LARGE SCALE STRUCTURE AND KINEMATICS OF THE LMC FROM A STUDY OF LONG-PERIOD VARIABLE STARS

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ABSTRACT. A recently completed study of the kinematics of Long-Period (or red) Variables (LPVs) in the LMC by Hughes *et al.* (1990) has shown that those with short periods (100 to 225 days) have spheroidal kinematics (high velocity dispersion and low rotational velocity about the LMC). This is the first evidence of the LMC's possessing a spheroidal population. The spheroid is flattened (with axial ratio c/a ~0.3 to 0.5), and is not much thicker than the intermediate age disk. The velocity distribution of the old LPVs indicates that the mass of the LMC is $\sim 6.2 \pm 1.5 \times 10^9\ M_\odot$, and that of the spheroid represented by the old LPVs is ~2 % of the LMC's total mass. If these old LPVs are members of the LMC's disk, then their velocity dispersion implies that they have an age of ~10 Gyr. The LPVs with intermediate periods (225 to 450 days) are members of the LMC's rotating disk population, with an age ~4 Gyr derived from their velocity dispersion, and similar to that of the planetary nebulae, CH stars and old cluster populations.

1. Introduction

Although the LMC has a complex morphology, the velocities of its bright populations, such as the H I gas, H II regions, supergiants and planetary nebulae (PN), all have the kinematics of a single rotating disk. In contrast, when Freeman *et al.* (1983) analysed the kinematics of the oldest LMC clusters (ages $\gtrsim$1 Gyr) they found them to be rotating in a *different* disk, and in contrast to those in the Galaxy, they were not members of a halo population. However, the ages of many of these 'old' clusters were later found to be $\lesssim$4 Gyr (e.g. Jensen *et al.* 1988; da Costa 1990), similar to the intermediate age of the LMC's disk population (Meatheringham *et al.* 1988). In addition, their velocities have been remeasured by Schommer *et al.* (1990), who found many of the published velocities to have systematic errors.

Another possible old population of stars that are found in the Galactic halo (bright enough to study in the LMC, and so of possible use in determining if the LMC possesses a halo), is the group of CH stars (Hartwick & Cowley 1988, 1990). Hartwick & Cowley (1988) observed 39 CH stars, and found they had kinematics similar to the old clusters of Freeman *et al.* (1983). This means that they are therefore likely to be of a similar age ($\lesssim$4 Gyr) implying that the CH stars in the LMC may be like the younger 'CH-like' stars in the Galaxy that were observed by Yamashita (1975) to have disk kinematics.

Yet another group of potential halo candidates are the shorter period Long-Period Variables (LPVs). The LPVs in the Galaxy with periods ~200 days have ages $\gtrsim$9 Gyr, as they have Population II kinematics (Feast 1963) and are members of Galactic globular clusters (Feast 1965, 1973; Sawyer Hogg 1973). This age is also confirmed by the small theoretical

R. Haynes and D. Milne (eds.), The Magellanic Clouds, 81–87.

https://doi.org/10.1017/S0074180900200065 Published online by Cambridge University Press

pulsation masses derived by Wood (1989). Bessell *et al.* (1986) obtained the velocities of a small group of these short period LPVs. Their sample were mostly in the bar of the LMC, and consequently unsuited for determining a rotation solution, but the systemic velocity was similar to that of the H I, and the velocity dispersion, although larger than that of any other population, was consistent with that of a flattened disk.

Two large-scale (Schmidt plate) surveys for LPVs in the northern and southern halves of the LMC were recently made by Reid *et al.* (1988) and Hughes (1989). The resultant LPV distribution, although concentrated in the bar, is still well distributed across the LMC. A kinematic survey of most of the older (63 OLPVs, P = 100 to 225 days), many of the intermediate age (81 ILPVs, P = 225 to 450 days), and a few of the younger (10 YLPVs, P = 450 to 1000 days) LPVs has been made recently by Hughes *et al.* (1990). The mean observational uncertainty in velocity for their sample of LPVs was 8 km s^{-1}, a combination of the pulsational velocity uncertainty (5 km s^{-1}) and a cross-correlation uncertainty (6 km s^{-1}). They analysed these in terms of disk and spheroidal kinematics.

2. Disk Kinematics of the LPVs

The disk model used was solid body rotation ($V(R) \propto R$) out to a radius R_m, with an approximately flat rotation curve beyond this. All radii were calculated in kpc in the plane of the galaxy, assuming a distance modulus to the LMC of 18.5 (Feast 1984).

To compare the LPV results, the same model was applied to various other recent studies: the H I gas (Rohlfs *et al.* 1984), CO molecular clouds (Cohen *et al.* 1988), PN (Meatheringham *et al.* 1988), the CH stars (Hartwick & Cowley 1988), and the old clusters (Freeman *et al.* 1983). A transverse velocity of 200 km s^{-1} parallel to the Magellanic Stream was required to match the kinematic and photometric lines of nodes for the H I, which is intermediate between the 275 km s^{-1} component introduced by Feitzinger *et al.* (1977) and 150 km s^{-1} derived by Prévot *et al.* (1989) from a sample of supergiants.

The OLPVs were found, however, to have a different kinematic line of nodes. When only the data beyond the bar (>1.8 kpc) are considered, they are also the only population for which the best fit was a pure solid body rotation. This is probably due to the OLPVs' not seeming to have any convincing rotation (Figure 1a), and hence giving an unreliable rotation solution. This is a consequence of the OLPVs' having a large intrinsic velocity dispersion (σ_i =33 km s^{-1}, for R >1.8 kpc) compared to 23 km s^{-1} for the PN, 22 km s^{-1} for the CH stars, 18 km s^{-1} for the ILPVs, and just 5 km s^{-1} for the old clusters. The run of velocity dispersion with radius for the OLPVs was found to be quite flat, even out to 4 kpc. In addition, the rotational velocity found for the OLPVs at a radius of 2 kpc was the smallest of all samples, being only 21 km s^{-1}. This suggests that the OLPVs are pressure supported by random motions to a significant extent, with additional support from some possible circular rotation. The ratio of these two support mechanisms can be approximated by $V_{\rm rot}/\sigma_i$, where $V_{\rm rot}$ is the de-projected rotational velocity at a radius of 2 kpc. This ratio is only 1.0 for the OLPVs, compared to 1.9 for the ILPVs, 2.2 for the PN, 2.8 for the CH stars and 6.0 for the clusters.

2.1. DISK SCALE HEIGHTS

Assuming an exponential disk with a scale length of 1.7 kpc (derived below from the ILPV distribution, but which is a slightly longer scale length than the value of 1.6 kpc used by Freeman *et al.* 1983), the velocity dispersion of the PN implies that the scale height for the LMC's intermediate age disk is 0.8 kpc, similar to the ILPV scale height of 0.5 kpc.

However, the same calculation for the OLPV dispersion results in a scale height of 1.6 kpc, implying that the OLPVs form a very thick disk indeed! However, such a large scale height for the OLPVs is inconsistent with their being rotating members of the disk (i.e. their z and circular motions will not be decoupled). This means that the above value for their scale height will be in error, and that they are likely to occupy a spheroid rather than a rotating thick disk.

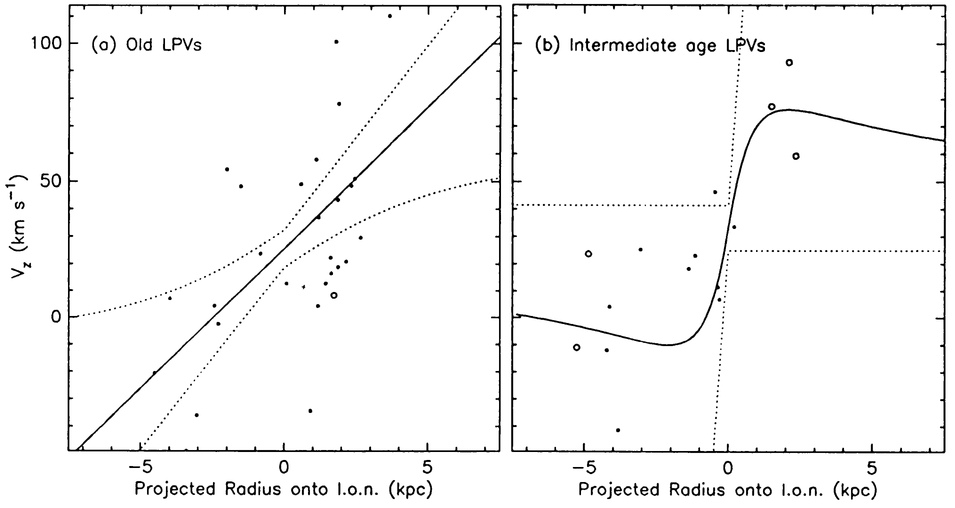

Figure 1: The observed Galactocentric velocities beyond a radius of 2° and within 15° of the kinematic line of nodes (circles), and the rotation solutions for (a) the OLPVs and (b) ILPVs. The solid line is the rotation curve plotted against the projected distance along the line of nodes. The dotted lines on either side of this are the upper and lower bounds of the 1-sigma uncertainties.

This is partially confirmed by comparing the dispersion in magnitude about the *Period–Luminosity* relation for OLPVs and ILPVs (using the data from Feast *et al.* 1989) which implies, at the 1-sigma level, that 95% of all OLPVs lie within ~2.8 kpc of the LMC plane (Hughes *et al.* 1990). If the OLPV vertical distribution were to be approximated by that of an exponential disk, then 95% will be within three scale heights of the central plane, implying a scale height less than ~ 0.9 kpc. This is only slightly greater than the scale height of the intermediate age disk, but significantly smaller than the (erroneous) kinematic scale height of the OLPVs.

2.2. VELOCITY DISPERSION AGES

Meatheringham *et al.* (1988) used Wielen's (1977) relation between the observed velocity dispersion of various disk populations (in the Galaxy) and their age to derive sensible ages for the PN in the LMC. Applying this relation to the other LMC populations yields ages of 4.8 Gyr for the ILPVs, 3.6 Gyr for the CH stars (similar to that for the PN), and 0.9 Gyr for the YLPVs. If the OLPVs were also part of the intermediate age disk, then their age estimate is 9.5 Gyr. This age for the OLPVs is surprisingly similar to the age of the Galactic OLPVs. If the mechanism for the Wielen relation is collisions with large molecular clouds in the disk, then this is another indication that the OLPVs of the LMC are closely associated with the disk. The Wielen relation has been used to derive a quantitative age-period relation for the LMC LPVs (Figure 2).

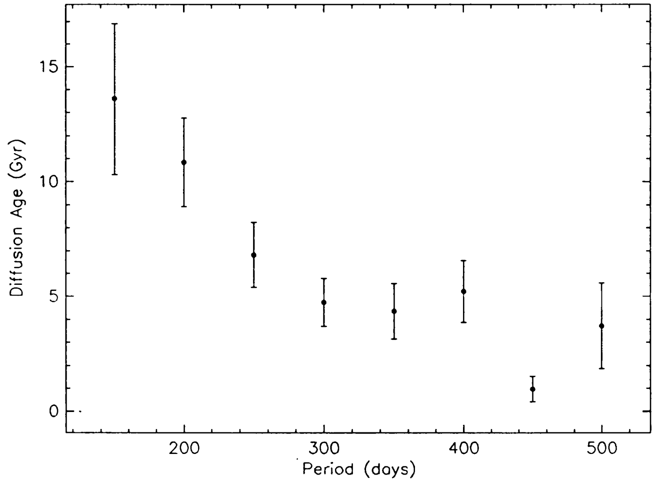

Figure 2: The dispersion age derived from Wielen (1977) has been applied to the dispersions about the H I gas to give an Age-Period relation for the LPVs. The error bars are due to the number in each bin.

3. Spheroidal Kinematics

The large σ_i of the OLPVs and small rotation implies that their kinematics are likely to be mainly spheroidal. As this might be reflected in their surface density distribution, two simple density distributions were fitted: a spherical power law and, for comparison, an exponential disk. The volume density of the spherical power law ($\nu = \nu_0 r^{-\alpha}$) has a projected surface density distribution $\mu = S_0 R^{1-\alpha}$, where r is the true radial distance, and R is the projection of r in the plane of the sky. The exponential surface density distribution has the form $\mu = D_0 e^{-\frac{R}{h}}$, where h is the scale length. The results of these fits are $\alpha = 1.8 \pm 0.1$ ($\sigma = 5.2$), and $h = 1.6 \pm 0.2$ ($\sigma = 4.8$). A power law distribution might be expected for a true spheroidal halo population, but the similar dispersions (σ) about these fits indicates there are too few data to distinguish between a disk and a spheroid on the basis of counts alone. Note, however, that the value of the exponent in the power law density distribution (1.8) is significantly different to the density distribution of the Galaxy's halo, for which Frenk & White (1982) find $\propto r^{-3.0}$ (and it may be as steep as $r^{-3.5}$ [Freeman 1987 and references therein]).

The distribution for the ILPVs gives solutions of $\alpha = 1.7 \pm 0.1$ ($\sigma = 6.4$), and $h = 1.7 \pm 0.2$ ($\sigma \doteq 3.7$), which marginally favours an exponential disk. The results of the exponential fit are dominated by the bar: for $R >$1.6 kpc, $h = 2.9 \pm 1.1$ for the ILPVs, and $h = 2.3 \pm 0.9$ for the OLPVs..

3.1. SHAPE OF THE OLPV DISTRIBUTION

Models based on the tensor virial theorem by Sommer-Larsen & Christensen (1989) and White (1989) applied to the OLPV kinematics imply a range in axis ratio ($q = c/a$) ~0.3

https://doi.org/10.1017/S0074180900200065 Published online by Cambridge University Press

to 0.5. The range in q is due to a range in possible shape of the LMC's total gravitational potential, from disk-like to spherical. White's (1989) model also implies that the mean velocity ellipsoid for the OLPVs has an anisotropy of $\sigma_z = 0.6\sigma_R$.

The range in q for the OLPVs is remarkably similar to that derived by White (1989) for the Galaxy (0.33 to 0.47) from the velocity ellipsoid for halo stars near the sun. Such a similarity might suggest common galactic formation histories, but the number counts of halo stars in the Galaxy suggest a q of $\sim$0.8 (Bahcall 1986), entirely different to that allowed for the LMC.

If the radial extent of the OLPV spatial distribution were well known, then the maximum height above the plane derived from the $P-L$ relation (2.8 kpc) would give an independent estimate for the likely value for q. Unfortunately, the radial distribution of the OLPVs is not well defined (see above). A crude estimate may be made, however, from the scale length of the ILPVs (which implies that 95% of all ILPVs will be found within a radius of 5.1 kpc) and the distribution of C stars (Blanco & McCarthy 1983 found that these stars occupied a disk of radius $\sim$7 kpc). If from these figures a value of 6 kpc is assumed for the OLPV radial axis, then their likely q will be $\lesssim$ 0.5, which is entirely consistent with the range of q from the virial estimates. (However, if the influence of the bar is ignored, then the longer scale length of the ILPVs implies a radial axis length for the OLPVs of between 7 and 8.7 kpc, implying a q of less than $\sim$0.4.)

If it is assumed that the LMC's dominant potential is approximated by the intermediate age disk, with a scale height of $\sim$0.8 kpc that is reasonably constant with radius, then this would suggest that the LMC's gravitational potential has $q \sim 0.5$, implying for the OLPV population $q \sim 0.5$.

The slow rotation of the OLPVs might indicate that they have similar dynamics to the bulges of S0 - Sb galaxies studied by Kormendy & Illingworth (1982), who found that the ratio of bulge rotation to velocity dispersion was in the range 0.45 to 1.06 (compared with 1.0 for the OLPVs). The velocity dispersions of the bulges all seem to be nearly isotropic, and an isotropic velocity dispersion for the OLPVs would require $q \sim 0.45$ (Kormendy & Illingworth 1982), which is consistent with the limits imposed by the $P-L$ dispersion.

3.2. MASSES OF THE LMC AND ITS OLD POPULATION

Bahcall & Tremaine (1981) highlight the inherent difficulties of obtaining mass estimates of spheroidal galaxies from the virial theorem, and recommend an isotropic orbits estimator M_I (based on the distribution of $v_z^2 R$). This mass estimator does, however, assume a spherical distribution of mass, and will therefore lead to an overestimate of the true mass. Minimising the effects of the bar by only using the distribution of OLPV velocities beyond a radius of 1.8 kpc (2°) from the bar's center gives $M_I = 6.2 \pm 1.5 \times 10^9\ M_\odot$(compared to a virial mass of $4.4 \times 10^9\ M_\odot$). This mass estimate compares very favourably with the LMC mass estimate of $6 \times 10^9\ M_\odot$ derived from the H I rotation curve by Meatheringham *et al.* (1987).

The population mass per OLPV, and thus the mass of the old population represented by the OLPVs, can be estimated by calculating the mass (Π) of the population which each OLPV represents. The ratio of OLPV lifetime to main sequence lifetime (Hughes & Wood 1990) implies that $\Pi_\tau = 1.8 \times 10^5\ M_\odot$. This compares very favourably with a similar estimate $\Pi_{GC} = 2.2(\pm 2.2) \times 10^5\ M_\odot$ derived from the ratio of Galactic globular cluster masses to the number of associated OLPVs. A mean Π of $2.0 \times 10^5\ M_\odot$ per OLPV is adopted.

The total number of OLPVs in the LMC is estimated to be between 430 and 500 (by integrating the exponential and power law density distributions to a radius of 6 kpc), giving the mass of the old population represented by the OLPVs as $M_{sph} = 0.9 - 1.0 \times 10^8\ M_\odot$, or ~ 2 % of the total mass of the LMC.

The Galactic OLPVs are not found in metal poor galactic globular clusters, and have [Fe/H] $\sim -1.0 \pm 0.5$, implying that they are representative of only a moderately metal poor population. The RR Lyraes, on the other hand, have a (ΔS) metallicity of -1.5 (Butler *et al.* 1982), but have been estimated by Frogel (1984) to represent a population with a mass of $\sim$6% of the LMC.

4. Conclusions

The OLPVs are the oldest field population in the LMC whose kinematics have so far been studied. Their velocity dispersion of 33 km s^{-1}indicates that they belong to a spheroid population (i.e. their kinematics are dominated by random velocities, not by rotation), and either have a velocity anisotropy of $\sigma_z = 0.6\sigma_R$, or are a bulge population with an isotropic velocity dispersion and a rotational velocity of $\sim$30 km s^{-1}. The shape of this spheroid is flattened with axis ratio c/a $\sim$0.3 to 0.5, implying that they are associated with the old disk.

The OLPV velocities implies a mass of the LMC of $6.2 \pm 1.5 \times 10^9\ M_\odot$. The total population represented by the OLPVs has a mass $\sim 1 \times 10^8\ M_\odot$ (2% of the LMC's total mass).

Because of the probable restriction of OLPVs to moderate metal deficiencies ([Fe/H] $\gtrsim -1.5$), their flattened spheroidal kinematics do not rule out the possibility of the LMC's possessing a more metal poor halo with a less flattened distribution.

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