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EVIDENCE OF A COUNTERROTATING CORE IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Stellar radial velocity data in the central region of the Large Magellanic Cloud (LMC) are used to estimate its radial velocity curve along various position angles (P.A.'s), including the line of nodes (LON). The central part of the radial velocity profile, along the LON, shows a V-shaped profile—a clear indication of counterrotation. The counterrotating region and the secondary bar have similar location and P.A. The origin of the counterrotating core could be internal (a secondary bar) or external (accretion). To explain the observed velocity profile, we propose the existence of two disks in the inner LMC, with one counterrotating. This two-disk model is found to match the H I velocities as well. Two disks with different LONs and velocity profiles can create regions that are kinematically and spatially separated. Their predicted locations are found to match the observed locations where the H I clouds are found to have two velocities.

Subject headings: galaxies: stellar content — galaxies: structure — Magellanic Clouds

Online material: color figure

1. INTRODUCTION

The Large Magellanic Cloud (LMC) has been the subject of a large number of surveys over the years in a wide variety of wave bands (see Westerlund 1990). The radial velocity curve of the LMC was estimated out to 8 kpc by van der Marel et al. (2002) using carbon stars. The linear inner part of the rotation curve has one peculiarity, which is the presence of negative velocities near the center. This result was not given any importance in that paper, because of a statistically insignificant number of stars near the center. Two kinematic components in CH stars were found by Hartwick & Cowley (1988), and a lower velocity component in carbon stars was found by Graff et al. (2000). The H I velocity studies also revealed two kinematic components, the L and D components (Rohlfs et al. 1984; Luks & Rohlfs 1992). Double-peaked H I velocities, indicating H I clouds with two velocities in the same line of sight, have been found in some locations in the LMC, suggestive of H I gas being located in two layers in the LMC. The galactocentric radial velocity curve as shown in Figure 8 of Rohlfs et al. (1984) indicates that the central, linear part of the velocity profile has a reversal of slope near the center. All the above point to the possibility of a kinematically distinct component in the inner LMC. Zhao et al. (2003) estimated and studied the radial velocity of 1347 stars in an attempt to detect the presence of a kinematically different component in the inner LMC, and they assigned a probability of less than 1% for its presence. Here we reanalyze the above data and search for evidence of a second kinematic component in the inner LMC.

The variation of stellar velocity as a function of radial distance along various position angles (P.A.'s) is used to study the inner kinematics of the LMC. In a barred galaxy, the linear part of the curve near the center would correspond to the bar. As we go away from the center, toward the ends of the bar, the presence of the disk starts to dominate, which is indicated by a flattening of the curve. If a kinematically different component is present near the central region, one would expect to see a deviation from a straight-line profile in the central region well inside the point of flattening of velocity. Thus, we use deviations in the radial velocity curve near the center, estimated along various P.A.'s, including the line of nodes (LON), to search for the kinematic signature of a second component within the primary bar of the LMC. So far, no model has been proposed to explain the different kinematics shown by the gas and stars. In this Letter, we propose a two-disk model for the LMC. We model these disks with the observed inclination and the LONs estimated from the radial velocity profiles along various P.A.'s. We also demonstrate that this simple model for the LMC is capable of explaining most of the observed kinematic features.

2. ROTATION CURVE AND THE V-SHAPED PROFILE

The radial velocities of 1347 stars presented by Zhao et al. (2003) were used to obtain the stellar radial velocity curves. The bar region of the LMC is more or less covered by these data. The main advantage of these data is that they are homogeneous, in that the same setup was used to estimate all the velocities, thereby reducing the systematic errors. On the other hand, the observed stars do not belong to any particular evolutionary category and thus represent a heterogeneous population. We also used the stellar velocities of red supergiants (Massey & Olsen 2003), carbon stars (Kunkel et al. 1997), and red giants (Cole et al. 2005). The center of the LMC is taken to be $\alpha = 5^{h}19^{m}38\overset{s}{.}0$, $\delta = -69°27'05\overset{''}{.}2$ (J2000) (de Vaucouleurs & Freeman 1973), which is the optical center. The α and δ are converted to linear (X, Y)-coordinates using this center.

Van der Marel et al. (2002) estimated the LON to be $129\overset{\circ}{.}9 \pm 6\overset{\circ}{.}0$ using carbon stars. Therefore, stars located along P.A. = 130° and located up to $0\overset{\circ}{.}4$ away from the P.A. in the perpendicular direction, on both sides, are selected. These stars were plotted as a function of radial distance and were found to show a variation from the expected straight-line profile. This can be more clearly identified if we bin the data in the radial distance and study the variation of the average velocity. The plot is shown in Figure 1 (*bottom left*). The error bars shown in the figure indicate the dispersion in the velocity among the stars in each bin. The striking feature of the plot is the "V" shaped velocity profile in the central region, where we expect a straight-line profile corresponding to the primary bar. The radial distance along any P.A. is taken positive for the northern part and negative for the southern part of the LMC (Feitzinger

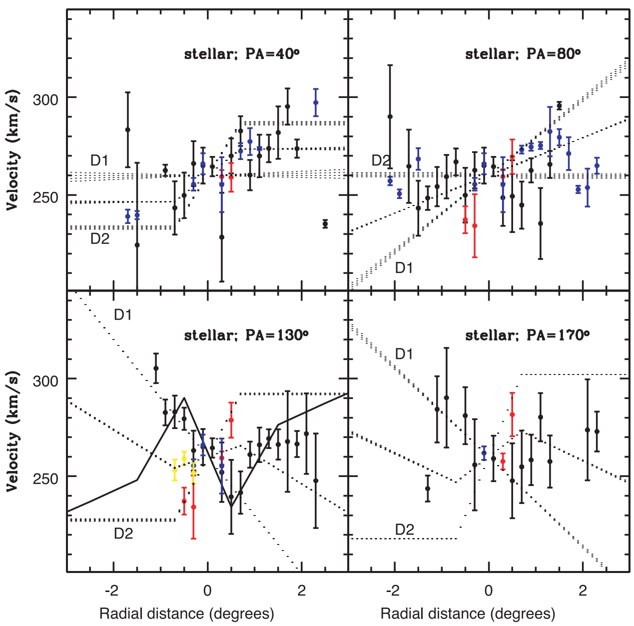

FIG. 1.—Radial velocity profiles of stars along various P.A.'s. Black points indicate stellar velocities from Zhao et al. (2003), red points indicate carbon star velocities from Kunkel et al. (1997), blue points indicate velocities of red supergiants from Massey & Olsen (2003), and yellow points indicate velocities of red giants from Cole et al. (2005). The solid line in the bottom left panel is the rotation curve estimated by van der Marel et al. (2002). "D1" and "D2" denote the two disk components. The dotted line between D1 and D2 denotes their average.

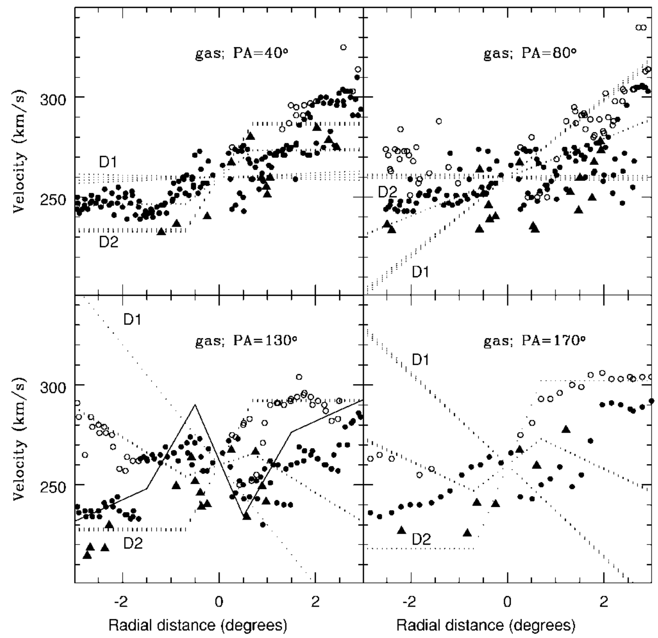

FIG. 2.—Same as Fig. 1, but for the gas. Filled circles indicate the H I data (main component), and open circles indicate the second component of the H I gas from Rohlfs et al. (1984). The triangles indicate velocities of the molecular clouds from Mizuno et al. (2001). [*See the electronic edition of the Journal for a color version of this figure.*]

1980). The rotation curve as estimated from carbon stars by van der Marel et al. (2002, their Table 2) is shown as a solid line. It can be seen that their suggestion of counterrotation near the center is confirmed here.

We obtained the radial velocity profile along various P.A.'s to estimate the value of the P.A. at which the maximum gradient is noticed, which will be the LON of the central region. Therefore, we used all the stellar data and estimated the radial velocity profiles for P.A.'s from 0° to 180°, with a gap of 10°. The slope of the counterrotating region was found to be maximal near 120°–130°, indicating that this is the LON of the inner region. The stars located immediately outside the counterrotating region were found not to have the LON of 130°. This can be seen in the top left panel of Figure 1, where the radial velocity profile along P.A. = 40°, which is the minor axis for the above LON, is shown. The radial velocity has a gradient about the minor axis. The stellar data shown here extend only up to 2°–2°.5; therefore, the above argument is valid out to this radial distance. The H I velocity data of the main component from Rohlfs et al. (1984) were also analyzed in the same way, and the radial velocity curve is shown in Figure 2 (*bottom left*). In the case of the gas, we have shown the actual data points and not the average. The velocity pattern clearly indicates two velocity components, where the inner region shows an S-shaped deviation. The P.A. of the LON of H I gas was found to be ~170° (Luks & Rohlfs 1992; Kim et al. 1998; Rohlfs et al. 1984). We also estimated the radial velocity curve along the H I LON for both stars and gas, and the plots are shown in the bottom right panels of Figures 1 and 2. The stellar radial velocity curve shows very large scatter, which is partly due to the smaller number of stars and partly due to inherent scatter in each bin. The H I profile clearly shows an S-shaped deviation in the inner region. NGC 3593 has been found to have a similar radial velocity profile, as shown in Figure 1 of Bertola et al. (1996). This was interpreted as a case of inner stars counterrotating with respect to the outer ones.

3. TWO-DISK MODEL AND THE FIT TO THE OBSERVED RADIAL VELOCITY PROFILES

We tried to model the disk of the LMC such that a counterrotating contribution is added to the main disk of the LMC. The main disk, which contains the bar and the majority of the mass, is responsible for most of the radial velocity curve. The LON of the counterrotating region is also found to be 130°. Thus, the inner kinematic change is produced by invoking counterrotation with respect to the main large-scale disk, whose parameters were estimated by van der Marel et al. (2002). On the other hand, the region just outside the counterrotating core was found to have LON ≠ 130°. The position of the LON of this region can be estimated from the fact that there is a positive slope observed at a P.A. of 40°. This indicates that the value of the LON is larger than 130°. A value of 160°–170° for the P.A. was able to reproduce the observed slope along 40°. It is found that the LON of the H I gas is 170° and extends only up to 2°.5–3°.0. The inclination of the H I distribution was found to be similar to that of the stellar disk. Thus it is quite possible that the intermediate region between the counterrotating core and the outer LMC is dominated by a disk that is more of H I gas having the aforementioned properties. The stellar data show a great deal of scatter for 170°, probably because of the fact that the stars are quite disturbed in this region.

Thus, we generated two disks, one with LON = 130° that follows the kinematics of the stellar disk (D1) and with an inclination of $i = 35°$ about the LON. The rotational velocity for this disk is chosen such that it fits the observed range of stellar velocities and has a linear rise up to a radial distance of 3°, staying flat beyond that. The systemic velocity of this disk is taken to be 260.0 km s^{-1}. The disk that is dominated

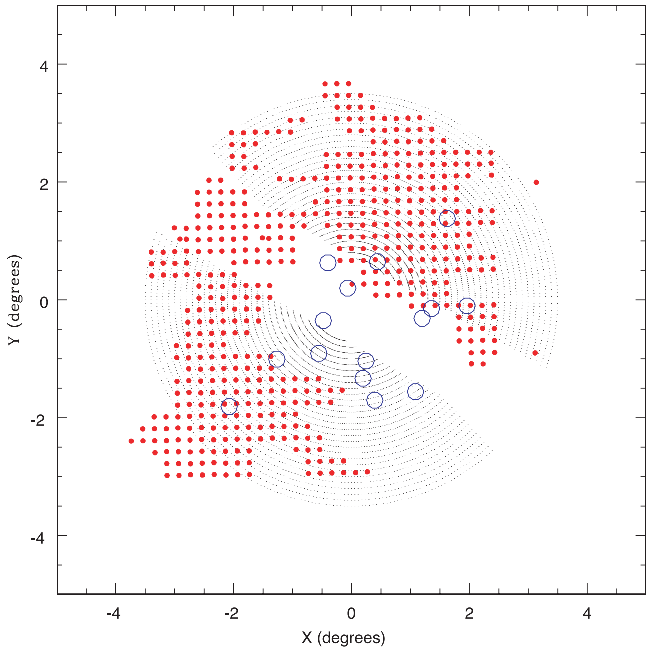

Fig. 3.—Locations in the LMC where the two disks are separated by more than 360 pc and have velocities differing by more than 20 km s^{-1} (*black dots*). Overplotted are the locations of H I gas where two components were detected by Rohlfs et al. (1984; *red circles*) and the locations of the microlensing events identified toward the LMC (*blue circles*).

by H I gas has LON = 170° (D2). The systemic velocity of this second disk was taken to be 275 km s^{-1} (Kim et al. 1998) initially, but it was found to fit well for 260 km s^{-1} too. The rotational velocity of D2 is chosen such that it fits the stellar data. Since the two disks have the same inclination about two different LONs, there will be a separation created between the disks. As their kinematics are also different, there will be regions in the LMC that have the same location in the sky but different velocities along the line of sight. When one estimates the radial velocity curve, both disks contribute, so that the observed velocities could be the same as that of the individual disks or an average of the two components, depending upon where they are located.

To compare with the observations, we generated the radial velocity curves as shown in Figure 1 (for stars) and Figure 2 (for gas). In both figures, the radial velocities of the individual disks, as well as the average, are shown. In Figure 1, the profile of D1 fits the central region between −1°.0 and 0°.5 very well for P.A. = 130°. The stars from Zhao et al. (2003) mostly follow the counterrotating disk. The carbon stars, on the other hand, follow D2, and the red giants follow the average velocity profile. Therefore, even inside the counterrotating core, a two-disk model is required in order to fit the observed data. The stellar data just outside the central region, toward the north, seem to fall closer to the average profile of D1 and D2. The assumption of the LON for D2 of 170° is justified from the fact that the velocity profile along the minor axis of D1 is found to fit well. The plot in the bottom right panel, for P.A. = 170°, is found to show a great deal of scatter, which is not expected. The minor axis of D2, which is at P.A. = 80°, also shows a scattered plot. Stars located in this intermediate region, between 1° and 2°.5, appear disturbed. In the case of the gas, as shown in Figure 2, the agreement is very good. For P.A. = 130°, the H I gas is found to follow D2 and the average. The open circles denote the second component of H I as given by Rohlfs et al. (1984). It is remarkable to see that the two-disk model naturally explains the presence of two velocities for clouds in the same line of sight. Molecular clouds also more or less follow the predicted velocities. The plot for P.A. = 40° is found to fit most of the data, except the high-velocity gas in the north and some scatter near the center. For P.A. = 170°, which is the LON for H I, the H I gas is found to follow D2, with some deviation near the center. For P.A. = 80°, molecular clouds are found to show deviations from the model, but the H I gas is found to be more or less located within the predicted locations and does not show any significant rotation about its minor axis. Therefore, we find that the velocity model, which was tuned to fit the stars, fits the H I gas remarkably well. The model velocities that were arrived at are as follows: the slope of D1 is 30.0 km s^{-1} deg^{-1} up to a radius of 3°, and D2 has a slope of 60.0 km s^{-1} deg^{-1} up to a radius of 0°.7 and a constant velocity of 42 km s^{-1} up to 3°.0. In reality, the extent of the counterrotating disk could be much less than 3°. Better data in the intermediate region are required in order to obtain the exact value. A variation of up to 15% in the above value seems to fit the observed profile, and hence the error in the estimation of the slope can be considered to be 15%. Assuming the already estimated inclination, we find that the main disk of the LMC is rotating in the clockwise direction. This result is similar to the finding of Kroupa & Bastian (1997). The core region has counterclockwise rotation.

In this model, there are some locations in the line of sight where the two disks are physically and kinematically separated. Points in the line of sight that are located in both disks and separated by more than 360 pc are assumed to be physically separated. The scale height of the H I disk has been estimated to be about 180 pc (Padoan et al. 2001), and thus the assumed value for the separation is just enough to physically separate the disks. Locations that are in the same line of sight but located in both disks with more than 20 km s^{-1} difference in velocity are assumed to be kinematically separated. Figure 3 shows the predicted locations in the LMC where the disks are physically and kinematically separated. One of the observed features in the LMC is the presence of H I clouds in layers. The locations of the double-peaked clouds (Rohlfs et al. 1984) are overplotted as red circles. One can see that the majority of the double-peaked clouds are located within the predicted region. H I on the northwest side is matched very well. Some part of the southeast lobe of H I is found to be extended outside, and this lobe is known to extend to a larger distance from the LMC, as a result of tidal effects (Staveley-Smith et al. 2003). Thus, a larger extent for the H I gas in this lobe may be expected. The presence of gas near the northeast side is not explained by this model. The more or less agreeable match between the predicted and observed locations of the double velocities indicates that the assumed two-disk model is very close to the true nature of the LMC.

If the microlensing in the LMC is indeed caused by self-lensing, then kinematic outliers are expected toward the LMC in their distribution of radial velocity, proper motion, projected distance from the center of the LMC, distance modulus, and reddening (Zhao 1999a, 1999b). In the two-disk model, stars present in different disks differ in radial velocity, projected distance, distance modulus, and maybe reddening as well. Though most of the stars are located in the main disk, D2 also hosts some stars, such as the young stars. Thus, stars located in different disks can increase the star-star microlensing in the line of sight, thereby increasing the probability of self-lensing within the inner LMC. The locations of the observed microlensing events toward the LMC are shown in Figure 3 as large open circles on the predicted physically and kinematically separated locations in the LMC. Many of the events can be seen to fall within the predicted region. This suggests that the two disks in the inner LMC fit most of the criteria required for self-lensing within the LMC.

4. DISCUSSION

The main result of the present study is in the identification of a counterrotating core in the LMC. The inner LMC, within a radius of 3°, is modeled as possessing two disks, with one counterrotating. This model is valid inside the 3° radius. The region outside is not studied here and probably follows the parameters estimated by van der Marel et al. (2002). The two-disk model presented here is very simple. In reality, the LMC is likely to be a more complicated system that requires detailed modeling. The velocity data used in the present analysis were able to bring out the counterrotation very clearly. The V-shaped profile obtained in the center should in fact be an S-shaped profile, just as in the case of H I. The lack of data is responsible for the V shape, which is a truncated S. More velocity data for stars belonging to various populations may lead to a more detailed model of inner and intermediate regions based on velocity dispersion, kinematics of different populations, and possibly differing rotation centers of the two disks.

Kinematically peculiar cores are generally understood as being fossil fingerprints of the merger history of host galaxies (see Mehlert et al. 1998). In disk galaxies, they are generally interpreted as the signature of an external origin to the gas component (Bertola et al. 1992), where less than 12% host counterrotating gas disks and less than 8% host counterrotating stellar disks (Pizzella et al. 2004). The presence of counterrotation in NGC 3593 was modeled as being due to two disks to fit the observed velocity profile (Bertola et al. 1996). The two-disk model proposed for the LMC thus closely resembles the model for NGC 3593. In the LMC, the Population I stars are found to show the kinematics of the H I gas, indicating that they belong to the second disk. It is possible that the young stars in the LMC are formed from gas that has been accreted recently. Brüns et al. (2005) have presented a complete H I survey of the Magellanic system. The LMC and the SMC were found to be associated with large gaseous features—the Magellanic Bridge, the interface region, and the Magellanic Stream. This gas connects the two not only in position, but also in velocity. As discussed by Brüns et al., a fraction of the gas present in the vicinity is likely to be accreted by the Clouds. The gas in the Magellanic Bridge has low velocities in the LMC standard-of-rest frame, making an accretion of some of this gas by the LMC very likely. Thus, it is very possible that the inner gas-rich disk of the LMC could have been formed from this infalling gas, which could provide new fuel for star formation.

There is also a second possibility for the formation of counterrotation near the center. The photometric location of an inner secondary bar was identified in Subramaniam (2004) as -1.3 to 0.5 kpc in radial distance along LON $= 120°$. This is in good agreement with the extent of the counterrotating component and its P.A. Thus, the identified counterrotation may be associated with the secondary bar of the LMC. Numerical simulations of secondary bars (e.g., Friedli 1996) indicate that nested, counterrotating, stable bars are viable and that such systems can exist. The proposed formation scheme is the accretion of a retrograde satellite. Counterrotating secondary bars could also be formed as a result of instabilities in the primary bar (Fredli & Martinet 1993). This scenario does not require any merger. Thus, the true nature and the reason for the formation of the counterrotating core in the LMC are to be understood as lying among a wide variety of possibilities that are of external and internal origin; some discussion in this direction can be found in Corsini et al. (1998). The proximity of the LMC makes it ideal for testing theories of the formation of counterrotating cores and possibly understanding their origin.

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