THE SO-CALLED “BAR” IN THE LARGE MAGELLANIC CLOUD

HongSheng Zhao
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, England, UK; hsz@ast.cam.ac.uk

and

N. Wyn Evans
Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1 3NP, England, UK; nwe@thphys.ox.ac.uk

Received 2000 June 8; accepted 2000 September 29; published 2000 November 28

ABSTRACT

We propose that the off-centered “bar” in the Large Magellanic Cloud (LMC) is an unvirialized structure slightly misaligned with, and offset from, the plane of the LMC disk. The small displacement and misalignment are consequences of recent tidal interactions with the Small Magellanic Cloud and the Galaxy. This proposal, although radical, is consistent with the kinematics of the LMC and the near-infrared star count maps from the Deep Near-Infrared Survey and the 2 Micron All-Sky Survey and, in particular, with the reported 25°–50° inclination range of the LMC and the east-west gradient of distance moduli of standard candles. Contributions to LMC microlensing originate mainly from the mutual lensing of stars in the disk and the “bar.” The predicted microlensing optical depth is at levels comparable to observation, even without including contributions from MACHOs. Observational tests are suggested to discriminate between our misaligned offset “bar” model and the conventional picture of an off-centered planar bar.

Subject headings: dark matter — galaxies: interactions — Galaxy: halo — Galaxy: kinematics and dynamics — Magellanic Clouds

1. INTRODUCTION

By now, self-lensing is very well established as the main cause of the high optical depth toward the Galactic center and the Small Magellanic Cloud (SMC). So the Large Magellanic Cloud (LMC) seems something of an anomaly, as estimates of its self-lensing optical depth appear to be too low to account fully for the entire microlensing optical depth (Gould 1995). The most striking feature of the LMC is an off-centered “bar.” Many of the computations of self-lensing assume implicitly a coplanar thin “bar” and disk, which leaves little room for star-lensing in the LMC (e.g., Sahu 1994; Gyuk, Dalal, & Griest 2000). Observationally, the coplanarity of the “bar” and the disk is established to no better than the uncertainty in the inclination of the LMC, between 25° and 50° according to the review by Westerlund (1997). The distance moduli of components of the LMC are known no more accurately than ±0.05 mag from the standard candles. Patchy extinction by dust clouds in the LMC makes the true isophotes of the bright “bar” elusive. There is less agreement on the center of the “bar.” van der Marel & Freeman (1995) take it to be (5h24m, –69°7), which is the center of the optical isophotes of the bright “bar.” There is less agreement on the center of the LMC disk. There are a number of population centroids within 0.5°–2° of the optical center of the “bar” (see Table 3.8 of Westerlund 1997). They are all approximately to the north of the “bar,” with significant scatter in the east-west directions. As in conventional models, the star count density of the disk in the sky plane is parameterized as a standard exponential disk with elliptical contours:

\[ I_\delta(X_\delta, Y_\delta) = \frac{N_\delta(1 - f_\delta)}{2\pi L_\delta W_\delta} \exp \left( -\sqrt{\frac{X_\delta^2}{L_\delta^2} + \frac{Y_\delta^2}{W_\delta^2}} \right), \] (1)

while the “bar” is parameterized to have boxy contours and sharp edges,

\[ I_b(X_b, Y_b) = \frac{N_b f_b}{3.286 L_b W_b} \exp \left( -\frac{X_b^4}{L_b^4} - \frac{Y_b^4}{W_b^4} \right), \] (2)

where the coordinates \((X_\delta, Y_\delta)\) are rotated from \((X, Y)\) by the required position angle to coincide with the apparent major and

Luks & Rolhfs 1992). Here we show that mild misalignment is not only in good agreement with the present data of the LMC (§ 2) but that it also enhances the star-star microlensing to values comparable to the observations (§ 3). In § 4, we return to the question of origin and sketch some evolutionary pathways that could give rise to the proposed misalignment.

2. MISALIGNED MODELS AND CONSISTENCY CHECKS

We set up a rectangular coordinate system of \(X, Y, \) and \(Z\), with \(Z\) being the line-of-sight direction through the optical center of the LMC “bar,” \(X\) being the direction of the decreasing right ascension, and \(Y\) being the direction of the increasing declination. There is general consensus on the location of the center of the “bar.” De Vaucouleurs & Freeman (1972) take it to be (5h24m, –69°7), which is the center of the optical isophotes of the bright “bar.” There is less agreement on the center of the LMC disk. There are a number of population centroids within 0.5°–2° of the optical center of the “bar” (see Table 3.8 of Westerlund 1997). They are all approximately to the north of the “bar,” with significant scatter in the east-west directions. As in conventional models, the star count density of the disk in the sky plane is parameterized as a standard exponential disk with elliptical contours:

\[ I_\delta(X_\delta, Y_\delta) = \frac{N_\delta(1 - f_\delta)}{2\pi L_\delta W_\delta} \exp \left( -\sqrt{\frac{X_\delta^2}{L_\delta^2} + \frac{Y_\delta^2}{W_\delta^2}} \right), \] (1)

while the “bar” is parameterized to have boxy contours and sharp edges,

\[ I_b(X_b, Y_b) = \frac{N_b f_b}{3.286 L_b W_b} \exp \left( -\frac{X_b^4}{L_b^4} - \frac{Y_b^4}{W_b^4} \right), \] (2)

where the coordinates \((X_\delta, Y_\delta)\) are rotated from \((X, Y)\) by the required position angle to coincide with the apparent major and
minor axes of the disk, which have characteristic length and width \((L_{\theta}, W_{\phi})\). Similarly, \((X_{\theta}, Y_{\phi})\) are the rotated and displaced axes, while \((L_{\theta}, W_{\phi})\) are the scales of the “bar.” These parameterizations are motivated by the appearance of the “bar” and the disk in the optical bands and in the Deep Near-Infrared Survey (DENIS) \(J, H,\) and \(K\) bands (e.g., Cioni, Habing, & Israel 2000). The default model parameters are given in Table 1. They reproduce a roundish outer disk offset by 1° to the northwest of a 1 × 3 kpc inner “bar” at a position angle of 120°. The model is normalized by \(N_0\), the total number of stars; the fractions of stars in the “bar” \(f_b\) and the disk \(1 - f_b\) are allowed to vary. Assuming a constant conversion factor \(M_{\text{LMC}}/N_0\) from the star count density of the disk and the “bar,” the surface density of all stars in the LMC is calculated via

\[
\Sigma(X, Y) = \frac{(f_b + L_b)M_{\text{LMC}}}{N_0},
\]

where the constant \(N_0\) drops out of the calculation of \(\Sigma\) eventually because of the scaling of the star count densities of the “bar” and the disk (see eqs. [1] and [2]).

The value of the inclination angle of the LMC has been a long-standing puzzle. It is roughly constrained by various tracers to lie between 25° and 50° (see Table 3.5 of Westerlund 1997); the most recent value from DENIS (Weinberg & Nikolaev 2000) is \(\sim42° \pm 7°\). The inclination results depend on the tracers and techniques used (surface brightness map fitting, deprojecting kinematic maps, or fitting of standard candles), and the differences might be a consequence of wrongly assuming a circularly symmetric, razor-thin disk for the LMC. In our misaligned model, the “bar” and the LMC disk are treated as two inclined slabs with their distances increasing from east to west. One slab, be it the disk or the “bar,” is inclined by 25°, and the other by 50°. The line-of-sight separation \(\Delta_{b,d}\) of the midplanes of the two slabs grows linearly with the projected coordinates \((X, Y)\):

\[
\Delta_{b,d} = |Z_0 + c_1 X + c_2 Y|, \quad c_1 \sim \tan 50° - \tan 25° \sim 0.7,
\]

where the dimensionless constants \(c_1\) and \(c_2\) are related to the inclination of the planes, while \(Z_0\) is the amount by which the “bar” is elevated from the LMC disk in the line-of-sight (\(Z\)) direction. A more sophisticated treatment of the three-dimensional, triaxial structures of the “bar” and the disk would introduce additional unconstrained parameters without obvious gain in insight to the problem. Motivated by the observation that the distance moduli in the LMC show a predominantly east-west gradient, we adopt \(c_2 \sim 0\). The elevation \(Z_0 = 0\) in our most conservative model, but we also explore the effects of a modest level of displacement of the “bar” from the disk, \(Z_0 \sim \pm 1\) kpc.

We compute the distribution of distance moduli of the LMC stars for our models and find that the distance moduli have a dispersion within 0.1 mag for all LMC stars, and even smaller along any given line of sight. This is comparable to typical uncertainties in the distance moduli of the LMC standard candles and is much smaller than, e.g., the spread in distance moduli of the RR Lyrae stars (\(\sim0.7\) mag; Westerlund 1997). Furthermore, Figure 1 shows the logarithmic contours of the surface density of our default model as thin solid lines. This resembles Figures 2–4 of Cioni et al. (2000), which show star counts from DENIS. We conclude that our model is consistent with the basic observational data on the LMC.

### 3. MICROLENSING IMPLICATIONS OF THE MISALIGNED DISK AND “BAR”

The microlensing map (Evans 1994) is the contour plot of the optical depth. In the limit in which the source and the lens...
are at roughly the same distance, it is calculated via
\[ \tau(X, Y) \sim 10^{-7} \frac{\Sigma(X, Y)}{160 \, \text{M}_\odot \, \text{pc}^{-2}} \frac{\Delta(X, Y)}{1 \, \text{kpc}}. \] (5)

Here the factor
\[ \Delta(X, Y) = \frac{I_X^\circ \Delta_X + I_Y^\circ \Delta_Y + I_Z \max (\Delta_X, \Delta_Y, \Delta_Z)}{(I_X + I_Y)^2} \] (6)
is the average separation between the source and the lens (cf. eq. [4]), where the three terms in the numerator account for the self-lensing of the “bar,” the self-lensing of the disk, and the mutual lensing between the “bar” and the disk, respectively. The depth parameters for self-lensing of the “bar” and disk components are \( \Delta_b \) and \( \Delta_d \), respectively. We set \( \Delta_b \sim 0.4 \Delta_d \sim 0.1 \) kpc (see Table 1). This is conservative as well, given that Weinberg & Nikolaev (2000) detected a spread of a few kiloparsecs in distance among their 2 Micron All-Sky Survey sample of disk and bar stars.

The observed microlensing optical depth is \( \tau_{\text{obs}} = 1.1^{+0.7 \times 10^{-7}} \) at a 95% confidence level (Alcock et al. 2000); the contribution from stellar lenses in the Milky Way disk and spheroid is only \( \sim 10^{-8} \). A comparison with our model is shown in Figure 1. Note that the regions enclosed by the optical depth contours encompass the locations of most of the microlensing events (the marked circles). This is because the typical density \( \Sigma \) (thin solid contours) near the events is in the range of 160–640 \( \text{M}_\odot \, \text{pc}^{-2} \) \( (M_{\text{LMC}}/10^9 \, \text{M}_\odot) \) independent of the division of the “bar” and the disk. So equation (5) predicts significant star-star lensing as long as observations allow for a modest dispersion in distance moduli (on the order of 0.05 mag, which corresponds to 1 kpc in the distances of the LMC stars). This is a general, robust result, insensitive to the exact division of mass between the “bar” and the disk and to the details of the three-dimensional structure of the LMC. This is verified by calculating 100 models, which are drawn randomly with the disk-bar offset between \( \pm 1.5 \) kpc in the \( X, Y, \) and \( Z \)-directions, the inclinations of the bar and the disk between 25° and 50°, the thicknesses in the range 0 kpc \( \leq \Delta_t \leq 0.4 \Delta_d \leq 0.1 \) kpc, and the lensable mass in the range \( 2.5 \times 10^6 \, \text{M}_\odot \leq M_{\text{bd}} \leq 5.5 \times 10^7 \, \text{M}_\odot \), with the bar making up between 25%–50% of it. These models span the likely range of the three-dimensional structure of the LMC. The average of these models (the thickest solid line in Figure 2) is consistent with the observed optical depth. The spatial profile of the optical depth is usually asymmetric and depends on the bar-disk division \( M_b/M_d \), the \( (X, Y, Z) \) offset of the disk, and the inclination of the bar. Models with a varying vertical offset \( (Z_0 = 0) \) generally produce an optical depth map similar to that shown in Figure 1, except that the magnitude of the optical depth and its asymmetry are often reduced.

Our optical depth is proportional to the total lensable mass of the LMC disk and “bar,” i.e., \( \tau \propto M_{\text{LDMC}} = M_b + M_d \), so that the reader can easily adjust our results to any preferred mass. Earlier estimates of the dynamical mass of the LMC are in the range of \( (0.6–2) \times 10^{10} \, \text{M}_\odot \) (see Table 3.4 of Westerlund 1997). These include a small amount of gas and a possible dark matter halo composed of elementary particles and therefore only give an upper limit to the stellar mass of the LMC halo. Recent data of Kim et al. (1998) suggest a dynamical mass \( \lesssim 3.5 \times 10^9 \, \text{M}_\odot \) inside a 4 kpc radius and a total disk mass \( \sim 2.5 \times 10^7 \, \text{M}_\odot \). Interestingly, even for our conservative, low-mass models (cf. Table 1), there are still enough lenses in the LMC to account for the observed optical depth at about the 2 \( \sigma \) level (Fig. 2, dashed curves). There is further supporting evidence from EROS-2, which covers a wider field in the LMC than MACHO—and thus is farther from the bar—and finds a lower event rate (Lasserre et al. 2000).

4. Discussion and Conclusions

In this Letter, we have argued that the LMC might have a radically different structure than the conventional picture of an in-plane, off-centered “bar.” Our modeling starts from the premise that the planes of the LMC “bar” and disk are misaligned. The centers of the bar and disk are offset both in the sky plane and along the line of sight. We have established, first, that the combined surface density distribution looks like the LMC as revealed by star counts in DENIS and, second, that the self-lensing optical depth lies within the interesting range \( (\sim 1 \times 10^{-7}) \). Of course, the quantitative prediction changes with the mass ratio of bar to disk. But, in all the cases we have investigated, misalignment can produce a significant fraction \( (\geq 50\%) \) of the mean observed optical depth. The point is that self-lensing is insensitive to the details of the mass ratio but is very sensitive to the relative separation of the LMC “bar” and disk stars \( (\tau \propto |Z_0|) \) roughly; cf. eqs. [4] and [5]). Our conclusion of significant self-lensing is a unifying one, as microlensing toward the LMC itself then falls into line with what is already well established for the Galactic bulge and the SMC. In principle, there are enough lenses in the LMC to provide some (perhaps most) of the observed optical depth. If we think of star-star lensing as noise on top of the signal from MACHO-
star lensing, then the noise is comparable to the signal. The uncertainty of the measured inclinations of the “bar” and the disk does not allow us to exclude the possibility of all lenses being from the LMC.

Now let us present two interpretations of our misaligned geometry. This is clearly a speculative matter, and, before we begin, let us emphasize that even the conventional picture of an in-plane, off-centered “bar” lacks a convincing evolutionary pathway. First, the “bar” could be a tidally stretched companion of the LMC, originating from the proto-Magellanic Cloud. Current data and models of the Magellanic Stream and objects along its great circle support the hypothesis, first made by Lynden-Bell (1982), that the LMC has a gas-rich progenitor with one or several small companions with different star formation and chemical evolution histories. The SMC was probably stretched and released from the grasp of the LMC by tidal interactions only 200–500 Myr ago, judging from its 20 kpc separation from the LMC. Ursa Minor and Draco must have been released at much earlier times, if they were also companions of the proto-Magellanic Cloud. Prior to its recent release, the SMC must have been a tidally stretched companion within a few kiloparsecs of the LMC, resembling the present off-centered “bar” of the LMC in projection. This suggests that the “bar” may be a cousin of the SMC, the only differences being that the “bar” is still within the grasp of the LMC and that the “bar” has slightly higher metallicity and total luminosity than the SMC. A possible objection is that it takes roughly ~200 × (10^9 M☉/M) Myr for a lump of mass M to spiral into the center, on account of the dynamical friction provided by the halo of the LMC (if it exists). We only remark that the very existence of the SMC argues empirically that somehow the multibody dynamics makes it possible for massive lumps to survive within the potential well of the LMC for most of the Hubble time. A second possibility is that the “bar” may be genuine, but offset and tilted from the plane of the disk. This works only if both “bar” and disk are dynamically young since dynamical friction is likely to enforce coplanarity on rotation period timescales (100 Myr at 1 kpc).

All these interpretations are consistent with the absence of any large offsets in the radial velocity and the distance of the “bar” and the LMC disk. If the “bar” is the projection of an unvirialized companion of the LMC, then it is likely to be orbiting well inside the tidal radius (about 6 kpc) of the LMC and moving with a velocity of less than 70 km s⁻¹ as a consequence of dynamical friction and orbital decay. Tidal stretching along the direction of motion means that the motion is primarily in the transverse direction across the sky, creating the impression of an elongated “bar.” The radial velocity offset can be small (<30 km s⁻¹) and may vary linearly across the “bar,” mimicking rotation.

How can our model be falsified? First, the source stars in our model tend to be on the back plane; thus, they experience more reddening because of extinction by dust in the foreplane than do average stars in the same field (Zhao 1999). This is a generic feature of star-star lensing, and MACHO-LMC-1a might be an example of such an event since the source star lies in an underpopulated region of the H-R diagram slightly to the fainter and redder side of the red clump (Zhao, Graff, & Guhathakurta 2000). Second, given enough events, the models are falsifiable with the likelihood estimators for the proper motion and spatial distribution of events (Kerins & Evans 1999; Evans & Kerins 2000). Our misaligned models predict a general lack of events outside the bar and a lack of mirror and point symmetries of the event distribution. This appears more consistent with the 14 MACHO events than with the two EROS events (see Fig. 1). Third, the models must explain the gas and stellar kinematics; in particular, why does the center of the rotation curve not coincide with the center of gravity of the “bar” in projection? If tides and interactions are ultimately responsible for the disturbed appearance of the LMC and for the offset between the “bar” and the disk in the X- and Y-directions (in the sky plane), it seems contrived to require exactly zero offset in the Z-direction (line of sight). The misaligned models presented here can serve as a general platform to explain these offsets most naturally. It would be interesting to test the generality of such models with other galaxies with mysterious, asymmetric bars (such as NGC 4027, NGC 4618, and NGC 4625) among the Magellanic irregulars studied by de Vaucouleurs & Freeman (1972).

We thank James Binney and Frank Israel for a number of helpful discussions, and Mario Mateo for a useful comment on Magellanic irregulars. N. W. E. is supported by the Royal Society. H. S. Z. is grateful for hospitality during visits to Oxford University, while N. W. E. thanks Leiden University for many kindnesses during working visits.

REFERENCES

Alcock C., et al. 2000, ApJ, 542, 281
Cioni, M.-R. L., Habing, H. J., & Israel, F. P. 2000, A&A, 358, L9
de Vaucouleurs, G., & Freeman, K. C. 1972, Vistas Astron., 14, 163
Evans, N. W. 1994, ApJ, 437, L31
Evans, N. W., & Kerins, E. J. 2000, ApJ, 529, 917
Gould, A. 1995, ApJ, 441, 77
Graff, D., Gould, A., Suntzeff, N., Schommer, R., & Hardy, E. 2000, ApJ, 540, 211
Gyuk, G., Dalal, N., & Griest, K. 2000, ApJ, 535, 90
Johnson, H. M. 1959, PASP, 71, 301
Kerins, E. J., & Evans, N. W. 1999, ApJ, 517, 734
Kim, S., Staveley-Smith, L., Dopita, M., Freeman, K. C., Sault, R. J., Kesteven, M., & McConnell, D. 1998, ApJ, 503, 674
Lasserre, T., et al. 2000, A&A, 355, L39
Luks, Th., & Rolhfs, K. 1992, A&A, 263, 41
Lynden-Bell, D. 1982, Observatory, 102, 202
Sahu, K. C. 1994, Nature, 370, 275
Weinberg, M. D., & Nikolaev, S. 2000, ApJ, in press (astroph/0003204)
Westerlund, B. E. 1997, The Magellanic Clouds (Cambridge: Cambridge Univ. Press)
Zhao, H. S. 1999, ApJ, 527, 167
Zhao, H. S., Graff, D., & Guhathakurta, P. 2000, ApJ, 532, L37