Kinematic Evidence for an Old Stellar Halo in the Large Magellanic Cloud

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The oldest and most metal-poor Milky Way stars form a kinematically hot halo, which motivates the two major formation scenarios for our galaxy: extended hierarchical accretion [1] and rapid collapse [2]. RR Lyrae stars are excellent tracers of old and metal-poor populations [3,4,5]. We measure the kinematics of 43 RR Lyrae stars in the inner regions of the nearby galaxy the Large Magellanic Cloud (LMC). The velocity dispersion, $\sigma_{\text{true}} = 53 \pm 10 \text{ km/s}$, indicates that a kinematically hot metal-poor old halo also exists in the LMC. This suggests that our galaxy and smaller late-type galaxies like the LMC have similar early formation histories.

In the Milky Way, the old metal-poor objects such as globular clusters and RR Lyrae stars, define an almost spherical halo population [3,4,5,6,7]. Models of halo formation by accretion [1] indicate that these old objects formed in small satellite galaxies which were subsequently accreted by the Galaxy, while dissipational collapse models [2] indicate that the halo formed
rapidly before the disk collapsed. If these models apply to small galaxies, we would expect them to show a halo population defined by its oldest objects [8]. At a distance of 50 kpc [9] the ideal laboratory to test this is the LMC, which is 10 times fainter than our Galaxy. The oldest LMC globular clusters appear to lie in a flat rotating disk whose velocity dispersion is 24 km/s [10, 11]. This disk suggests that the LMC has indeed no kinematical halo of old metal-poor objects, and that therefore the formation of the LMC proceeded without a halo phase. We measured the kinematics of field RR Lyrae stars in the LMC which are known to be among the oldest and most metal-poor objects in this galaxy [5]. This sample is a by-product of the MACHO microlensing project [12, 13, 14], which provided photometry for about 8000 RR Lyrae stars in a 10 square degree region around the bar of the LMC [15].

The observations were acquired with the FORS1 multi-slit spectrograph at the European Southern Observatory (ESO) Very Large Telescope (VLT) Unit Telescope 1 (UT1), during the nights of 10 and 11 January 2003. Two exposures of 20 minutes were obtained for each mask containing 5-10 RR Lyrae stars in six central fields of the LMC bar, at distances from 0.7 to 1.5 degrees away from the rotational center (RA = 05°17′.6, DEC = −69°02′.0). We used the GRIS_600B+12 grating, that gives $R = 1000$ and covers from $\lambda 3500$ to $\lambda 5900$ Å. This resolution is adequate for the measurement of radial velocities even in the broad-lined RR Lyrae spectra, provided that a good signal-to-noise is achieved (Fig. 1). The spectra were reduced using the standard packages APALL and ONEDSPEC within IRAF. HeNeAr lamps were used for the wavelength calibration, which typically have 14 usable lines that yield 0.2 Å rms. In order to measure the velocities, we used both cross correlations and line centroiding, and decided that the latter works better for these wide-line stars, in the presence of line variations with phase. Corrections for the phase [16] of the Ca line velocities in a few cases do not affect the results. Tests of both methods give similar velocities within 20 km/s rms.

We also measured the kinematical properties of known Mira and Cepheid variables from the MACHO and OGLE catalogue. We observed 64 RR Lyrae, 5 Cepheids, and 23 Miras of the LMC. About 10% of the observing time was devoted to calibrations. Two masks containing RR Lyrae of the globular cluster $\omega$ Cen [17, 18, 19] were acquired using the same setup. Thus, high quality spectra of 17 $\omega$ Cen RR Lyrae (5 RRab, 8 RRc, and 4 RRc) were obtained. In addition, a few repeat observations were taken in order to assess the velocity errors. The radial velocities (Fig. 2) were measured by centroiding the lines H$\beta$, H$\gamma$, H$\delta$, and Ca II K $\lambda 3933.66$ Å. We discarded 21 LMC stars that have only one line measured accurately, leaving 43 stars that have 2-4 lines accurately measured. The internal errors measured from the different lines range from 1 to 33 km/s. Of the final 43 stars considered, 29 are RRab, 11 are RRc, and 3 are RRc. The dispersions for the velocity measurements add quadratically:

$$\sigma_{\text{obs}}^2 = \sigma_{\text{true}}^2 + \sigma_{\text{rms}}^2 + \sigma_{\text{phase}}^2$$

where $\sigma_{\text{obs}}$ is the observed velocity dispersion (Table 1), $\sigma_{\text{true}}$ is the real velocity dispersion of the population, $\sigma_{\text{rms}}$ is the mean error of the individual velocities, and $\sigma_{\text{phase}}$ is the dispersion in the velocities created because we observe the stars at a random phase.

The $\omega$Cen RR Lyrae velocity dispersion varies as a function of distance from the cluster
center and as a function of metallicity [18, 20]. For the observed ωCen field, the velocity dispersion of its RR Lyrae should be $\sigma_{true} = 17$ km/s. We measure $\sigma_{obs} = 20$ km/s, indicating that $(\sigma_{rms}^2 + \sigma_{phase}^2)^{1/2} = 10$ km/s. The ωCen RR Lyrae spectra have S/N twice as high as the LMC RR Lyrae, and we expect that $\sigma_{rms \ LMC} > \sigma_{rms \ ωCen}$. The ωCen RR Lyrae were also observed at a random phase. Thus, we expect that the dispersion due to the phase correction of the LMC RR Lyrae should be low.

The Cepheids can be taken as another control sample for our measurements, as they have random phase errors comparable to RR Lyrae. Cepheids and carbon stars in the LMC should be kinematically similar. The velocity dispersion of C stars is $\sigma_{true} = 15$ km/s [22, 23, 24]. While we measured only 5 Cepheids, the measured velocity dispersion $\sigma_{obs} = 28$ km/s agrees with the C stars if $(\sigma_{rms}^2 + \sigma_{phase}^2)^{1/2} = 24$ km/s.

The LMC Miras have $\sigma_{true} = 33$ km/s [25]. This velocity dispersion is the largest of all kinematic tracers measured so far in the LMC [26]. Most of the tracers are of young or intermediate-age, and show disk kinematics. In our Galaxy, the Miras have kinematics intermediate between the disk and the halo [4]. The LMC Miras of our sample yield an observed velocity dispersion $\sigma_{obs} = 43 \pm 6$ km/s [27]. Subtracting in quadrature the true velocity dispersion, gives $(\sigma_{rms}^2 + \sigma_{phase}^2)^{1/2} = 28$ km/s, in agreement with the errors estimated above.

For the final sample of 43 LMC RR Lyrae we measure $\sigma_{obs} = 61 \pm 7$ km/s. This is much larger than the velocity dispersion of any other population, but in order to find $\sigma_{true}$, we need to estimate how much is due to errors or the phase correction. The contribution of phase to the dispersion budget was estimated to be $\sigma_{phase} = 20$ km/s using the radial velocity curves of known RR Lyrae [28, 29]. Based on the control samples discussed above, we assume conservatively $(\sigma_{rms}^2 + \sigma_{phase}^2)^{1/2} = 30$ km/s. This yields $\sigma_{true} = 53 \pm 10$ km/s for the LMC RR Lyrae [30].

One additional correction that cannot be added as a $\sigma$ in quadrature is the LMC rotation. Several young and intermediate-age kinematic tracers have been measured in the LMC, including HII regions, PN, CH stars, Miras, and carbon stars. In the inner regions of the LMC bar these populations are rotating as a solid body, with 25 km/sec/kpc. For a scale of 1 kpc = 1.2°, our fields should not show a rotation component larger than 10 km/s.

In addition, a correction for rotation may not be necessary for the RR Lyrae population, because there is no evidence that this old population follows the LMC rotation. Based on the Milky Way RR Lyrae, one might suspect that the LMC RR Lyrae do not rotate like the rest of the stars. However, a composite RR Lyrae population may be present. For example, earlier interpretation of the RR Lyrae number counts indicated an exponential disk distribution [31]. Multiple components (halo + thick disk) cannot be ruled out without rotation measurements. Our fields are not spread out enough to measure the rotation. In order to measure the systemic rotation of the RR Lyrae population, one would need to observe $N \simeq 50$ stars per field in fields located $>3°$ away on opposite sides of the bar. We estimate the correction in two ways: using the velocities from HI maps [32], and using the mean rotation fits of the disk [22, 24]. This correction does not change at all the LMC RR Lyrae velocity dispersion.

The large RR Lyrae velocity dispersion $\sigma_{true} = 53$ km/s implies that metal-poor old stars are distributed in a halo population. The velocity dispersion for the old RR Lyrae stars is higher than
that of the old LMC clusters, although there are too few old clusters to measure the kinematics in the LMC. The presence of a kinematically hot, old and metal-poor halo in the LMC suggests that galaxies like the Milky Way and small galaxies like the LMC have similar early formation histories [33].

The stellar halo traced by the RR Lyrae amounts only to 2% of the mass of the LMC, which is akin to the Milky Way halo [3, 22]. In consequence, its contribution to the microlensing optical depth should not be important [26, 34]. The ongoing Supermacho experiment would discover an order of magnitude more microlensing events towards the LMC [35], allowing to test this prediction.

References and Notes

[1] L. Searle, R. Zinn, Astrophys. J., 225, 358 (1978)
[2] O. Eggen, D. Lynden-Bell, A. Sandage, Astrophys. J. 136, 748 (1962)
[3] T. D. Kinman, L. L. Stryker, J. E. Hesser, J. A. Graham, A. R. Walker, M. L. Hazen, J. M. Nemec, Pub. Astron. Soc. Pacific, 103, 1279 (1991)
[4] Feast, M., in ”Variable Stars and Galaxies”, ed. Brian Warner (ASP: San Francisco), ASP Conf. Series 30, p. 143 (1992)
[5] E. W. Olszewski, N. B. Suntzeff, M. Mateo, Annual Rev. Astron. & Astrophys. 34, 511 (1996)
[6] D. Minniti 1996, Astrophys. J., 459, 175 (1996)
[7] A. Layden, in ASP Conf. Ser. 136 on ”Galactic Halos”, ed D. Zaritsky (ASP: San Francisco), p.14 (1998)
[8] D. Minniti, A. A. Zijlstra, Astrophys. J. 467, L13 (1996)
[9] D. R. Alves, M. Rejkuba, D. Minniti, K. H. Cook, Astrophys. J. 573, L51 (2002)
[10] K. C. Freeman, G. Illingworth, A. Oemler, Astrophys. J., 272, 488 (1983)
[11] R. A. Schommer, E. W. Olszewski, N. B. Suntzeff, H. C. Harris, Astron. J., 103, 447 (1992)
[12] C. Alcock, et al., Astrophys. J. 490, L59 (1997a)
[13] C. Alcock, et al., Astrophys. J. 482, 89 (1997b)
[14] C. Alcock, et al., Astrophys. J., 542, 257 (2000a)
[15] The MACHO RR Lyrae data is available in the WWW at the MACHO Project homepage ([http://wwwmacho.mcmaster.ca/](http://wwwmacho.mcmaster.ca/)). These RR Lyrae are classified on the basis of the MACHO light-curves, with RRab being fundamental pulsators, RRc first overtones, and RRc double mode pulsators.

[16] H. A. Smith, “The RR Lyrae Stars” (Cambridge Univ. Press) (1995)

[17] C. M. Clement, A. Muzzin, Q. Dufton, T. Ponnampalam, J. Wang, J. Burford, A. Richardson, T. Rosebery, J. Rowe, H. S. Hogg, Astron. J., 122, 2587 (2001)

[18] M. Mayor, G. Meylan, S. Udry, A. Duquennoy, J. Andersen, B. Nordstrom, M. Imbert, E. Maurice, L. Prevot, A. Ardeberg, H. Lindgren, Astron. & Astrophys., 114, 1087 (1997)

[19] J. Kaluzny, M. Kubiak, M. Szymanski, A. Udalski, W. Krzeminski, M. Mateo, K. Stanek, Astron. & Astrophys. Suppl. Series, 122, 471 (1997)

[20] J. E. Norris, K. C. Freeman, M. Mayor, P. Seitzer, Astrophys. J., 487, 187 (1997)

[21] D. S. Graff, A. Gould, N. B. Suntzeff, R., Schommer, E. Hardy, Astrophys. J., 540, 211 (2000)

[22] D. R. Alves, C. A. Nelson, Astrophys. J., 542, 789 (2001)

[23] E. Hardy, D. R. Alves, D. S. Graff, N. B. Suntzeff, R. A. Schommer, Astrophys. J. Suppl. Series, 277, 471 (2001)

[24] R. P. van der Marel, D. R. Alves, E. Hardy, N. B. Suntzeff, Astron. J., 124, 2639 (2002)

[25] S. M. G. Hughes, P. R. Wood, I. N. Reid, Astron. J., 101, 1304 (1991)

[26] G. Gyuk, N. Dalal, K. Griest, Astrophys. J., 535, 90 (2000)

[27] We eliminated a low velocity star, discrepant by more than $4\sigma$ from the mean, which could be a misidentified foreground star.

[28] G. Clementini, R. Megighi, C. Cacciari, C. Gouiffes, Monthly Notices R. A. S. 267, 83, (1994)

[29] I. Skillen, J. A. Fernley, R. S. Stobie, R. F. Jameson, Monthly Notices R. A. S., 265, 301, (1993)

[30] We adopt a conservative error of 10 km/s for this quantity, based on the uncertainties of the control samples.

[31] C. Alcock, et al., Astron. J., 119, 2194 (2000c)
[32] K. Rohlfs, J. Kreitschmann, B. C. Siegman, J. V. Feitzinger, Astron. & Astrophys., 137, 343 (1984)

[33] The sample is not large enough and the velocities are not accurate enough to (a) detect tidal streams in front or behind the LMC, and (b) measure the systemic rotation of the halo RR Lyrae population. However, from a sample of this size, and with velocities measured to this accuracy, there is no difficulty in measuring the velocity dispersion and thus distinguishing a disk population from a halo population in the LMC.

[34] C. Alcock, et al., Astrophys. J., 542, 281 (2000b)

[35] C. Stubbs, in ASP Conf. Ser. 165 on ”The Galactic Halo”, eds B. K. Gibson, T. S. Axelrod & M. E. Putman (ASP: San Francisco), p. 503 (2000)

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Figure 1: Fig. 1: Best spectrum (top) compared with the worst spectrum (bottom) of the LMC RR Lyrae sample used to measure the LMC kinematics.

Table 1: Observed Velocity Dispersions

| Sample                  | N  | $V$ (mag) | $V_{r\text{mean}}$ (km/s) | $\sigma_V$ (km/s) |
|-------------------------|----|-----------|---------------------------|-------------------|
| $\omega$ Cen RR Lyrae   | 17 | 14.0      | 237 ± 5                   | 20 ± 3            |
| MACHO LMC Cepheids      | 5  | 16.0      | 268 ± 12                  | 28 ± 9            |
| OGLE LMC Miras          | 23 | 17.0      | 225 ± 9                   | 43 ± 6            |
| MACHO LMC RR Lyrae      | 43 | 19.5      | 214 ± 9                   | 61 ± 7            |
Figure 2: Velocity histograms of LMC RR Lyrae, Cepheids, Miras, and ω Cen RR Lyrae.