the intrinsic uncertainty in velocities of LPVs obtained from cross-correlation of high signal-to-noise ratio spectra containing TiO bandheads. Since we are aiming to see if the velocity dispersion of the oldest LPVs in the LMC is significantly greater than the velocity dispersion of ~ 14 km s^{-1} found by FIO for old clusters in the LMC, the cross-correlation of spectra containing TiO bandheads should be sufficiently accurate for our purposes.

III. RADIAL VELOCITIES OF LARGE MAGELLANIC CLOUD STARS

The LPVs which we have observed in the LMC are listed in Table 3 and some sample spectra are shown in the bottom row of Figure 1. Radial velocities were obtained by cross-correlating with the template spectra HR 9089, HR 8991 or *o* Cet, the choice of template star being dictated by the requirement that the strength of the bandheads in the template and program objects should match as closely as possible. The adopted template velocities are those derived in the last section from the cross-correlation technique.

As the spectra of the LMC LPVs are of much lower signal-to-noise ratio than those of the velocity standards, we need some method of estimating the errors in our velocity estimates for the LMC stars. The method we have used is to add random noise to the spectra of our sample of standard stars until the resultant spectra have a signal-to-noise ratio similar to that of the LMC stars (see the middle row of Fig. 1). The synthetic noisy spectra were then cross-correlated with the template spectrum HR 9089 and the dispersion of the velocities of the noisy spectra about the velocities derived in the original cross-correlations was computed. For noise levels similar to those in the LPV spectra, we find a noise-induced velocity dispersion of

TABLE 3

LARGE MAGELLANIC CLOUD VARIABLES

Star	*P*(days)	v	v_{gas}	$v - v_{gas}$
		M Stars		
WBP 1	233	274	255	19
WBP 19	189	214	255	−41
WBP 53	222	328	255	73
WBP 74	227	268	255	13
WBP 94	220	211	265	−54
WBP 148	185	225	265	−40
WBP 151	172	272	260	12
WBP 158	185	247	265	−18
LE 120	213	236	260	−24
LE A11	200	272	260	12
LE A12	201	263	260	3
LE A20	207	324	260	64
DV 140	156	280	280	0
DV 197	169	273	290	−17
DV 206	151	312	300	12
HV 12990	162	285	290	−5
		K Stars		
WBP 132	155	300	255	45
LE A48	175	284	260	24

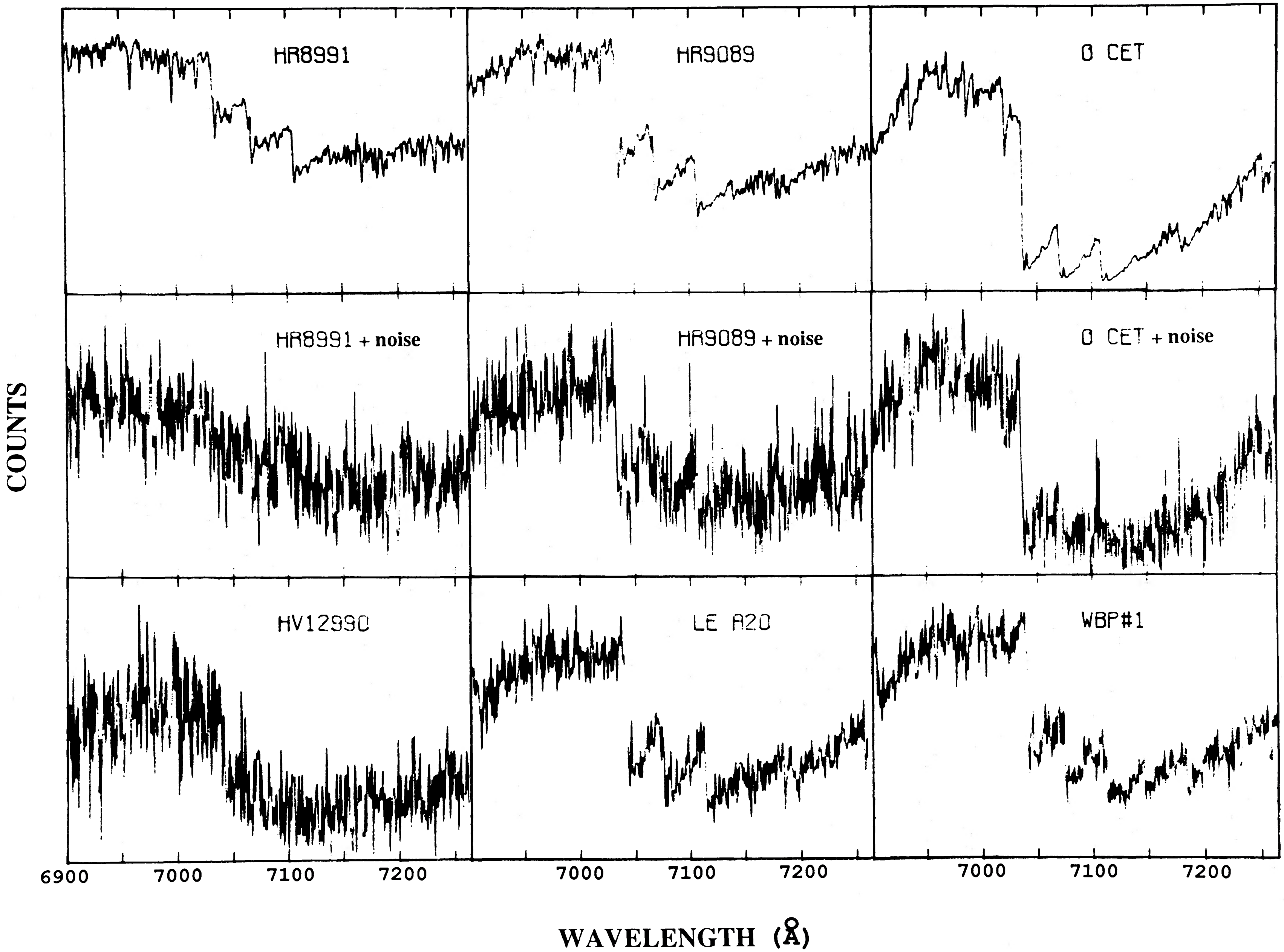

FIG. 1.—Some examples of spectra: the top row shows three velocity standards; the middle row shows the same three velocity standards after noise has been added to the spectra as described in the text; and the bottom row shows three of the LPVs in the LMC.

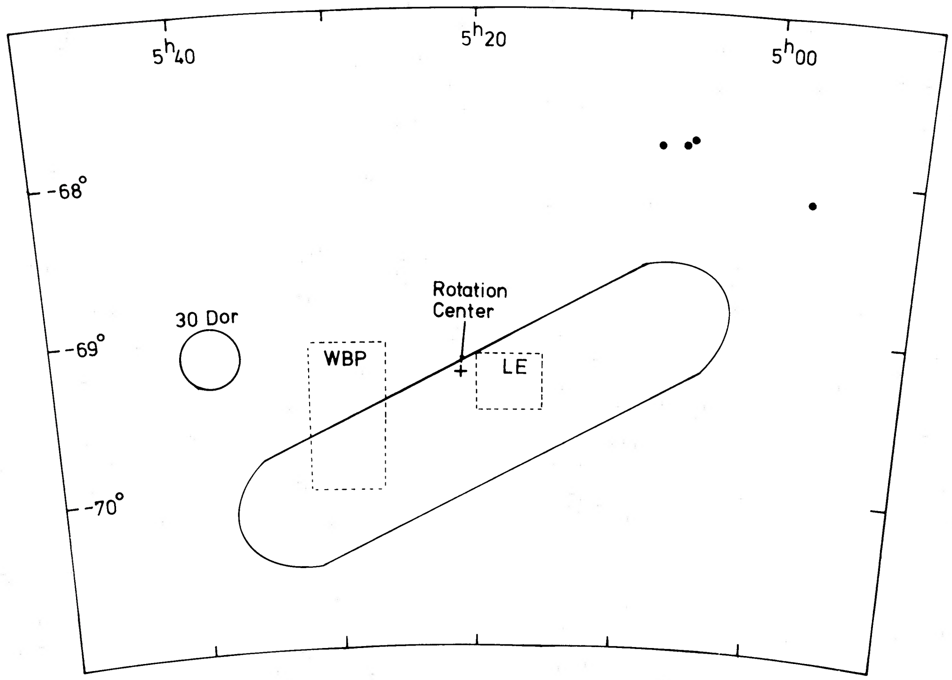

FIG. 2.—A schematic diagram of the LMC with the fields WBP of Wood, Bessell, and Paltoglou 1985 and LE of Lloyd Evans 1971 marked. The three Dunsink (DV) variables of Butler 1971 and HV 12990 are marked as circles. The rotation center is from Freeman and Carrick (1969).

$\sigma_{\rm noise}$ = 10–15 km s^{-1}; we will adopt 15 km s^{-1} as representative. Combining this noise-induced uncertainty with the intrinsic uncertainty in TiO bandhead velocities of $\sigma_{\rm TiO} = 7$ km s^{-1} derived in the last section, we find a total uncertainty in an individual velocity measurement of $\sigma_{\rm tot} = 16.5$ km s^{-1}.

The velocities derived for the LMC LPVs are listed in Table 3. Two of the stars have TiO bands too weak to be detected at the observed signal-to-noise ratio levels (they are listed as K stars in Table 3), but the cross-correlations give sensible velocities for them so they have been retained in the sample. (Note that the bandheads are not readily visible in the noise-enhanced spectrum of the velocity standard HR 8991 shown in Fig. 1, but a reasonable velocity was still obtained from this spectrum.) The mean velocity of the sample is 270 km s^{-1} and the dispersion of the velocities about the mean is 34 ± 6 km s^{-1}. Removing the component of this dispersion due to noise and uncertainty in the TiO bandhead positions as discussed above leaves an intrinsic velocity dispersion for the oldest LMC LPVs of 30 km s^{-1}.

The positions of the objects are shown projected on the LMC in Figure 2. The WBP and LE objects are mostly within ~1° of the rotation center of the H I gas in the LMC (McGee and Milton 1966; Freeman and Carrick 1969), while the three DV objects and HV 12990 are only slightly further away at ~2° from the rotation center.

IV. COMPARISON WITH H I VELOCITY DATA

The stars we have chosen have ages $\gtrsim 10^{10}$ yr. Such stars must have been among the first to form in the LMC; in particular, they will have formed before the bulk of the stars in the LMC which formed a few times 10^9 yr ago (Butcher 1977; Hardy *et al.* 1984; Wood, Bessell, and Paltoglou 1985). We will now examine the question: do the old LPVs rotate with the system defined by the H I gas and other young objects in the LMC? First, we have computed the projected rotation velocity at the position of each variable for a model of the LMC whose rotation is defined by the H I velocity observations of Freeman and Carrick (1969). This model has a rotation center at $\alpha(1950) = 5^{\rm h}21^{\rm m}$, $\delta(1950) = -69°18'$, a systemic velocity of 270 km s^{-1}, an inclination of 27°, a line of nodes at position angle 171°, and a rotation velocity about the center given by $v_{\rm rot}(r) = 81 - 3(3 - r)^3$ km s^{-1}, where r is the angular distance (degrees) from the center of the model measured in the plane of rotation (this expression is valid only for $r < 3°$). In Figure 3, we have plotted the observed velocity of each LPV against the projected rotation velocity at its position on the sky. The dispersion of the LPV velocities about the local rotation velocity is 34 km s^{-1}, identical to the dispersion of the LPV velocities

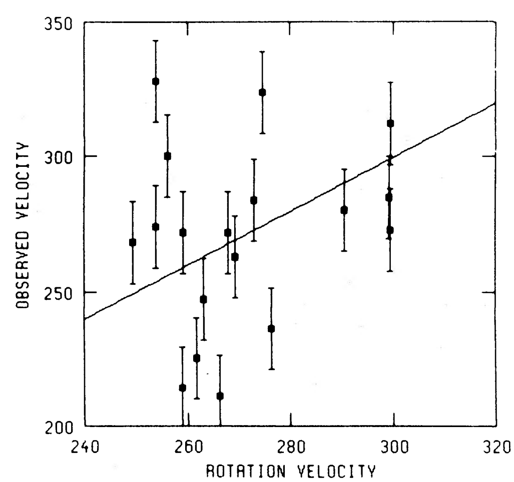

FIG. 3.—The observed velocity of the LPVs plotted against the projected rotation velocity of the model of the LMC described in the text. The line is the line of equality between observed and rotation velocity.

about their systemic mean. Thus, there does not appear to be any real evidence from this analysis that the old LPVs do, or do not, rotate with the young objects and gas in the LMC.

One small piece of evidence that the LPVs may belong to a rotating system is provided by the three DC objects and HV 12990 which lie further from the rotation center (at $\sim 2°$) than the other variables. As can be seen from Figure 3, these four objects have a higher mean velocity (287 ± 8 km s^{-1}) than the remaining 14 objects in the WBP and LE fields (mean velocity 265 ± 10 km s^{-1}). Such a difference in velocity is expected in the rotating system, although the velocity difference between the two groups is smaller than suggested by the model rotation curve (see Fig. 3).

The mean of the LPV velocities relative to the local H I rotation velocity is -0.4 ± 8 km s^{-1}. Hence, there is no evidence that the old LPVs have a systemic velocity which differs from that of the H I gas and young objects, in contrast to the results of FIO who found that the old [age $\gtrsim (1\text{–}2) \times 10^9$ yr] clusters had a systemic velocity that differed significantly from that of the young objects.

V. DISCUSSION

The results given above show that the old LPVs in the LMC with $150 < P(\text{days}) < 250$ have the same systemic velocity as the disk structure formed by the H I gas and other young objects. There is marginal evidence that these stars also rotate around the center of the LMC. The intrinsic line-of-sight velocity dispersion of the LPVs in this disk structure is 30 km s^{-1}.

The only other group of unambiguously old objects in the LMC which have been studied kinematically are the clusters studied by FIO. Our results differ from those of FIO in that they found the old clusters to have a systemic velocity significantly different from that of the H I gas. Note that the planetary nebulae in the Magellanic Clouds, which follow the H I rotation curve within $\sim 2°$ of the rotation center of the LMC (Smith and Weedman 1972), come from stars with masses ranging up to $\sim 5\ M_\odot$ (Wood, Bessell, and Fox 1983), so they are not necessarily old objects.

The intrinsic velocity dispersion about the H I gas which we have found for the old LPVs (30 km s^{-1}) is significantly greater than the velocity dispersion of the oldest clusters about their rotation curve (18 km s^{-1}, FIO), or of the planetary nebulae about the H I gas (22 km s^{-1}, Feast 1968; 15 km s^{-1}, Smith and Weedman 1972). However, a large part of the higher dispersion exhibited by the LPVs can be explained by their being near to the center of the LMC where the local mass density is higher. Using a van der Kruit and Searle (1981) model of the LMC ($\rho[r, z] = \rho_0 \exp[-r/h] \operatorname{sech}^2 [z/z_0]$), and assuming $h = 1.6$ kpc and that the maximum rotation velocity of ~ 81 km s^{-1} in the LMC fits the model, we find the scale height z_0 is ~ 0.3 kpc if we require that the z velocity dispersion in the model be equal to the LPV velocity dispersion of 30 km s^{-1} at ~ 1.0 kpc from the rotation center. Thus the old LPVs appear to belong to a flattened disk, as FIO found for the old clusters; there is no evidence that they belong to a kinematic halo of the LMC even though they formed before the bulk of the stars in the LMC.

VI. SUMMARY

The velocity dispersion of a sample of 18 very old (age $\gtrsim 10^{10}$ yr) LPVs within $\sim 2°$ of the rotation center of the LMC has been derived. These old LPVs have the same systemic velocity as the young objects and H I gas. The intrinsic line-of-sight velocity dispersion of the old LPVs (30 km s^{-1}) indicates that they belong to a flattened disk with a scale height of ~ 0.3 kpc. There is marginal evidence that the kinematic system to which the old LPVs belong rotates.

As our sample of old LPVs lies within $\sim 2°$ of the rotation center of the LMC we cannot say whether the rotating disk to which the LPVs belong follows the rotation curve of the H I gas over large areas of the LMC. Studies of more LPVs, as well as of other old objects (e.g., RR Lyrae variables), are required to further investigate the kinematical properties of the first populations of stars in the LMC. A search for further old LPVs over large areas of the LMC is currently under way, and the kinematics of these LPVs will be studied in a future paper. The main purpose of the current paper has been to show that kinematic data on the oldest stellar populations in the LMC can be obtained quickly and easily by studying the spectra of LPVs.

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