COUNTERROTATING CORE IN THE LMC: ACCRETION AND/OR MERGER?

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Abstract The stellar radial velocity in the central region of the Large Magellanic Cloud (LMC) is used to estimate the radial velocity curve along various position angles (PA) including the line of nodes (LON). The central part of the radial velocity profile along the LON shows a V-shaped profile instead of a straight line profile. This is a clear indication of counterrotation. 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 HI velocities as well. The presence of a counter-rotating core could be due to internal (secondary bar) / external (gas accretion) origin.

Keywords: Magellanic Clouds - galaxies: interactions - galaxies: kinematics and dynamics

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 wavebands (see Westerlund 1990). The radial velocity curve of the LMC was estimated up 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 velocity near the center. This result was not given any importance in the paper due to 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 HI velocity studies also revealed two kinematic components, the L and the D components (Rohlfs 1984; Luks & Rohlfs 1992). Double peaked HI velocities, indicating HI clouds with two velocities in the same line of sight have been found in some locations in the LMC, suggestive of HI gas being located in two layers in the LMC. The galacto-centric radial velocity curve as shown in figure 8 of Rohlfs et al. (1984) shows that the central linear part of the velocity profile has a reversal of the slope near the center. All the above point to the possibility

R. S. de Jong, Island Universes, 83–88.

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 assigned a probability of less than 1% for its presence. We re-analyze the above data and search for evidence of a second kinematic component in the inner LMC.

2. Rotation Curve and the V-shaped Profile

The radial velocity of 1347 stars presented by Zhao et al. (2003) is used to obtain the stellar radial velocity curves. The bar region of the LMC is more or less covered by this data. The main advantage of this data is that it is homogeneous such that the same set up is 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, thus represents a heterogeneous population. We also used the stellar velocities of red super giants (Olsen & Massey 2003), carbon stars (Lunkel et al. 1997) and red giants (Cole et al. 2005). The center of the LMC is taken to be α = $05^h19^m38^s.0$; δ = $-69^o27'5".2$ (J2000) of de Vaucouleurs & Freeman (1973), which is the optical center. The α and δ are converted to the linear X, Y co-ordinates using this center.

Stars located along PA = 130° and located up to 0.4° away from the PA in the perpendicular direction, on both sides are selected and their average velocity was estimated. The plot is shown in figure 1, bottom left panel. The error bars as 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 PA is taken positive for the northern part and negative for the southern part of the LMC (Feitzinger 1980). The rotation curve as estimated from carbon stars by van der Marel et al. (2002) (their table 2) is shown as solid line. It can be seen that their suggestion of counterrotation near the center is confirmed here.

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 of the LMC which contains the bar and 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

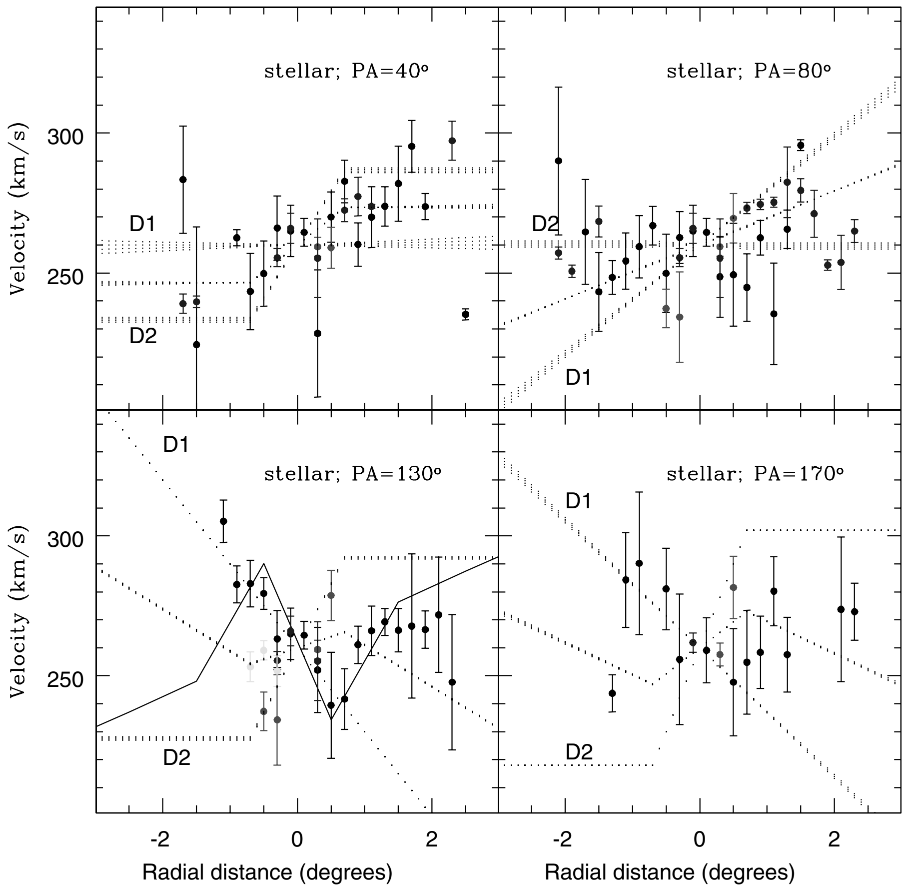

Figure 1. The radial velocity profiles of stars along various PAs. Black points indicate stellar velocities of Zhao et al. (2003), red points indicate carbon star velocities from Kunkel et al. (1997), blue points indicate velocities of red super giants from Olsen & Massey (2003) and yellow points indicate velocities of red giants from Cole et al. (2005). The bold line in the bottom left panel is the rotation curve estimated by van der Marel et al. (2002). D1 and D2 denote the disk1 and disk2 respectively. The dotted line between D1 and D2 denote the average of the two. This figure also appears in Subramaniam & Prabhu (2005).

counterrotating core was found to have a LON $\neq$ 130°. The position of the LON of this region can be estimated from the fact the there is a positive slope observed at a PA of 40°. This indicates that the value of LON is larger than 130°. A value of 160° – 170° for the PA was able to reproduce the observed slope along 40°. It is found that the LON of HI gas is 170° and it extends only up to 2.5 – 3.0°. The inclination of the HI 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, which is more of HI gas and having the above mentioned properties. The stellar data shows a lot of scatter for 170°, probably due to the fact that the stars are quite disturbed in this region.

We generated two disks. One with the LON=130° that follows the kinematics of the stellar disk (D1) and with an inclination of $i = 35^o$ about the LON. The other disk, that is dominated by HI gas, has the LON=170° (D2). The detailed model can be found in Subramaniam & Prabhu (2005). 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 which are located in two disks and separated by more than 360 pc are assumed to be physically separated. The scale-height of the HI disk was estimated to be about 180 pc (Padoan et al. 2001), thus the assumed value for separation is just enough to physically separate the disks. Locations which are in the same line of sight, but located in two disks and have more than 20 kms^{-1} difference in velocity are assumed to be kinematically separated. Figure 2 shows the predicted locations in the LMC. One of the observed features in the LMC is the presence of HI clouds in layers. The location of the double peaked clouds of Rohlfs et al. (1984) are over plotted as red points. One can see that the majority of the double peaked clouds are located within the predicted region. HI in the north-western side is matched very well. Some part of the south-east lobe of HI is found to be extended outside, and this lobe is known to extend to larger distance from the LMC, due to tidal effects Staveley-Smith et al. (2003). Thus a larger extent of the HI gas in this lobe may be expected. 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. Stars located in two 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 micro-lensing events towards the LMC are shown in figure 2 as big open circles on the predicted physically and kinematically separated locations on the LMC. Many of the events can be found 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.

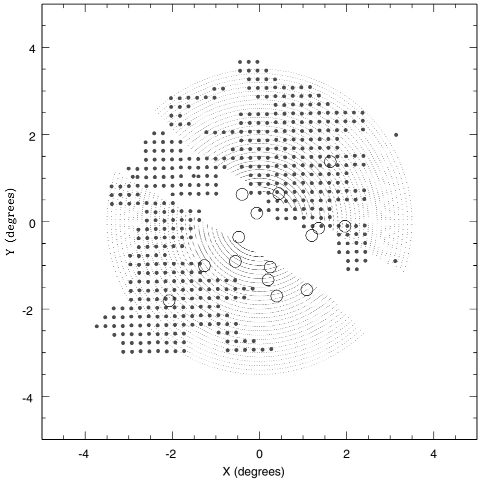

Figure 2. Locations in the LMC where the two disks are separated by more than 360 pc and have velocity differing by more than 20 kms^{-1} are shown as black points. Over plotted are the locations of HI gas (red filled circles) where two components were detected by Rohlfs et al. (1984) and the locations of the micro-lensing events identified towards the LMC (blue open circles). This figure also appears in Subramaniam & Prabhu (2005).

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 having the presence of 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 as estimated by van der Marel et al. (2002).

Kinematically peculiar cores are generally understood as being fossil fingerprints of merging history of host galaxies (see Mehlert et al. (1998)). The identified counterrotation may also be associated with the secondary bar of the LMC (Subramaniam (2004)). The proposed formation scheme is the accretion of a retrograde satellite. Counterrotating secondary bars could also be formed due to the instabilities in the primary bar (Friedli & 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 is to be understood from a wide variety of possibilities which are of external/internal origin.

In the LMC, the population I stars are found to show the kinematics of HI gas indicating that they belong to the disk2. It is possible that the young stars in the LMC are formed from the gas which has been accreted recently. Bruns et al. (2004) presented a complete HI 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. 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 likely that the inner gas-rich disk of the LMC could be formed from this infalling gas, which could provide new fuel to star formation.

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