Proper Motions of the LMC and SMC: Reanalysis of Hubble Space Telescope Data

Slawomir Piatek

Dept. of Physics, New Jersey Institute of Technology, Newark, NJ 07102
E-mail address: piatek@physics.rutgers.edu

Carlton Pryor

Dept. of Physics and Astronomy, Rutgers, the State University of New Jersey, 136 Frelinghuysen Rd., Piscataway, NJ 08854–8019
E-mail address: pryor@physics.rutgers.edu

Edward W. Olszewski

Steward Observatory, University of Arizona, Tucson, AZ 85721
E-mail address: eolszewski@as.arizona.edu

ABSTRACT

Kallivayalil et al. have used the Hubble Space Telescope to measure proper motions of the LMC and SMC using images in 21 and five fields, respectively, all centered on known QSOs. These results are more precise than previous measurements, but have surprising and important physical implications: for example, the LMC and SMC may be approaching the Milky Way for the first time; they might not have been in a binary system; and the origin of the Magellanic Stream needs to be re-examined. Motivated by these implications, we have reanalyzed the original data in order to check the validity of these measurements. Our work has produced a proper motion for the LMC that is in excellent agreement with that of Kallivayalil et al., and for the SMC that is in acceptable agreement.

We have detected a dependence between the brightness of stars and their mean measured motion in a majority of the fields in both our reduction and that of Kallivayalil et al. Correcting for this systematic error and for the errors caused by the decreasing charge transfer efficiency of the detector produces better agreement between the measurements from different fields. With our improved reduction, we do not need to exclude any fields from the final averages and, for the first time using proper motions, we are able to detect the rotation of the LMC. The best-fit amplitude of the rotation curve at a radius of 275 arcmin in the disk plane is $120 \pm 15 \text{ km s}^{-1}$. This value is larger than the 60–70 km s$^{-1}$
derived from the radial velocities of HI and carbon stars, but in agreement with the value of 107 km s\(^{-1}\) derived from the radial velocities of red supergiants.

Our measured proper motion for the center of mass of the LMC is \((\mu_\alpha, \mu_\delta) = (195.6 \pm 3.6, 43.5 \pm 3.6)\) mas century\(^{-1}\); that for the SMC is \((\mu_\alpha, \mu_\delta) = (75.4 \pm 6.1, -125.2 \pm 5.8)\) mas century\(^{-1}\). The uncertainties for the latter proper motion are 3 times smaller than those of Kallivayalil et al.

Subject headings: galaxies: dwarf — Magellanic Clouds — astrometry: proper motion

1. Introduction

The Magellanic Clouds span many degrees on the sky owing to their relatively large size and proximity to the Milky Way (heliocentric distances are 50 kpc for the LMC and 62 kpc for the SMC). The LMC is the most luminous among the satellite dwarf galaxies of the Milky Way. With nascent spiral arms and a bar, the LMC is a late-type spiral rich in gas and with active star formation. Spectroscopic studies of the galaxy show a sizeable rotation \(\text{(e.g., Olsen & Massey 2007)}\). In contrast, the SMC is a dwarf irregular with less active star formation and a smaller and still poorly-measured rotation. The LMC and SMC are close together on the sky and are connected in projection by a bridge of HI. The Magellanic Stream, an approximately 100°-long distribution of HI, extends from the HI around the Clouds. A second stream containing less HI emanates in the opposite direction \(\text{(Putman et al. 1998; Bruns et al. 2005)}\). The apparent gaseous bridge between the LMC and SMC could have arisen from an interaction between these two galaxies, and modeling has suggested that they may have been or may be a bound pair \(\text{(e.g., Gardiner & Noguchi 1996)}\). There is a long-standing interest in understanding the relations between the LMC, SMC, and Stream \(\text{(e.g., Mathewson et al. 1974; Putman et al. 2003; Besla et al. 2007; Nidever et al. 2007)}\).

Because of the proximity of the two galaxies to the Milky Way, it is intriguing to speculate that the tidal field of the Milky Way has had a significant impact on the evolution of the Magellanic Clouds. For example, the Stream is widely considered to consist of gas removed from the LMC or SMC by a combination of ram pressure and tidal interaction with the Milky Way. Such an origin of the Stream implies that it shares the orbital plane of

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the LMC or SMC. Among the several quantities needed to answer the above questions, the proper motions are crucial since, together with the radial velocities and distances, they give the current space velocities of the galaxies. These velocities are necessary initial conditions in determining the past or the future orbits for a given Galactic potential. Alternatively, modeling the Magellanic Stream may constrain the potential of the Galaxy if the proper motions of the LMC and SMC are known with sufficient precision (e.g., Heller & Rohlfs 1994; Lin et al. 1995).

Recognizing the importance of the proper motions of the Magellanic Clouds, several groups have attempted to measure them. In chronological order, the measurements for the LMC are: Jones et al. (1994), Kroupa et al. (1994), Kroupa & Bastian (1997), Drake et al. (2001), Pedreros et al. (2002), Pedreros et al. (2006), and Kallivavilil et al. (2006a, K06a). For the SMC, the measurements are: Kroupa & Bastian (1997), Irwin (1999), and Kallivavilil et al. (2006b, K06b).

The measurements by K06a and K06b used images taken with the Hubble Space Telescope (HST) and they have uncertainties that are only one-third as large as those of the best previous measurements. Each of the 21 fields in the LMC and five in the SMC has a confirmed QSO which serves as a standard of rest. The analysis is based on the methodology developed by Anderson & King (2003). Similar data and analyses have measured proper motions for dwarf spheroidal companions of the Milky Way with comparable uncertainties to those in K06a and K06b (e.g., Piatek et al. 2007). The proper motion for the LMC reported by K06a is \((\mu_\alpha, \mu_\delta) = (203 \pm 8, 44 \pm 5)\) mas century\(^{-1}\) and by K06b for the SMC is \((\mu_\alpha, \mu_\delta) = (116 \pm 18, -117 \pm 18)\) mas century\(^{-1}\). These values yield large space motions which then imply that, for example, the LMC and SMC may be on their first approach to the Milky Way, that the LMC and SMC may not initially have been bound to each other, and that models for the formation of the Magellanic Stream via an interaction with the Milky Way need to be re-examined (see Besla et al. 2007; Nidever et al. 2007). Thus, an independent check of the results in K06a and K06b is worth having and this article reports on a reanalysis of their data. Section 2 describes the data; section 3 explains the process of deriving the proper motion using our method; section 4 presents our results and compares them to those in K06a and K06b; section 5 discusses the implications of the measured proper motions; and section 6 is a summary of the main results.

2. Observations and Data

The data consist of images in the F606W and F814W bands obtained with the High Resolution Camera (HRC) of the Advanced Camera for Surveys (ACS). The images were
produced by the ACS data-reduction pipeline and provided by the Space Telescope Science Institute archive; these are the same data as those used by K06a and K06b. The images were taken in a snapshot mode at two epochs. In the case of the LMC, 21 fields are common to both epochs and, in the case of the SMC, five are common to both. The time between epochs ranges from 1.1 to 2.8 years. Each field is centered on a confirmed QSO. Almost all of the pairs of images have orientations (i.e., the HST ORIENTAT angle) differing by tens of degrees between the epochs. For comprehensive information about the observations and data, see Table 1 and Figure 1 in K06a for the LMC and in K06b for the SMC.

3. Measuring Proper Motion

A series of articles beginning with Piatek et al. (2002) describe our basic technique for deriving proper motions. Central to our method is the presence of a QSO in each observed field which serves as an extragalactic “reference point.” The crucial steps of the method are: 1. Derive an effective point-spread function (ePSF; Anderson & King 2000) at each epoch using stars and the QSO in dithered images. Our experience shows that the PSF for a QSO is similar to that for a star, making the bright, compact QSO an ideal reference point. 2. Determine accurate centroids for the stars and the QSO by fitting the ePSF. 3. Correct the centroids for the known geometrical distortions in the camera and CCD. 4. Transform the centroids of stars and the QSO measured at different epochs to a common coordinate system which moves together with the stars of the galaxy. For the QSO and those stars that are not members of the galaxy, a fitted linear motion is included in the coordinate transformation. The proper motion of the galaxy derives from the motion of the QSO.

When deriving the transformation to a common coordinate system, a linear motion is always fitted for the QSO. A motion is also fitted for objects whose contribution to the total $\chi^2$ of the scatter around the transformation is above 9.21, the value which should be exceeded by chance only 1% of the time. Except for the QSO, the objects with fitted motion are likely to be foreground stars of the Milky Way. Once the parameters of the transformation are determined, the motion of each remaining object without a fitted motion is calculated from the transformed coordinates at each epoch; this motion should be zero within its uncertainty.

Our method uses the most general linear transformation, which contains six fitted parameters, between the coordinate systems at different epochs. Plots of position residuals versus location on the CCD showed that more parameters were unnecessary. The transformation also corrects for the effects caused by the degrading charge transfer efficiency (CTE) of the CCD in the HRC (see Bristow et al. 2005). The method used is similar to that in Piatek et al. (2003) and Piatek et al. (2007): the $Y$ coordinate of an object is corrected by
an amount that depends on the brightness of the object and is linearly proportional to $Y$ and to the time since ACS was installed. This last dependence is supported by the evidence provided in the ACS Handbook (Pavlovsky et al. 2006). We adopted a correction that varies with the $S/N$ of the object as $(S/N)^{-0.42}$ between a $S/N$ of 10 and 100 and is constant at the boundary values outside of that range. The exponent also comes from data in the ACS Handbook. The final proper motions do not depend sensitively on the details of how the CTE corrections are made. The above method depends on a single parameter, which is the rate of change with time of the correction applied to the $Y$ coordinate of an object with a $S/N$ of 15 at a $Y$ location of 1024 pixels. Fitting for this parameter using some of the data least affected by the systematic errors discussed below indicated a value of 0.030 pixel yr$^{-1}$. All results reported in this article used corrections calculated with this value.

K06a and K06b did not make corrections as a function of stellar flux for the shifts in centroids due to degrading CTE. With many independent fields in the LMC, K06a argue that the effect of these shifts on the average proper motion approaches zero as $N^{-1/2}$, provided that the $N$ fields have an isotropic distribution of position angles. However, the effect on the proper motion of the SMC may be greater because there are only five fields and the distribution of image orientations is not isotropic (four of these fields have similar HST ORIENTAT angles at the first epoch).
Fig. 1.— Motion in the common coordinate system, $p_x$ and $p_y$ in pix yr$^{-1}$, versus $S/N$ for the 21 fields in the LMC and five in the SMC. The points are color-coded depending on the location of objects in their respective CMDs, which are shown in Figure 2. Star symbols represent the QSOs and squares represent the stars. Filled squares correspond to those stars that have fitted motion. Note the trends between $p_x$ or $p_y$ with $S/N$ for a majority of fields, e.g. L13. To reduce the impact of these trends on the proper motion, only objects with $S/N$ greater than the value indicated by a vertical dashed line were used in fitting for a transformation. Column 2 of Tables 1 and 3 gives these values of $S/N$ for the fields in the LMC and SMC, respectively.
Fig. 2.— Color-magnitude diagrams for the LMC *left panel* and the SMC *right panel*. The diagrams show only those objects that were matched at the two epochs and, thus, whose motion in the common coordinate system can be determined. The QSOs are marked with a star symbol. The points are color-coded depending on their location in the diagram. No corrections for reddening or extinction were applied.
To examine the effect of degrading CTE on our data, we plotted the motions in the common coordinate system, $p_x$ and $p_y$ in pix yr$^{-1}$, of all objects versus their $S/N$. Figure 1 shows these plots for all of the fields in the LMC and SMC. A majority of the fields show trends in these plots, particularly for $S/N$ less than about 20. However, these trends were sometimes along the direction orthogonal to that expected from a degrading CTE and sometimes in the expected direction, but with the opposite of the expected sign. None of the large trends were well removed by fitting our model for the CTE correction. We conclude that these trends arise from some effect other than the degrading CTE. A possible explanation could be an error in the ePSF, but varying the parameters used in the construction of the ePSF had no effect on the trends. As we discuss below, these trends are likely to be present in the results of K06a and K06b too. To minimize the effect of the dependence of mean motion on $S/N$, we limit the sample of stars used to determine the transformation between epochs to stars with $S/N$ above a limit that is usually 25 but can be as large as 50. These limits are indicated in Figure 1 by vertical dashed lines and they are also listed in column (2) of Tables 1 (for the LMC) and 3 (for the SMC). The limit is chosen empirically so that the mean motion of stars with a $S/N$ similar to that of the QSO is zero. A concern is that a change in the PSF with color, which has not been modeled in either analysis, is causing the observed trends. The points in the plots depicted in Figure 1 are color-coded depending on the location of objects in their respective color-magnitude diagrams (CMDs), which are shown in Figure 2. The photometry for each CMD was derived using HSTPhot (Dolphin 2000) from the first-epoch images taken in the F606W and F814W filters and has not been corrected for reddening and extinction. Visual inspection of Figure 1 does not provide evidence for a systematic difference between the mean motions of red and blue stars at high $S/N$. While fields such as L13 hint at such a difference, the majority of the fields do not. To quantitatively estimate the size of any possible color effect, we calculated separately the weighted mean motion for the red and blue stars with $S/N > 100$ and located in all of the fields in the LMC. The resulting differences in the $X$ and $Y$ directions between the weighted mean motions for the red and blue stars are $-1.2 \times 10^{-4} \pm 6.6 \times 10^{-4}$ pix yr$^{-1}$ and $3.4 \times 10^{-4} \pm 6.2 \times 10^{-4}$ pix yr$^{-1}$, respectively. Both differences are consistent with zero within their uncertainties and, thus, the measured motion of the QSO in our derived common coordinate system is an accurate reflection of the motion of the LMC or the SMC.
Fig. 3.— Comparison of measured proper motions for the LMC. Squares represent the values reported by this article, whereas triangles represent those in K06a. Both sets of values are from Table 1. Solid triangles correspond to those fields that were excluded in the calculation of the mean proper motion in K06a. Top panel: $\mu_\alpha$ versus field number. Bottom panel: $\mu_\delta$ versus field number. Both panels have the same vertical scale.
4. Results

We have derived proper motions for all 21 fields in the LMC (L1 — L21) and all five fields in the SMC (S1 — S5). Table 1 provides a side-by-side comparison of our results for the LMC with those of K06a. Column (1) gives the name of a field, column (2) gives the S/N limit, and column (3) gives the resulting number of stars used in fitting the transformation between epochs. Columns (4) and (5) give the components of the measured proper motion derived by us in the equatorial coordinate system, whereas columns (6) and (7) do the same for the proper motions in K06a. Columns (8) and (9) are the difference between our results and those in K06a. The listed uncertainty for a difference is the sum in quadrature of the uncertainties in the two values, even though this uncertainty indicates the difference expected between two independent measurements rather than the difference arising from different methods of analyzing the same data. Figure 3 plots the components of the proper motions in columns (4) — (7) versus field number. The \( \mu_\alpha \) values are in the top panel and the \( \mu_\delta \) values are in the bottom. Squares are our values and triangles are those in K06a. Filled triangles are those measurements in K06a that were not used in their calculation of the average proper motion. In the LMC, the difference between the observed proper motion for a field and the proper motion of the center of mass is significant because of the changing perspective of the space velocity and the internal rotation. Thus, Table 2 lists and Figure 4 plots the values from Table 1 corrected for these effects. The corrections are from K06a. For the SMC, these corrections are negligible. Table 3 and Figure 5 compare our results for the SMC with those of K06b.
Fig. 4.— Comparison of center-of-mass proper motions for the LMC. Filled squares represent the values reported by this article, whereas triangles represent those in K06a. Both sets of values are from Table 2. The corrections for rotation and changing perspective are from K06a. Top panel: $\mu_\alpha$ versus field number. Bottom panel: $\mu_\delta$ versus field number. The dashed horizontal lines are mean proper motions for each component from K06a. Both panels have the same vertical scale, which is also the same as in Figure 3.
The agreement between our results and those in K06a and K06b is good in most cases. Because the data in the two studies are the same, any differences are due to the methods of analysis. The bottom two lines of both Table 1 and Table 3 give the mean difference and rms scatter between our results and those of K06a and K06b. We give the mean instead of the weighted mean because, as noted above, the listed uncertainties are not directly related to the size of the differences. The means of the differences are, for the LMC, comparable to the uncertainty in the galaxy proper motion given by K06a and, for the SMC, are smaller. Tables 1 and 3 show that ten fields in the LMC (L1, L3, L4, L7, L11, L12, L13, L15, L16, and L21) and two fields in the SMC (S4 and S5) have differences in at least one component that are larger than the listed uncertainty. Most of these twelve fields show trends of the mean measured motion with $S/N$ and the field with the largest difference, L13, has one of the largest trends (see Figure 4). For these twelve fields, reducing the $S/N$ limit from our adopted values, i.e., including more of the stars in the transformation, makes our measured proper motions closer to the values found by K06a. Thus, we conclude that the K06a and K06b results for these twelve fields are affected by the same systematic errors that depend on $S/N$. K06a and K06b rejected from their samples individual stars with discrepant or uncertain proper motions, but this will not necessarily eliminate a systematic error that affects all of the stars with the same brightness similarly. The systematic error does not appear in their plot of the amplitude of the stellar proper motions versus magnitude because the data from all of the fields are shown together and the different fields have different trends. K06a note that their fitted transformation between epochs for field L13 had an unusually large $\chi^2$ per degree of freedom, leading them to reject this field from their average despite it containing one of the largest samples of stars. Also rejected were fields with 16 or fewer stars in the final sample and this tends to eliminate fields whose mean proper motion could be strongly affected by the systematic error. Thus, the procedures adopted by K06a and K06b tended to limit the effect of the systematic error on their final result. However, figures 4 and 5 show that our values derived with a $S/N$ limit of 25 or higher make the proper motions of the twelve fields more consistent with those of the other fields.
Fig. 5.— Comparison of measured proper motions for the SMC. Squares represent the values reported by this article, whereas triangles represent those in K06b. Both sets of values are from Table 3. The solid triangle corresponds to the field that was excluded in the calculation of the mean proper motion in K06b. The dashed horizontal lines are mean proper motions for each component from K06b. Top panel: $\mu_\alpha$ versus field number. Bottom panel: $\mu_\delta$ versus field number. Both panels have the same vertical scale.
K06a and K06b identified several “low-quality” fields, marked with solid triangles in Figures 3 and 5, on the basis of small sample size or a large $\chi^2$ per degree of freedom and excluded them from the calculation of the mean proper motion. Most, though not all, of these fields had poor agreement with the mean proper motion (see Figures 4 and 5). After removing the effects of trends with S/N, we find no indication of serious problems at any stage of the analysis for all 26 fields. Thus, we conclude that all of the fields contain useful information about the motions of the LMC and SMC. Some fields do deviate from the mean proper motion by more than is expected on the basis of their uncertainties, most notably L1, L11, L16, L17, and S4. These fields are likely providing information about internal motions in the LMC and SMC, and we test for such motions in Sections 5.1 and 5.2.

5. Discussion

Numerous factors can influence the internal motions of a galaxy. The distribution of mass with radius determines the shape and amplitude of the rotation curve in a disk system or the dependence of velocity dispersion on radius in a pressure-supported system. The presence of a bar or a strong tidal disturbance can induce their own streaming motions. Old and young stellar populations can have distinct kinematics, as is well known in the case of the Milky Way. Below we discuss what information the measurements of the proper motions in the LMC and SMC contain about internal motions.

5.1. The LMC

Figure 6 shows the location of the LMC fields along with the distribution of young stars as mapped by Zaritsky et al. (2004). The figure also shows the CMD for each field. Most fields contain both a young and an old stellar population. Exceptions are the fields in the northern spiral arm, which contain mostly a young population, and field L2, which contains only an old population.
Fig. 6.— Locations on the sky in a tangent plane projection and CMDs of the 21 fields in the LMC superimposed on a map showing the distribution of young stars from Zaritsky et al. (2004). North is up, east is to the left, and the figure is centered at \((\alpha, \delta) = (5^h 18^m 8, -68^\circ 34')\). Each field location is marked with a filled circle. All of the CMDs have the same color and magnitude range, \(-1 < m_{606W} - m_{814W} < 2\) and \(26 > m_{606W} > 14\), respectively.
Fig. 7.— Magnitude and direction of proper motions remaining after subtracting the contributions due to the changing perspective of the center-of-mass space velocity. These proper motions contain information about internal motions. Each filled circle is at the location on the sky of one of the 21 fields in the LMC in a tangent plane projection. North is up and east is to the left. The line emanating from each field location is the proper motion for that field and the uncertainty is indicated by the error bars at its tip. The asterisk symbol marks the kinematical center of the LMC at \((\alpha, \delta) = (5^{h}27^{m}6, -69^{\circ}52.2')\) and the line originating from it has a length and direction proportional to the adopted proper motion of the center of mass: \(\mu_{\alpha,cm} = 195.6\) mas century\(^{-1}\) and \(\mu_{\delta,cm} = 43.5\) mas century\(^{-1}\). The line segment in the lower-left corner shows a proper motion corresponding to a tangential velocity of 100 km s\(^{-1}\). A visual inspection of the figure shows a clear signature of a clockwise rotation.
The LMC is known to exhibit rotation on the basis of the radial velocities of HI and stars (e.g., Kim et al. 1998; van der Marel et al. 2002; Olsen & Massey 2007) and Figure 6 shows that the fields are distributed widely in azimuth around the galaxy center. Thus, the measured proper motions listed in Table 1 must contain contributions from both the center-of-mass space motion, including the effect of changing perspective, and disk rotation. They may also contain contributions from the precession and nutation of the disk (van der Marel et al. 2002), and from streaming due to the bar or a tidal interaction. To search for internal motions we must remove the effect of the changing perspective, which is calculable given a line-of-sight velocity and proper motion of the galaxy center of mass and the galaxy distance (see van der Marel et al. 2002). Adopting values for these three quantities of 262.2 km s$^{-1}$ (van der Marel et al. 2002), our best estimate obtained as described below (it depends slightly on the adopted rotation), and 50.1 kpc (van der Marel et al. 2002) yields the results in Figure 7. It plots at the location of each field the direction and magnitude of the proper motion that arises only because of the internal motions of the LMC. Visual inspection shows a clear signature of a clockwise rotation, albeit with superimposed noise. The amplitude of the proper motions for the fields farthest from the kinematical center implies tangential velocities larger than 100 km s$^{-1}$. K06a noted a hint of this rotational pattern in their equivalent Figure 12, but it was not as clear as in Figure 7.

Each proper motion in Figure 7 can be resolved into a component along and perpendicular to the direction expected for circular rotation in an inclined disk. The first of these components implies an amplitude for the rotation curve at a radius in the disk plane. The formulae for translating positions and proper motions in the sky to radii and rotation velocities in the disk are given by van der Marel et al. (2002). Figure 8 plots the amplitude of the rotation curve, $V_{rot}$, versus radius in the plane of the disk, $R_{plane}$, for each field. The uncertainties are determined from the uncertainties in the measured proper motions using propagation of errors. The calculations assume that the kinematical center of the disk is at $(\alpha, \delta) = (5^{h}27^{m}6, -69^{\circ}52.2')$ and that the disk inclination and position angle of the line of nodes are $34^{\circ}7$ and $129^{\circ}9$, respectively (van der Marel et al. 2002). All of the fields except one have positive $V_{rot}$, so the proper motions imply the presence of rotation. Figure 8 shows that $V_{rot}$ increases with increasing $R_{plane}$. Some of the largest values of $V_{rot}$ are for L1, L11, and L16, which are in the northern spiral arm. This suggests that the spiral arm has a motion different than that of the rest of the disk, possibly because of a warp in the disk plane or because it is a tidal tail. However, other fields in the northern spiral arm, such as L4, L6, and L18, have values of $V_{rot}$ similar to those of the rest of the disk.
Fig. 8.— Rotational velocity, $V_{\text{rot}}$, implied by a proper motion that was corrected for changing perspective plotted as a function of radius in the plane of the disk, $R_{\text{plane}}$. This is a velocity in the plane of the disk and perpendicular to the line of sight of a stationary observer at the center of the LMC. For easy reference, each point is labeled with a field number. The dashed curve is the best-fitting model rotation curve assumed to be linearly increasing to a radius of 275 arcmin and flat beyond; it has $V_{275} = 120 \text{ km s}^{-1}$. 
Estimates of the rotation of the LMC using radial velocities of carbon stars (K06a; van der Marel et al. 2002) and HI (Kim et al. 1998; Olsen & Massey 2007) find $V_{\text{rot}}$ increasing approximately linearly with $R_{\text{plane}}$ to a value of 60 – 80 km s$^{-1}$ at a radius of about 275 arcmin (4.0 kpc) and roughly constant beyond. Figure 8 shows a larger amplitude for the rotation. We adopt a simple rotation curve that rises linearly to a radius of 275 arcmin and is constant beyond. Correcting the observed proper motions of each field for perspective and rotation produces an estimate of the proper motion of the center of mass. The best estimates of the rotation curve and the center-of-mass proper motion minimize the scatter of these estimates around their weighted mean. We add an additional uncertainty of 12.4 mas century$^{-1}$ in quadrature to both components of the measured proper motion of each field in order to produce a $\chi^2$ per degree of freedom of 1.0 for the best fit. The result for the center-of-mass proper motion and amplitude of the rotation curve at a radius of 275 arcmin are

$$\mu_{\alpha,\text{cm}} = 195.6 \pm 3.6 \text{ mas century}^{-1}$$

$$\mu_{\delta,\text{cm}} = 43.5 \pm 3.6 \text{ mas century}^{-1}$$

$$V_{275} = 120 \pm 15 \text{ km s}^{-1}.$$  

These are our best estimates for these quantities. The uncertainties are derived by increasing $\chi^2$ by 1.0 above the minimum (e.g., Press et al. 1992) and so include the adopted additional uncertainty. Estimating the uncertainties in the right ascension and declination components of the mean proper motion from the scatter of the estimates around their weighted mean, as done by K06a, yields 4.1 mas century$^{-1}$ and 4.5 mas century$^{-1}$, respectively. The rotation curve implied by Equation 3 is shown as the dashed curve in Figure 8.
Fig. 9.— Center-of-mass proper motion for the LMC determined by each of 21 fields as found in this article using $V_{275} = 120$ km s$^{-1}$. The error bars do not include the additional uncertainty discussed in the text. Top panel: $\mu_\alpha$ versus field number. Bottom panel: $\mu_\delta$ versus field number. The dashed horizontal lines are our weighted mean proper motions for each component. For easy comparison, both panels have the same vertical scale, which is also the same as in Figures 3 and 4.
The difference between the rotation curves determined from the radial velocities (K06a; Kim et al. 1998) and ours could be reduced by decreasing the inclination of the disk. A complete reanalysis would simultaneously fit the radial velocity and proper motion data to determine the rotation curve and orientation of the disk. However, such a fit is beyond the scope of this article. Recently, Olsen & Massey (2007) used the K06a proper motion to study the internal motions of the LMC implied by the radial velocities of the HI, carbon stars (an intermediate age stellar population), and red supergiants (a young stellar population). They confirm the HI rotation curve and the other spatially and kinematically distinct features first seen in the HI by Kim et al. (1998) and Staveley-Smith et al. (2003). The carbon stars share the kinematics of the HI, but the rotation curve of the red supergiants rises to a value of 107 km s$^{-1}$, which is similar to what we find from the proper motions and, in particular what we find for those fields in the northern spiral arm that are dominated by a young stellar population. Some of the red supergiants implying the largest rotation velocity are also in the northern spiral arm: the magenta dots in Figure 2 of Olsen & Massey (2007). Future proper motions with a longer time baseline may be able to distinguish between the kinematics of different stellar populations. Radial velocities for stars in the 21 fields would also help to compare the rotation measured using radial velocities and proper motions.

Figure 9 plots the center-of-mass proper motions for each field derived with $V_{275} = 120$ km s$^{-1}$ versus field number. The dashed horizontal lines are the weighted means for each component listed in Equations 1 and 2. The scatter of the points around the weighted mean for each component is smaller than the scatter in Figure 4, which uses the smaller rotation amplitude of K06a. The significant reduction in the scatter supports the larger amplitude for the rotation found in this article.

The additional 12.4 mas century$^{-1}$ of scatter in each component of the measured proper motions found above implies the presence of some combination of internal motions that depart from our adopted rotation curve and errors larger than our measurement uncertainties. Our measurement uncertainties are derived from the scatter around the best-fit coordinate transformation between epochs and should be realistic in most cases. An undetected systematic error might be present if there is a gap between the high S/N of the QSO and the lower S/N values of the stars. Only fields L1, L3, and L11 have such gaps. L1 has a significant departure from the mean in Figure 9 but L3 and L11 do not. L17 has the largest departure in Figure 9 and shows strong trends with S/N and contains few stars, making correcting for those trends difficult. A proper motion of 12.4 mas century$^{-1}$ corresponds to a tangential velocity of 30 km s$^{-1}$ and internal motions of this size would indicate significant departures from circular motion. Figure 10 plots the proper motions remaining after subtracting the contributions due to the rotation curve shown in Figure 8 from the proper motions in Figure 7. The figure does not show a clear pattern of streaming motions. The most significant
residuals are found among the fields in the northern spiral arm, but it is unclear what physical mechanism could produce larger incoherent departures from the adopted rotation curve there. Again, it would be useful to obtain radial velocities for stars in the proper motion fields.
Fig. 10.— Magnitude and direction of the proper motions remaining after subtracting the contributions due to our best-fit rotation from the proper motions in Figure 7. The resulting residual vectors have directions and magnitudes determined by measurement errors and by departures from the circular motions of the fitted rotation curve. The figure shows no clear pattern of streaming motions. The most significant residuals are found among the fields in the northern spiral arm.
Our proper motion for the center of mass of the LMC differs from that of K06a by 7.4 mas century\(^{-1}\) in the right ascension component and 0.5 mas century\(^{-1}\) in the declination component. The difference in the right ascension components is as large as the uncertainty quoted by K06a. However, our proper motion confirms the surprising result of K06a that led us to begin this investigation: the large space velocity for the LMC. The proper motion for the LMC found in this article implies a galactocentric radial and tangential velocity of \(93.2 \pm 3.7\) km s\(^{-1}\) and \(346 \pm 8.5\) km s\(^{-1}\), respectively.
Fig. 11.— Locations on the sky in a tangent plane projection and CMDs of the five fields in the SMC superimposed on a map showing a distribution of young stars from Zaritsky et al. (2000). North is up, east is to the left and the figure is centered at $(\alpha, \delta) = (0^h51^m6, -72^\circ52')$. Each field location is marked with a filled circle. All of the CMDs have the same color and magnitude range, $-1 < m_{606W} - m_{814W} < 2$ and $26 > m_{606W} > 14$, respectively.
5.2. The SMC

Figure 11 shows the location of the SMC fields, their CMDs, and the distribution of young stars as mapped by Zaritsky et al. (2000). The figure shows that the surface density of young stars at the location of S4 is lower than that for the other fields. The CMD for S4 contains mostly old stars, whereas the CMDs for the other fields contain both old and young stars.

Figure 12, which is analogous to Figure 7, shows proper motions that were corrected for the changing perspective of the center-of-mass space velocity of the SMC. We adopt a distance of 61.7 kpc (Cioni et al. 2000), our best estimate of the proper motion of the galaxy, and a line-of-sight velocity of 146.0 km s$^{-1}$ (Harris & Zaritsky 2006). Visual inspection shows no clear signature of rotation. There is a suggestion of radial streaming motions along a north-west — south-east line. However, measurements of the proper motions in more fields are necessary to confirm the presence of this streaming.
Fig. 12.— Magnitude and direction of proper motions remaining after subtracting the contributions due to the changing perspective of the center-of-mass space velocity. These proper motions contain information about internal motions. Each filled circle is at the location on the sky of one of the five fields in the SMC in a tangent plane projection. North is up and east is to the left. The line emanating from each field location is the proper motion for that field and the uncertainty is indicated by the error bars at its tip. The asterisk symbol marks the kinematical center of the SMC at \((\alpha, \delta) = (0^h52^m8^s, -72^\circ30')\) and the line originating from it has a length and direction proportional to the adopted proper motion of the center of mass: \(\mu_{\alpha,cm} = 80.8\) mas century\(^{-1}\) and \(\mu_{\delta,cm} = -125.6\) mas century\(^{-1}\). The line segment in the lower-left corner shows a proper motion corresponding to a tangential velocity of 100 km s\(^{-1}\). A visual inspection of the figure shows no evidence of rotation, but suggests the presence of radial streaming away from the center.
Figure 13, which is analogous to Figure 8, confirms that the circular velocities derived from the five fields are consistent with no rotation. The calculations assume that the kinematical center of the disk is at \((\alpha, \delta) = (0^\text{h}52^\text{m}3, -72^\circ30')\) and that the disk inclination and position angle of the line of nodes are 40° and 220°, respectively (Stanimirović et al. 2004). The velocity gradient seen in the HI (Stanimirović et al. 2004) and red giants (Harris & Zaritsky 2006), if interpreted as rotation, would imply a rotation curve in Figure 13 linearly rising to an amplitude of \(\pm50 \text{ km s}^{-1}\) at \(R_{\text{plane}} = 120\) arcmin. The data in Figure 13 cannot rule out such a curve.
Fig. 13.— Rotational velocity, $V_{\text{rot}}$, implied by a proper motion that was corrected for changing perspective plotted as a function of radius in the plane of the disk, $R_{\text{plane}}$. This is a velocity in the plane of the disk and perpendicular to the line of sight of a stationary observer at the center of the SMC. For easy reference, each point is labeled with a field number. There is no indication of rotation.
As for the LMC, each field yields a measurement of the center-of-mass proper motion and these are plotted in Figure 14. The calculations assume no rotation. The dashed lines are the weighted means for each component and their values are

\begin{align}
\mu_{\alpha,\text{cm}} &= 75.4 \pm 6.1 \text{ mas century}^{-1} \\
\mu_{\delta,\text{cm}} &= -125.2 \pm 5.8 \text{ mas century}^{-1}.
\end{align}

(4) \hspace{1cm} (5)

These are our best estimates for these quantities. We add an additional uncertainty of 7.2 mas century\(^{-1}\) in quadrature to both components of the measured proper motion of each field in order to produce a \(\chi^2\) per degree of freedom of 1.0 for the scatter around the means. Estimating the uncertainties in the right ascension and declination components of the mean proper motion from the scatter of the estimates around their weighted mean yields 7.0 mas century\(^{-1}\) and 3.9 mas century\(^{-1}\), respectively. Our uncertainties for \(\mu_{\alpha,\text{cm}}\) and \(\mu_{\delta,\text{cm}}\) are a factor of 3 smaller than those of K06b. The principal reason for our smaller uncertainties is that we treat all five fields as independent measurements, whereas K06b treated fields S1, S2, and S3 as a single measurement, S5 as another, and excluded S4. Our reanalysis, which corrects for the effects caused by degrading CTE and for the trends of mean proper motion with \(S/N\), has reduced the systematic errors and, thus, justifies treating these fields as independent. The additional uncertainty, added in quadrature to the measurement uncertainties of the SMC, is similar to that for the LMC, which further supports our quoted uncertainties.
Fig. 14.— Center-of-mass proper motion for the SMC determined by each of five fields as found in this article assuming no rotation. The error bars do not include the additional uncertainty discussed in the text. Top panel: $\mu_\alpha$ versus field number. Bottom panel: $\mu_\delta$ versus field number. The dashed horizontal lines are our weighted mean proper motions for each component. For easy comparison, both panels have the same vertical scale, which is also the same as in Figure 5.
Our proper motion for the center of mass of the SMC differs from that of K06b by 40.6 mas century$^{-1}$ in the right ascension component and 8.2 mas century$^{-1}$ in the declination component. The difference in the declination components is smaller than the uncertainty quoted by K06b, whereas the difference in the right ascension components is 2.3 times larger than the K06b uncertainty and 6.7 times larger than our uncertainty. The difference in the right ascension component arises because we include field S4 in the average, have a lower value from field S5 because of the correction of trends with S/N, and, as discussed above, treat all five measurements as independent.

The proper motion for the SMC found in this article implies a galactocentric radial and tangential velocity of $6.8 \pm 2.4$ km s$^{-1}$ and $259 \pm 17$ km s$^{-1}$, respectively. The relative velocity between the LMC and SMC is $142 \pm 19$ km s$^{-1}$, which is $37$ km s$^{-1}$ higher than that found by K06b.

6. Summary

This article reports a reanalysis of images taken with the HRC of the ACS on HST first analyzed by K06a and K06b to measure the proper motions of the LMC and SMC. Central to the method is the presence of a QSO in a field; the proper motion derives from the reflex motion of a QSO with respect to the stars of the galaxy. There are 21 fields in the LMC and five in the SMC. The key findings and conclusions from our analysis are:

1. We have detected a trend between the mean measured motion and the brightness of objects that is present to a varying degree in a majority of the fields. We are unable to identify the source of these trends. If not accounted for, the trend can significantly affect the measured proper motion. Because the QSO is one of the brightest objects in the field, we minimize the influence of the trends by restricting the sample of stars contributing to the measurement of the proper motion in a field to those whose S/N is above some limit. Proper motions derived with a wider range for the S/N of the sample agree better with those of K06a and K06b, thus arguing that the trends are present in their analyses too.

2. Our analysis also approximately corrects the effects caused by the decreasing charge transfer efficiency with time in the CCD of the HRC. These corrections are smaller than those for the trends with S/N.

3. For most of the fields in the LMC and SMC, our measured proper motion agrees within the quoted uncertainties with that of K06a or K06b. In those cases where the
measurements differ (notably fields L13, L15, L21, and S5), the difference is due to our measurements being corrected for the trends with S/N. Our measured proper motions for the 21 fields in the LMC and the five fields in the SMC show less scatter around the two mean center-of-mass proper motions. With our improved analysis, it is no longer necessary to exclude any of the fields from the calculations of the means.

4. Removing a contribution to the measured proper motions from the changing perspective of the space velocity gives proper motion vectors that contain information about the internal motions of the LMC. Plotting these vectors on the sky shows a pattern of clockwise rotation. Converting each vector into an estimate of the rotation velocity at a radius in the disk plane shows that the rotation of the LMC has been clearly detected from the proper motions for the first time. Assuming a model rotation curve that rises linearly to a radius of 275 arcmin and that is flat beyond yields a best-fit amplitude at this radius of $120 \pm 15$ km s$^{-1}$.

5. Our best estimate of the mean center-of-mass proper motion of the LMC is $(\mu_\alpha, \mu_\delta) = (195.6 \pm 3.6, 43.5 \pm 3.6)$ mas century$^{-1}$.

6. We do not detect rotation in the SMC. The proper motions suggest the presence of radial expansion, however more fields and more precise measurements are needed to confirm the reality of these streaming motions.

7. Our best estimate of the mean center-of-mass proper motion of the SMC is $(\mu_\alpha, \mu_\delta) = (75.4 \pm 6.1, -125.2 \pm 5.8)$ mas century$^{-1}$. The uncertainties are 2.5 times smaller than those of K06b because the improved internal consistency of our proper motions permits treating all five fields as independent measurements.

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REFERENCES

Anderson, J., & King, I. R. 2000, PASP, 112, 1360

Anderson, J., & King, I. R. 2003, AJ, 126, 772

Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R. P., & Alcock, C. 2007, submitted [astro-ph/0703196]

Bristow, P., Piatek, S., & Pryor, C. 2005, ST-ECF Newsletter, 38, 12

Bruns, C., et al. 2005, A&A, 432, 45

Cioni, M.-R. L., van der Marel, R. P., Loup, C., & Habing, H. J. 2000, A&A, 359, 601

Dolphin, A. E. 2000, PASP, 112, 1383

Drake, A. J. et al. 2001, BAAS, 33, 1379

Gardiner, L. T., & Noguchi, M. 1996, MNRAS, 278, 191

Harris, J. & Zaritsky, D. 2006, AJ, 131, 2514

Heller, P. & Rohlfs, K. 1994, A&A, 291, 743

Irwin, M. 1999, in IAU Symp. 192, The Stellar Content of Local Group Galaxies, ed. P. Whitelock & R. Cannon (San Francisco: ASP), 409

Jones, B. F., Klemola, A. R., & Lin, D. N. C. 1994, AJ, 107, 1333

Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J., & Geha, M. 2006, ApJ, 638, 772 (K06a)

Kallivayalil, N., van der Marel, R. P., Alcock, C. 2006, ApJ, 652, 1213 (K06b)

Kim, S., Staveley-Smith, L., Dopita, M. A., Freeman, K. C., Sault, R. J., Kesteven, M. J., & McConnell, D. 1998, ApJ, 503, 674

Kroupa, P., & Bastian, U. 1997, NewA, 2, 77

Kroupa, P., Roser, S., & Bastian, U. 1994, MNRAS, 266, 412

Lin, D. N. C., Jones, B. F., & Klemola, A. R., 1995, ApJ, 439, 652

Mathewson, D. S., Cleary, M. N., & Murray, J. D. 1974, ApJ, 190, 291
Nidever, D. L, Majewski, S. R., & Burton, W. B., 2007, ApJ, submitted (astro-ph/0706.1578)

Olsen, K. A. G., & Massey, P. 2007, ApJ, 656, L61

Pavlovsky, C., et al. 2006, “Advanced Camera for Surveys Instrument Handbook for Cycle 16”, Version 7.1, (Baltimore: STScI)

Pedreros, M. H., Anguita, C., & Maza, J. 2002, AJ, 123, 1971

Pedreros, M., Costa, E., Mendez, R. A. 2006, AJ, 131, 146

Piatek, S., et al. 2002, AJ, 124, 3198

Piatek, S., et al. 2005, AJ, 130, 95

Piatek, S., et al. 2007, AJ, 133, 818

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes, The Art of Scientific Computing, 2nd ed., (Cambridge: Cambridge Univ. Press)

Putman, M. E. et al. 1998, Nature, 394, 752

Putman, M. E., Staveley-Smith, L., Freeman, K. C., Gibson, B. K., & Barnes, D. G. 2003, ApJ, 586, 170

Stanimirović, S., Staveley-Smith, L., Jones, P. A. 2004, ApJ, 604, 176

Staveley-Smith, L., Kim, S., Calabretta, M. R., Haynes, R. F., & Kesteven, M. J. 2003, MNRAS, 339, 87

van der Marel, R. P., Alves, D. R., Hardy, E., & Suntzeff, N. B. 2002, AJ, 124, 2639

Zaritsky, D., Harris, J., Grebel, E. K., & Thompson, I. B. 2000, ApJ, 534, 53

Zaritsky, D., Harris, J., Thompson, I. B., & Grebel, E. K. 2004, AJ, 128, 1606

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Table 1. Comparison of Measured Proper Motions for the LMC

| Field | S/N | N  | $\mu_\alpha$ | $\mu_\delta$ | $\Delta\mu_\alpha$ | $\Delta\mu_\delta$ |
|-------|-----|----|---------------|----------------|---------------------|---------------------|
| L1    | 25  | 25 | 139.6 ± 7.4   | 65.9 ± 8.3    | 116.2 ± 12.1       | 80.0 ± 8.9          |
|       |     |    |               |               | 23.4 ± 14.2        | −14.1 ± 12.2        |
| L2    | 25  | 19 | 223.3 ± 14.6  | −35.8 ± 14.8  | 222.0 ± 7.0        | −27.4 ± 6.7         |
|       |     |    |               |               | 1.3 ± 16.2         | −8.4 ± 16.3         |
| L3    | 25  | 86 | 179.0 ± 6.1   | 33.8 ± 7.0    | 197.6 ± 8.2        | 41.3 ± 6.1          |
|       |     |    |               |               | −18.6 ± 10.2       | −7.5 ± 9.3          |
| L4    | 25  | 22 | 180.5 ± 8.8   | 17.8 ± 8.4    | 212.1 ± 15.0       | 52.1 ± 11.8         |
|       |     |    |               |               | −31.6 ± 17.4       | −34.3 ± 14.5        |
| L5    | 25  | 43 | 204.1 ± 11.6  | 3.2 ± 9.0     | 205.4 ± 8.6        | 10.2 ± 9.7          |
|       |     |    |               |               | −1.3 ± 14.4        | −7.0 ± 13.3         |
| L6    | 25  | 14 | 153.2 ± 14.7  | 91.9 ± 14.4   | 165.8 ± 19.1       | 98.3 ± 29.8         |
|       |     |    |               |               | −12.6 ± 24.1       | −6.4 ± 33.1         |
| L7    | 30  | 93 | 198.0 ± 7.7   | 25.5 ± 7.7    | 206.8 ± 7.3        | 42.6 ± 6.4          |
|       |     |    |               |               | −8.8 ± 10.6        | −17.1 ± 10.0        |
| L8    | 50  | 16 | 191.4 ± 5.2   | −7.0 ± 6.7    | 196.1 ± 8.1        | −5.0 ± 5.8          |
|       |     |    |               |               | −4.7 ± 9.6         | −2.0 ± 8.8          |
| L9    | 25  | 58 | 199.2 ± 10.9  | −6.3 ± 8.5    | 202.3 ± 7.7        | −4.7 ± 8.4          |
|       |     |    |               |               | −3.1 ± 13.4        | −1.6 ± 11.9         |
| L10   | 25  | 60 | 180.9 ± 10.4  | 64.8 ± 9.2    | 193.4 ± 9.9        | 60.0 ± 8.7          |
|       |     |    |               |               | −12.5 ± 14.4       | 4.8 ± 12.7          |
| L11   | 25  | 15 | 141.6 ± 8.0   | 96.4 ± 7.4    | 108.9 ± 35.2       | 118.6 ± 18.7        |
|       |     |    |               |               | 32.7 ± 36.1        | −22.2 ± 20.1        |
| L12   | 50  | 14 | 200.9 ± 13.4  | −23.2 ± 11.6  | 244.7 ± 16.9       | −2.4 ± 18.3         |
|       |     |    |               |               | −43.8 ± 21.5       | −20.8 ± 21.7        |
| L13   | 50  | 25 | 221.1 ± 15.9  | 48.7 ± 16.6   | 245.5 ± 13.4       | 116.8 ± 7.8         |
|       |     |    |               |               | −24.4 ± 20.8       | −68.1 ± 18.4        |
| L14   | 25  | 37 | 177.8 ± 18.7  | −6.2 ± 16.5   | 183.7 ± 17.4       | 13.6 ± 22.5         |
|       |     |    |               |               | −5.9 ± 25.5        | −19.8 ± 27.9        |
| L15   | 50  | 19 | 229.9 ± 14.4  | 38.1 ± 15.6   | 273.8 ± 17.3       | 57.3 ± 21.7         |
|       |     |    |               |               | −43.9 ± 22.5       | −19.2 ± 26.7        |
| L16   | 25  | 33 | 151.8 ± 5.3   | 9.7 ± 8.0     | 152.5 ± 14.1       | 27.7 ± 11.7         |
|       |     |    |               |               | −0.7 ± 15.1        | −18.0 ± 14.2        |
| L17   | 25  | 16 | 224.8 ± 24.8  | 108.9 ± 22.5  | 231.3 ± 28.9       | 104.0 ± 18.5        |
|       |     |    |               |               | −6.5 ± 38.1        | 8.5 ± 29.1          |
| L18   | 25  | 24 | 165.1 ± 14.0  | 76.3 ± 14.2   | 177.9 ± 13.3       | 91.4 ± 12.8         |
|       |     |    |               |               | −12.8 ± 19.3       | −15.1 ± 19.1        |
| L19   | 25  | 104| 171.4 ± 21.3  | 77.6 ± 17.7   | 173.5 ± 16.3       | 84.4 ± 20.8         |
|       |     |    |               |               | −2.1 ± 26.8        | −6.8 ± 27.3         |
| L20   | 25  | 51 | 181.3 ± 7.9   | −12.9 ± 7.0   | 181.3 ± 7.1        | 0.5 ± 11.6          |
|       |     |    |               |               | 0.0 ± 10.7         | −13.4 ± 13.6        |
| L21   | 25  | 115| 202.2 ± 13.0  | −14.6 ± 11.7  | 246.4 ± 11.5       | 5.4 ± 12.2          |
|       |     |    |               |               | −44.2 ± 17.3       | −20.0 ± 16.9        |

Note. — Proper motions are all in milli-arcseconds century$^{-1}$. 

Average: $-10.48$, $-14.69$

rms: $19.65$, $15.73$
Table 2. Comparison of Center-of-Mass Proper Motions for the LMC

| Field | This Article | Kallivayalil et al. |
|-------|--------------|---------------------|
|       | $\mu_\alpha$ | $\mu_\delta$ | $\mu_\alpha$ | $\mu_\delta$ |
| L1    | 156.8 ± 7.4 | 40.9 ± 8.3 | 133.4 ± 12.1 | 55.0 ± 8.9 |
| L2    | 211.1 ± 14.6 | 15.4 ± 14.8 | 209.8 ± 7.0 | 23.8 ± 6.7 |
| L3    | 178.3 ± 6.1 | 47.8 ± 7.0 | 196.9 ± 8.2 | 55.3 ± 6.1 |
| L4    | 190.2 ± 8.8 | 34.9 ± 8.4 | 221.8 ± 15.0 | 69.2 ± 11.8 |
| L5    | 199.4 ± 11.6 | 16.4 ± 9.0 | 200.7 ± 8.6 | 23.4 ± 9.7 |
| L6    | 173.2 ± 14.7 | 47.9 ± 14.4 | 185.8 ± 19.1 | 54.3 ± 29.8 |
| L7    | 195.7 ± 7.7 | 37.2 ± 7.7 | 204.5 ± 7.3 | 54.3 ± 6.4 |
| L8    | 197.1 ± 5.2 | 30.9 ± 6.7 | 201.8 ± 8.1 | 32.9 ± 5.8 |
| L9    | 193.6 ± 10.9 | 39.0 ± 8.5 | 196.7 ± 7.7 | 40.6 ± 8.4 |
| L10   | 188.9 ± 10.4 | 38.5 ± 9.2 | 201.4 ± 9.9 | 33.7 ± 8.7 |
| L11   | 163.2 ± 8.0 | 60.5 ± 7.4 | 130.5 ± 35.2 | 82.7 ± 18.7 |
| L12   | 204.0 ± 13.4 | 13.0 ± 11.6 | 247.8 ± 16.9 | 33.8 ± 18.3 |
| L13   | 219.7 ± 15.9 | 54.9 ± 16.6 | 244.1 ± 13.4 | 123.0 ± 7.8 |
| L14   | 181.5 ± 18.7 | 28.6 ± 16.5 | 187.4 ± 17.4 | 48.4 ± 22.5 |
| L15   | 226.5 ± 14.4 | 52.7 ± 15.6 | 270.4 ± 17.3 | 71.9 ± 21.7 |
| L16   | 159.0 ± 5.3 | 42.9 ± 8.0 | 159.7 ± 14.1 | 60.9 ± 11.7 |
| L17   | 238.4 ± 24.8 | 115.2 ± 22.5 | 244.9 ± 28.9 | 106.7 ± 18.5 |
| L18   | 178.0 ± 14.0 | 74.6 ± 14.2 | 190.8 ± 13.3 | 89.7 ± 12.8 |
| L19   | 172.3 ± 21.3 | 74.0 ± 17.7 | 174.4 ± 16.3 | 80.8 ± 20.8 |
| L20   | 183.3 ± 7.9 | 30.7 ± 7.0 | 183.3 ± 7.1 | 44.1 ± 11.6 |
| L21   | 199.2 ± 13.0 | 5.4 ± 11.7 | 243.4 ± 11.5 | 25.4 ± 12.2 |

Note. — Proper motions are all in milli-arcseconds century$^{-1}$. 
Table 3. Comparison of Measured Proper Motions for the SMC

| Field | S/N | N  | $\mu_\alpha$  | $\mu_\delta$ | $\Delta\mu_\alpha$ | $\Delta\mu_\delta$ |
|-------|-----|----|--------------|--------------|-------------------|-------------------|
|       | (1) | (2) | (3)          | (4)          | (5)               | (6)               |
| S1    | 25  | 36  | 72.5 ± 13.5  | −125.6 ± 12.5| 86.0 ± 11.3       | −113.6 ± 9.5      |
|       |     |     |              |              | −13.5 ± 17.6      | −12.0 ± 15.7      |
| S2    | 25  | 90  | 78.3 ± 8.1   | −130.3 ± 8.3 | 82.5 ± 7.3        | −120.8 ± 7.6      |
|       |     |     |              |              | −4.2 ± 10.9       | −9.5 ± 11.3       |
| S3    | 25  | 61  | 91.1 ± 11.5  | −132.2 ± 10.9| 102.2 ± 9.1       | −120.1 ± 10.9     |
|       |     |     |              |              | −11.1 ± 14.7      | −12.1 ± 15.4      |
| S4    | 25  | 11  | 43.8 ± 11.5  | −111.0 ± 9.0 | 30.3 ± 7.3        | −86.6 ± 17.7      |
|       |     |     |              |              | 13.5 ± 13.6       | −24.4 ± 19.9      |
| S5    | 50  | 17  | 103.9 ± 16.5 | −125.5 ± 15.9| 147.1 ± 10.8      | −114.3 ± 13.0     |
|       |     |     |              |              | −43.2 ± 19.7      | −11.2 ± 20.5      |
|       |     |     |              |              | Average: −11.69   | −13.84            |
|       |     |     |              |              | rms: 20.57        | 5.99              |

Note. — Proper motions are all in milli-arcseconds century$^{-1}$. 