THE VELOCITY STRUCTURE OF LMC CARBON STARS: YOUNG DISK, OLD DISK, AND PERHAPS A SEPERATE POPULATION

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ABSTRACT

We analyze the velocity residuals of 551 carbon stars relative to a rotating-disk model of the inner ~ 70 deg² of the Large Magellanic Cloud (LMC). We find that the great majority of the stars in this sample are best fit as being due to two different populations, a young disk population containing 20% of the stars with a velocity dispersion of 8 km s⁻¹, and an old disk containing the remaining stars with a velocity dispersion of 22 km s⁻¹. The young disk population has a metallicity ~ 0.25 dex higher than the old disk.

With less certainty, the data also suggest at the 2σ level that there may be a third kinematically distinct population that is moving towards us at 30 km/sec relative to the LMC, consistent with measurements of 21 cm velocities. If real, this population contains about 7% of the carbon stars in the sample. It could be a feature in the disk of the LMC or it could be tidal debris in the foreground or background. If it is tidal debris, this population could account for some or all of the microlensing events observed towards the LMC.

Stars:carbon – Magellanic Clouds

1. INTRODUCTION

Carbon stars are an important tracer of the kinematics of the disk of the Large Magellanic Cloud (LMC). Kunkel et al. (1997) have analyzed the velocities of carbon stars in the outer LMC disk. Hardy, Schommer, & Suntzeff (1999) have measured the radial velocities of 551 carbon stars in the inner ~ 70 deg² of the LMC and fit these velocities to a disk model. Here we focus on the residuals to this disk solution in order to isolate different kinematic components of the LMC carbon star population.

The Milky Way disk has a multi-components structure that may be describable as a kinematically cold thin disk and a hotter thick disk as originally advocated by Gilmore & Reid (1983), or may comprise a continuum of structures of increasing thickness (Norris & Ryan 1991). The LMC provides a unique laboratory to study the kinematic substructure of a quite different galaxy that also has disk kinematics. By studying this substructure, we can eventually learn about the relations between formation history, disk heating, and enrichment in a non-Milky Way setting.

Schommer et al. (1992) and Hughes, Wood, & Reid (1991) have presented data suggested that older components of the LMC disk are kinematically hotter than younger components, although these studies are limited by poor statistics. In this paper, we analyze a much larger radial-velocity sample to extract a substantially more detailed picture of the LMC’s disk substructure. From both conceptual and practical standpoints, the analysis of the Carbon star radial velocities is best divided into two steps. In the first step Hardy et al. (1999) fit for the global properties of the disk including its projected rotation curve and its transverse velocity. Here we apply the second step and examine the residuals to that fits in order to extract information about the kinematic structure of the disk. This study yields unambiguous evidence that the LMC disk, like the Milky Way disk, has a multi-component structure. We go on to show that, just as with the Milky Way, the colder disk component is more metal rich than the hotter one.

In addition to determining the structure of the LMC disk, we also search for a non-disk component. One of the motivations for this research is the microlensing conundrum. At present ~ 20 microlensing events towards the Magellanic clouds have been analyzed (Alcock et al. 1997; Lassere et al. 2004). If these microlensing events are due to halo objects, or MACHOS, then the detected MACHOS make up 10 — 30% of the mass of the halo. All obvious astrophysical candidates for halo microlensing have severe problems (e.g. Graff, Freese, Walker & Pinsonneault 1999). An alternative hypothesis is that the microlensing events are due to lenses within the LMC (Wu 1994, Sahu 1994). However, if these lenses are virialized, they must have a large velocity dispersion (Gould 1993). In that case, we should see this population in the carbon star velocities, unless the carbon stars do not trace the lens population (Aubourg et al. 1999).

Another possibility is that the observed microlensing is due to an unvirialized foreground or background population of lenses, such as a tidal streamer (Zhao 1998; Zaritsky & Lin (1997); Zaritsky et al. 1999). In this case, we would expect the velocities of the lenses to be different...
from those of LMC stars. Again, we should see this population in the carbon star velocities, unless the carbon stars do not trace the lens population or unless, by coincidence, the lens population has the same radial velocity as the main LMC population. We find that the data provide evidence at the 2σ level for additional velocity structure that could be due to an unvirialized foreground or background population. While this detection cannot be regarded as compelling, the problem of explaining the observed microlensing events by other routes has proven so difficult that this proposed solution should be given serious consideration: our marginal detection should be checked by a much larger radial-velocity study.

2. THE DATA

Hardy et al. (1999) obtained radial velocities \( v \) for 551 carbon stars in 35 fields, each about 0.25 deg\(^2\) scattered more or less uniformly over the inner 70 deg\(^2\) of the LMC. The measurement errors are typically \( \sim 1 \) km s\(^{-1}\). Hardy et al. (1999) fit these velocities to a planar, inclined disk with a circular velocity that is allowed to vary in 5 bins. Table 1 shows a summary of the parameters for the solution used in this paper; see Hardy et al. (1999) and Schommer et al. (1992) for details and descriptions of the rotation curve parameters and other possible fits. The fit adopted here is basically a solid body rotation model (constant dV/dr) out to 3.5 degrees, a flat rotation curve beyond that (3.5-5.5\(^\circ\)), a slightly twisting line of nodes (\( \Theta \) in Table 1), an overall dispersion around the fit (\( \sigma \)) which is characteristic of an intermediate to old disk population, and an orbital transverse motion consistent with the proper motion measurements of the LMC (e.g., Kroupa & Bastian 1997). The solution simultaneously fits for the transverse velocity of the LMC \( v_\perp \), since this gives rise to a gradient in radial velocities across the face of the LMC with respect to angular position, \( \nabla v = v_\perp \). In this paper we primarily use the residuals to this fit, \( \Delta v \), (§ 3 and § 4.1) but also make use of the heliocentric radial velocities, \( v \) (§ 4.2).

| Table 1. Rotation Curve Parameters |
|------------------------------------|
| \( V_{sys} \) & dV/dr & \( V_{circ} \) |
| 50 km/s & 21.5 km/s/kpc & 75 km/s |
| \( \Theta(PA) \) & \( \sigma \) & \( V_T \) |
| \(<-20^\circ\) & 18-22 km/s & 250 km/sec |

3. DETECTION OF TWO POPULATIONS

A histogram of the residuals \( \Delta v \) is shown in Figure 1. We attempt to represent these residuals as various sums of Gaussians of the form

\[
P(\Delta v) = \sum_{i=1}^{n} \frac{N_i}{\sqrt{2\pi\sigma_i}} \exp \left[ -\frac{(\Delta v - \Delta v_i)^2}{2\sigma_i^2} \right],
\]

subject to the constraint \( \sum_i N_i = 551 \). Here \( n \) is the number of Gaussian components, and for each component \( i \), \( N_i \) is the number of stars, \( \Delta v_i \) is the mean residual velocity, and \( \sigma_i \) is the dispersion. We fit the velocity residuals to these functional forms by adjusting the parameters to maximize the log likelihood estimator,

\[
\ln L = \sum_{k=1}^{551} \ln[P(\Delta v_k)].
\]

This is equivalent to a \( \chi^2 \) minimization measurement in the Poisson limit of infinitely small bin size. Probabilities can be inferred from the log likelihood estimator by comparing likelihoods to the solution with maximum likelihood and using the relation

\[
\Delta \chi^2 = -2\Delta \ln L.
\]

Figure 1 shows fits to the (unbinned) residuals using a single Gaussian (with two free parameters) and a double Gaussian. In the latter fit, we impose the physically plausible additional constraint \( \Delta v_1 = \Delta v_2 \), so there are a total of 4 free parameters. The double Gaussian solution has 20% of the stars in a thin disk population with a velocity dispersion of 8 km s\(^{-1}\), and the remaining 80% of the stars in a thicker disk population with a velocity dispersion of 22 km s\(^{-1}\). The improvement is \( \Delta \chi^2 = 20 \) for the addition of two degrees of freedom, i.e. a statistical significance of \( 1 - \exp(-\Delta \chi^2/2) \sim 1 \times 10^{-4.3} \). Thus, LMC carbon stars are better represented as two populations than one. However, this does not prove that we have detected two distinct populations. It could also be that there are a continuum of populations with a range of dispersions from below 8 to above 22 km s\(^{-1}\). Nevertheless, for clarity of discussion, we will refer to two discrete populations.

3.1. Metallicity of the two populations

Costa & Frogel (1996) (CF) published RI photometry of 888 LMC carbon stars and 204 with infrared (JHK) photometry. Within this sample, 103 of the stars that have infrared photometry had velocities measured by Hardy et al. (1999). CF showed that the infrared colors differ between samples of carbon stars from the Milky Way, the LMC, and the SMC. The carbon stars in the three galaxies can be fit by

\[
(J - H)_0 = 0.62(H - K)_0 + \zeta
\]

with \( \zeta \approx \{0.72, 0.67, 0.60\} \) respectively for the Galaxy, the LMC, and the SMC. Cohen et al. (1981) suggested that this shift in colors is due to a metallicity related blanketing effect, in which case \( \zeta \) can be used as a metallicity indicator. As can be seen in Figure 5 of CF, there is substantial scatter in the color-color relations compared to the differences among the three galaxies. Thus, this metallicity indicator cannot reliably determine the metallicity of an individual carbon star: it should be used only as a statistical estimator for stellar populations.

Even though the metallicities of carbon stars in the three galaxies are unknown, if we assume that [Fe/H] \( \sim \{0, -0.4, -0.8\} \) for the three galaxies, we can make a rough calibration of this metallicity indicator:

\[
\delta[Fe/H] \approx 6.7 \delta \zeta.
\]

This relation should be taken only as rough estimate. However, one can be more confident of the relative order of the metallicities of carbon stars in the three galaxies, and hence \( \zeta \) can robustly distinguish between a high-metallicity population and a low-metallicity population.

We find that the metallicity indicator \( \zeta \) is different for high velocity-residual stars than for low velocity stars.
Specifically, for stars with $|\Delta v| < 10 \text{ km/sec}$, we find $\zeta = 0.678 \pm 0.007$ while for $|\Delta v| > 10 \text{ km/sec}$, we have $\zeta = 0.662 \pm 0.005$. These two values of $\zeta$ are different at the 93% confidence level. However, since most of the “low velocity” stars chosen this way are actually from the more numerous thick-disk velocity sample, dividing up the sample in this way is not the best way to measure the metallicity difference. To isolate the thin and thick disks, we modify equation (1) to read

$$P(\Delta v) = \prod_{i=1}^{n} \frac{N_i}{2\pi\sigma_i} \exp \left[ -\frac{(\Delta v - \bar{\Delta v}_i)^2}{2\sigma_i^2} \right] \exp \left[ -\frac{(\zeta - \bar{\zeta}_i)^2}{2\sigma_i^2} \right],$$

where $\bar{\zeta}_i$ is the mean value of $\zeta$ for each population and $\sigma_i = 0.044$ is the observed dispersion of $\zeta$ in the sample for the 103 stars with velocities and infrared data. Note that for stars without infrared data, the last term is simply set to unity. We then find $\bar{\zeta}_1 = 0.663 \pm 0.04$, $\bar{\zeta}_2 = 0.700 \pm 0.16$, and $\bar{\zeta}_2 - \bar{\zeta}_1 = 0.037 \pm 0.017$, i.e. a 2 $\sigma$ difference, which corresponds to $\Delta [\text{Fe/H}] \sim 0.25$.

Given the combination of different velocities and different metallicities, we claim that we have detected either two different disks within the LMC representing different metallicities, we claim that we have detected either two different disks within the LMC representing different metallicities, or a continuous distribution of ages of stellar populations or a continuous distribution of disk populations with a range of ages. In either case, the younger populations have higher metallicity and lower velocity dispersion.

3.2. No virialized lenses

Gould [1995] showed that for microlensing within a virialized disk, the microlensing optical depth is

$$\tau = \frac{2 \langle v^2 \rangle}{c^2} \sec^2 i \quad (7)$$

where $i$ is the angle of inclination of the disk with respect to the line of sight, $30 - 40^\circ$ in the case of the LMC. In the case of the carbon stars, the total velocity dispersion is $21 \text{ km s}^{-1}$ and thus the optical depth due a virialised stellar population traced by the carbon stars is $\lesssim 2 \times 10^{-8}$, much smaller than that measured by the MACHO experiment (Alcock et al. [1997]) of $1.2 \pm 0.4 \times 10^{-7}$. Thus, the virialized population traced by carbon stars cannot account for microlensing. However, a virialized population too old to be traced by carbon stars would not be seen in our data (Aubourg et al. 1999).

3.3. Conclusion

We have explicitly assumed that hotter, more metal poor population is older than the younger, metal rich population in analogy with the Milky Way, even though the LMC may have a different disk heating mechanism than the Milky Way. The age-velocity dispersion relation has been confirmed previously by Hughes, Wood & Reid [1991] and Schommer et al. [1992]. Since we detect a metallicity difference based on our infrared colors within this population, we also determine that some noticeable metal enrichment occurred during the Carbon star formation epoch.

The velocity dispersion of the thick disk component, $22 \text{ km s}^{-1}$, is much higher than the thin disk, and is close to the velocity dispersion of the oldest objects measured in the LMC, $\sim 30 \text{ km s}^{-1}$ (Hughes, Wood & Reid 1991, Schommer et al. 1992). Thus, we can show that the bulk of disk heating occurred during the Carbon star formation epoch.

4. SEARCH FOR A KINEMATICALLY DISTINCT POPULATION

The analysis of Gould [1992] only applies to virialized populations. It is still possible that an unvirialized population of stars could be causing microlensing. Such a population might be a streamer of stellar material pulled out by tidal interactions between the LMC and the Milky Way, or between the LMC and the SMC (Zhao [1998]). Zaritsky & Lin [1997] claimed that they may have seen such a streamer in LMC clump giants. This paper caused numerous counter-arguments which are summarized and debated in (Zaritsky et al. 1999).

Ibata, Lewis & Beaulieu [1998] examined the velocities of 40 clump giants in the LMC of which 24 were candidate foreground stars according to the criteria of Zaritsky & Lin [1997]. Ibata et al. [1998] found no difference in the mean velocities of the candidate foreground stars and the other clump stars and concluded that these stars did not form a separate kinematic population from the LMC. Zaritsky et al. [1999] confirmed the results of Ibata et al. (1998) using a much larger sample of 190 candidate foreground clump stars. However, the carbon-star sample that we analyze here is potentially more sensitive to the presence of tidal streamers than either of these two clump-star samples, in part because it is larger (551 stars) and in part because the velocity errors are much smaller ($\sim 1 \text{ km s}^{-1}$).

4.1. Search for third population in disk-fit residuals

We search the data for a non-virialized, kinematically distinct population (KDP) in two different ways. First, we fit the residuals to the disk solution to the sum of three Gaussians, two representing the LMC, and one for the KDP. That is, we apply equation (3) with $n = 3$. We find a solution which is somewhat better than the two Gaussian fit, $\Delta \chi^2 = 8$ for a change of 4 degrees of freedom. The off-center KDP peak is found to be moving towards us at $27 \text{ km s}^{-1}$ relative to the bulk of the LMC and to contain 63 stars, about 10% of the total. Thus, the data suggest that there may be a KDP, but at a statistically weak level of confidence. A Monte Carlo simulation was performed to verify the statistical confidence (details of which are described in § 4.3) which showed that this third bump is only present at the 75% confidence level. The fit to the third bump is shown in Fig 2.

4.2. Search for a third population in velocities

In the model considered in the previous section, the KDP stars have a common motion relative to the LMC. Possibly, the KDP stars are moving steadily away from the LMC disk, or are not associated with the LMC disk. The KDP should be seen in the original heliocentric radial velocities $v$ better than it is seen in the disk-fit residuals $\Delta v$. We therefore fit the data to a functions of the form...
where \((\theta_x, \theta_y)\) is its angular position on the sky, and \(A_x\) and \(A_y\) are planar coefficients for the heliocentric velocity distribution of the KDP. This equation is similar to equation (6) but we have replaced the \(\Delta v\) distribution of the KDP. This equation is similar to equation (6) but we have replaced the \(\Delta v\) distribution of the KDP.

Initially, we set \(A_x = A_y = 0\), so that there are same number of degrees of freedom as in the three-Gaussian fit to the residuals. We find no solution here that has a lower \(\chi^2\) than the two-Gaussian solution, implying that there is no evidence for the existence of a third population having a common heliocentric velocity outside the LMC disk.

We therefore repeat the search, but allow \(A_x\) and \(A_y\) to vary as free parameters. We find that the likelihood is not significantly different from the "young disk" component with \(\bar{v}\).

Relative to the two-Gaussian solution, this KDP solution shows an improvement of \(\Delta \chi^2 \geq 14\) in 26 cases. Hence, our detection is significant only at the 94% level, roughly equivalent to 2 \(\sigma\).

4.4. Evidence of the KDP in Other LMC components

Given the intriguing signal we see in the C star velocities, but also the marginal level of significance, it is worth exploring other possible signs of the KDP. One such tracer is the 21cm gas emission, mapped, e.g., by Luks & Rohlfs (1992), and Kim et al. (1998). Luks & Rohlfs note that a lower velocity component ("L-component") contains about 19% of the HI gas in the LMC, is separated from the main velocity component by \(\sim 30\) km/s. Although Kim et al. (1998) do not specifically comment on such a component in their paper based on higher spatial resolution HI imaging, a similar signal seems evident in their position-velocity maps (e.g., Figs. 7a and 7b in their paper) at RA 05:37:05:47 and DEC -30 to -120 arcm. The standard interpretation of this substructure in gas is that it is due to hydrodynamic effects on gas within the LMC disk. However, the correlation of the gas velocity "L-component" with the stellar KDP suggests that the gas may be outside the LMC disk.

An intriguing but somewhat more ambiguous signature may be evident in the CH star velocities of Cowley & Hartwick (1991). Velocities for a sample of \(\sim 80\) CH stars show a low velocity asymmetric tail, consistent with a component at \(\sim 20\) km/sec lower systematic velocity. Cowley & Hartwick (1991) even suggest that one explanation of this population is that it is a result of an earlier violent tidal encounter between the LMC-SMC system and the Milky Way. The small sample statistics and asymmetric spatial distribution of these stars make a more detailed exploration difficult.

5. MICROLENSING INTERPRETATION

We may have detected a kinematically distinct population of carbon stars in the direction of the LMC. If real, this population could be either a structure within the LMC disk or tidal debris that is well separated from the disk and hence either in front of or behind the LMC. If it is well separated from the LMC, then it would give rise to microlensing: either it would be in front of the LMC and so would act as lenses, or it would be behind the LMC and would act as sources.

The microlensing optical depth due to a thin sheet of stellar matter with density \(\Sigma_1\) and the LMC with density \(\Sigma_2\) separated by a distance \(D\) which is small compared to the distance from the Sun to the LMC is:

\[
\tau_{KDP} = \frac{4\pi G}{c^2} D \frac{\Sigma_1 \Sigma_2}{\Sigma_1 + \Sigma_2}. \tag{9}
\]

The distance between the two sheets, \(D\), cannot be determined from velocity data alone. However, since the two sheets must have similar velocities, the tidal tail cannot be a random interloper in the halo, but must be somehow related to the LMC. Lacking further information, we make the somewhat ad hoc assumption that the material in the tidal tail has been moving away from the LMC at a constant velocity of \(30\) km/s since close tidal encounter between the LMC and the SMC, 200 Myr ago (Gardiner & Noguchi 1996). In that case, we have

\[
D \sim v_{KDP} \times 200\text{ Myr} \sim 5\text{ kpc}. \tag{10}
\]
In fact, it is likely that the foreground object has had its velocity substantially changed by gravitational interaction with the LMC, and to a lesser extent, the SMC and the Milky Way, so this calculation only indicates that the object could have moved several kpc from the LMC in the past 200 Myr. All the results of this section will hold if the object is several kpc either in front of or behind the LMC.

The total surface mass density, \( \Sigma_1 + \Sigma_2 \), can be estimated from the observed surface brightness of the LMC, which is \( R \sim 21.2 \text{ mag arcsec}^{-2} \) (De Vaucouleurs 1957) near the center. If we assume a mass to light ratio of 3 (in solar units), this corresponds to a total surface mass density of \( 300 \, M_\odot \, \text{pc}^{-2} \).

It is possible that the surface densities of the disk and KDP populations are not traced by carbon stars. Still, lacking further information, we estimate the optical depth by setting \( \Sigma_1/\Sigma_2 = 39/(551-39) \) according to the solution of § 4.2, we obtain

\[
\tau = 6 \times 10^{-8} \frac{D}{5 \, \text{kpc}}. \quad (11)
\]

This optical depth is substantially larger than the optical depth due to a virialized disk population traced by the carbon stars (\( \lesssim 2 \times 10^{-8} \)). It is consistent with the value observed by the MACHO collaboration (Alcock et al. 2000). There could be more tidal material which we have not found in this search because its velocity is by chance too close to the velocity of the LMC, and which would raise the optical depth. If \( D \) were greater than 5 kpc, then \( \tau_{\text{KDP}} \) would rise proportionately.

The transverse motion of such a population with respect to the LMC is probably 70 km s\(^{-1}\), the circular orbital velocity of the LMC. To calculate the typical transverse velocity in a microlensing event, this velocity should be added in quadrature to all the other sources of transverse velocity. The stars in the LMC are orbiting about the LMC center with a transverse motion of 70 km s\(^{-1}\) at 4 kpc (Kunkel et al. 1997; Hardy et al. 1999). The LMC system has a transverse velocity with respect to the Sun of some 250 km s\(^{-1}\) (Hardy et al. 1999) which will translate to a projected transverse motion of 25 km s\(^{-1}\) (at 5 kpc from the LMC). Adding these velocities in quadrature, the derived typical transverse velocity of a microlensing event is 100 km s\(^{-1}\), in which case the typical mass of a lens is

\[
M \sim 0.13 M_\odot \left( \frac{D}{5 \, \text{kpc}} \right)^{-1}. \quad (12)
\]

This is significantly below the mean mass of stars in the neighborhood of the Sun (e.g. Gould, Bahcall, & Flynn 1997), but the LMC may have a different mass function. However, it is important to recognize that if \( D \) is made larger so as to account for more of the optical depth, then the mean mass is driven lower

\[
M \sim 0.075 M_\odot \left( \frac{\tau}{1 \times 10^{-7}} \right)^{-1}. \quad (13)
\]

### 6. Conclusion

We report two primary new results, one with high statistical confidence, one which is shakier, but perhaps more interesting if true. We show that Carbon stars in the LMC are divided into a hot and cold population, with a clear difference in metallicity between the two populations. Thus, we show that the epoch of LMC disk heating had to occur during the Carbon Star formation epoch.

We also show with less confidence the existence of a third population, outside the LMC. If this population is real, it suggests that some fraction of the Carbon stars in the LMC are not in the disk, and thus could explain microlensing events. Although at present the statistical significance of this detection is not enviable, this result is still the best extant solution to the microlensing conundrum. The microlensing conundrum poses such a difficult problem that several extreme explanations have been proposed including mirror matter and cosmological populations of population III white dwarfs (Graff, Freese, Walker & Binnsoualit 1999, and references therein). The kinematically distinct population is unique amongst these explanations in that it is not only allowed by the data, but even supported by the data at the 95% confidence level, and requires no modifications to the standard models of Particle Physics or Cosmology. We thus present it as the strongest explanation of LMC microlensing.

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FIG. 1.— The residuals of the carbon stars with respect to the LMC disk fit. The grey line is the best fit single gaussian. The black line is the best fit two gaussian model of eq. (1).

FIG. 2.— A fit to the residuals with three gaussians. Although the third peak is not significant in the fit to the residual, it is shown to be statistically significant when searched for in velocities, and shows the location of the KDP.

FIG. 3.— The residuals of the stellar velocities with respect to the KDP. The KDP stands out as a strong peak near residual = 0.
Carbon Stars
LMC+KDP
young disk
old disk
KDP
