

# On the motion of the Magellanic Clouds

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## ABSTRACT

We have measured the proper motion of the Large and Small Magellanic Clouds using Magellanic Cloud stars in the PPM Catalogue, and obtain  $\mu = 1.7 \pm 0.9$  mas yr<sup>-1</sup> for the LMC. Systematic uncertainties are discussed. Bound and unbound orbits of the Magellanic Clouds around the Galaxy are consistent with our result. The various models of the Magellanic Stream and their predictions for the motion of the Magellanic Clouds are discussed. The predictions by several authors for the same type of model differ by up to 0.3 mas yr<sup>-1</sup>. All models proposed to date that assume the Magellanic Clouds to lead the Magellanic Stream predict a proper motion for the LMC of between 1.5 and 2.0 mas yr<sup>-1</sup>, the smallest value being a prediction for a Galaxy with no halo. Other independent measurements of the proper motion of the LMC are discussed. These lie between 1 and 1.5 mas yr<sup>-1</sup>. Future astrometry will have to allow measurement of the proper motion of the LMC with an uncertainty no larger than one-tenth of a milliarcsecond per year in order to help to distinguish significantly between models of the halo of the Galaxy. The proper motion of the LMC cannot by itself distinguish between models of the Magellanic Stream.

**Key words:** Galaxy: halo – galaxies: interactions – galaxies: kinematics and dynamics – Magellanic Clouds.

## 1 INTRODUCTION

The two Magellanic Clouds are separated by about 20° on the sky and share a common hydrogen envelope. The associated Magellanic Stream (Mathewson, Cleary & Murray 1974) spans a near-great circle on the sky, nearly crossing the South Galactic Pole, and appears to consist primarily of hydrogen gas (Irwin 1991). From the geometry of the Magellanic Stream, it has generally been concluded that the orbit of the Magellanic Clouds lies in a plane perpendicular to the Galactic disc. The offset position of the Sun from the Galactic Centre appears to lead to an insignificant distortion of the Magellanic Stream, so that the closest approach of the Magellanic Stream to the Galactic Centre is likely to exceed 40 kpc. The motion of the Magellanic System takes place in the gravitational potential of our Galaxy, and so probes the mass of the Galaxy within a distance of a few tens to a hundred kiloparsecs. The Large and Small Magellanic Clouds (LMC and SMC, respectively) lie at heliocentric distances of approximately 52 and 63 kpc, respectively (Allen 1973). The two galaxies recede with heliocentric radial velocities of +274 km s<sup>-1</sup> (Luks & Rohlf 1992) and +148 km s<sup>-1</sup> (Hardy, Suntzeff & Azzopardi 1989), respectively. By contrast, the tip of the Magellanic Stream, which is

situated about 90° away from the LMC, has a large heliocentric velocity of infall of about 380 km s<sup>-1</sup> (Wannier & Wrixon 1972). Reviews of the Magellanic System are given by Westerlund (1990) and Wayte (1991).

In this paper we measure the proper motion of the LMC and SMC using data from the newly finished PPM Catalogue (Röser & Bastian 1993). Proper motions in the PPM Catalogue are derived from data spanning almost a century. Other approaches using background galaxies as the inertial frame (for preliminary reports, see Tucholke & Hiesgen 1991 and Lin 1993) are based on epoch differences of some 15 yr. Proper motion results based on the PPM Catalogue should therefore be an interesting addition to the discussion of the theme addressed here inasmuch as no final proper motions for the Magellanic Clouds have been reported to date. Our specific aim is to investigate whether the Magellanic Clouds have proper motions significantly different from the values expected from current theories.

In Section 2 we introduce the data and in Section 3 we use these to obtain the proper motion. In Section 4 we use radial velocities to study the space motion of the Clouds. We discuss the implications of our proper motion of the LMC and the required accuracy for choosing between model scenarios which we discuss in Section 5. Section 6 concludes the paper.

## 2 THE DATA

To measure the proper motion of the Magellanic Clouds we make use of the PPM Catalogue data discussed in Section 2.1. In Section 2.2 we identify those stars in the catalogue that are also members of the Magellanic Clouds.

### 2.1 Proper motions for the southern hemisphere

In order to discuss the dynamical implications of the motions derived in this paper, these motions must be measured in an inertial reference frame. Here we are working in the reference frame of the PPM Catalogue, which extends the FK5 coordinate system to fainter magnitudes. The southern part of the PPM Catalogue has been completed recently (Bastian et al. 1993), and is based on observational catalogues spread over almost one century. Proper motions in the PPM/FK5 system are based on the International Astronomical Union (IAU) (Lieske et al. 1977) value for the constant of precession. There are indications from lunar-laser ranging measurements (Williams et al. 1991) that the IAU constant of precession should be corrected by  $-2.7 \text{ mas yr}^{-1}$ . This yields a correction to the proper motions of the LMC of  $+0.1 \text{ mas yr}^{-1}$  in right ascension and  $-0.1 \text{ mas yr}^{-1}$  in declination. The corresponding numbers for the SMC are  $-0.5$  and  $-1.0 \text{ mas yr}^{-1}$ . A rotation of the FK5 equinox would be another cause of systematic error of the FK5 system. As yet there are no FK5-independent observations to verify this.

The change of the constant of precession affects the rotation of the FK5 system as a whole. Systematic errors of the FK5 proper motion system at the position of the Magellanic Clouds are another cause of uncertainty. As a further cause of uncertainty, we have to consider how well the PPM Catalogue approximates the FK5 system. We note that mainly OB stars of the Magellanic clouds are in the PPM Catalogue. The proper motions of these may suffer from systematic errors due to the different spectral responses of the astrophotographic systems at short wavelengths (i.e. 'colour equations' in the jargon of photographic astrometry). Once the deviation of the FK5 system from the inertial system at the position of the Magellanic Clouds is known, the proper motions given here can easily be transformed to this system. Being aware of all the points mentioned above, we adopt the PPM Catalogue as a representation of the inertial system. In view of the specific aim of this paper, we believe this to be an adequate assumption.

The root-mean-square errors of individual proper motion in the PPM Catalogue are estimated from the accuracies of the observational catalogues used in deriving these proper motions. Comparison of the PPM Catalogue data with preliminary *Hipparcos* data (Turun et al. 1992) allows us to conclude that these estimates are reliable. The average root-mean-square error of a component of proper motion from the PPM Catalogue in the regions of the Magellanic Clouds is  $2.7 \text{ mas yr}^{-1}$ . We need only about 10 common motion stars to reduce the uncertainty to about  $1 \text{ mas yr}^{-1}$  which, at a distance of 50 kpc, corresponds to the circular velocity of the isothermal halo if it extends that far.

### 2.2 Magellanic Cloud stars in the PPM Catalogue

Sanduleak (1970) provides a deep objective-prism survey of the LMC and lists proven or probable LMC members. We

identify the PPM Catalogue stars in Sanduleak's list by matching of coordinates, coincidence of HD numbers and/or spectral types and magnitudes. The common subset of stars contained in the PPM Catalogue and in the catalogue compiled by Sanduleak is given in Table 1. The first column lists the star number in the PPM Catalogue and the second column gives the number listed by Sanduleak (1970). The third and fourth columns contain, respectively, the photographic apparent magnitude and spectral type, the fifth and sixth columns give the right ascension and declination, respectively, and the seventh and eighth columns list the corresponding proper motions. In what follows, we always quote  $\mu_a^* = \mu_a \cos \delta$ , where  $\mu_a^*$  is given in units of  $\text{mas yr}^{-1}$ . The last two columns contain the radial velocity and the HD number.

Proven and probable SMC member stars are provided by Sanduleak (1968, 1969). Stars also contained in the PPM Catalogue are listed in Table 2 with the same columns as in Table 1. The distribution of proper motions of LMC and SMC stars is shown in Fig. 1.

We draw attention to the two stars San 193 and 194 in Table 2. They lie in the wing of the SMC, about  $3^\circ$  to the east of the central region. We need to keep this in mind when we address the kinematics of the SMC, especially in view of the complex kinematic situation in and around the SMC. Observations have shown that the heliocentric radial velocity varies by about  $100 \text{ km s}^{-1}$  along the line of sight (Hatzidimitriou, Cannon & Hawkins 1993) and across the SMC (Torres & Carranza 1987). The numerical simulation by Gardiner, Sawa & Fujimoto (1994) shows that the expected heliocentric radial velocities in the tidally highly perturbed SMC vary by up to  $200 \text{ km s}^{-1}$ . Specifically, either the wing of the SMC appears to be a separate entity with a rotational motion of its own, or streaming motions exist along the LMC-SMC intercloud region with a velocity gradient of  $165 \pm 53 \text{ km s}^{-1} \text{ deg}^{-1}$  towards the LMC (Hardy et al. 1989). This situation suggests that the SMC has suffered significant tidal perturbation, and makes the interpretation of the measured proper motion of the SMC rather difficult.

## 3 THE PROPER MOTION OF THE MAGELLANIC CLOUDS

Having identified a subsample of stars from the PPM Catalogue that are members of the LMC (Table 1) and the SMC (Table 2), we can now proceed to determine the proper motions of both galaxies. We calculate the means  $\bar{\mu}_a^*$  and  $\bar{\mu}_\delta$  of all proper motion values in Tables 1 and 2. In Table 3 we list the resulting proper motions in equatorial coordinates. The uncertainties are the standard deviations of the mean values, except for  $\bar{\mu}$  for which we have combined the uncertainties in  $\bar{\mu}_a^*$  and  $\bar{\mu}_\delta$ .

The standard deviations of a single proper motion for LMC members in right ascension and declination are  $3.5$  and  $4 \text{ mas yr}^{-1}$ , respectively. This is quite consistent with the estimate of  $2.7 \text{ mas yr}^{-1}$  from the PPM Catalogue, supporting our assumption that the data form a common-motion set. Similar values hold for the SMC.

There are six other independent attempts at measuring the proper motion of the LMC, which we now discuss in turn. Indirect methods based on the difference in position angle between the kinematical and photometric lines of nodes

**Table 1.** LMC stars with proper motion measurements.

| PPM    | San     | $m_V$ | Sp | RA          | DEC          | $\mu_\alpha^*$ | $\mu_\delta$ | $V_R$                | HD     |
|--------|---------|-------|----|-------------|--------------|----------------|--------------|----------------------|--------|
|        |         |       |    | 2000        |              | mas            | mas          | km sec <sup>-1</sup> |        |
|        |         |       |    | hh mm ss    | ° ' "        | per year       |              |                      |        |
| 354346 | -69 007 | 9.6   | B0 | 4 49 12.425 | -69 27 22.94 | +03            | +04          | 266                  | 268654 |
| 354360 | -67 005 | 9.5   | B  | 4 50 18.938 | -67 39 38.04 | +00            | -10          | 309                  | 268605 |
| 354415 | -67 017 | 9.8   | Pe | 4 55 11.104 | -67 10 10.24 | +04            | +00          | 295                  | 32034  |
| 354417 | -67 019 | 9.4   | B  | 4 55 21.619 | -67 26 11.06 | -01            | +00          | 304*                 | 268719 |
| 354418 | -69 037 | 10.1  | F8 | 4 55 32.482 | -69 57 44.76 | +04            | +00          | 246*                 | 268819 |
| 354436 | -69 046 | 9.4   | B  | 4 56 47.091 | -69 50 24.32 | +01            | +01          | 271                  | 268835 |
| 354474 | -65 018 | 9.5   | B  | 5 00 06.490 | -65 45 39.22 | +01            | -10          | 286*                 | 270933 |
| 354527 | -66 058 | 9.1   | Oe | 5 05 12.268 | -66 44 12.33 | +08            | +00          | 297                  | 268946 |
| 354533 | -67 044 | 9.1   | B  | 5 05 55.548 | -67 53 10.79 | +08            | +02          | 253                  | 33579  |
| 354587 | -68 063 | 10.4  | B  | 5 10 22.767 | -68 46 23.48 | +01            | +02          | 227                  | 269128 |
| 354606 | -67 060 | 9.2   | F8 | 5 12 44.329 | -67 15 57.59 | +01            | -03          | 278*                 | 269154 |
| 354616 | -69 075 | 9.4   | B  | 5 13 30.814 | -69 32 23.45 | +08            | +01          | 250*                 | 269216 |
| 354664 | -69 091 | 9.5   | B  | 5 17 46.330 | -69 50 57.37 | +02            | -03          | —                    | 269327 |
| 354669 | -69 093 | 10.3  | G0 | 5 18 01.834 | -69 33 37.62 | +01            | +02          | 289*                 | 269331 |
| 354686 | -69 107 | 9.4   | Oa | 5 19 17.763 | -69 39 13.94 | +01            | +03          | 285                  | 35517  |
| 354698 | -67 078 | 9.5   | B  | 5 20 19.041 | -67 18 05.45 | +00            | +04          | 335*                 | 269371 |
| 354712 | -65 048 | 9.7   | K0 | 5 21 01.729 | -65 48 02.23 | +09            | +02          | 322                  | 271182 |
| 354715 | -65 054 | 10.0  | B  | 5 21 42.879 | -65 44 57.02 | +08            | -01          | 291                  | 271191 |
| 354756 | -69 129 | 10.0  | G0 | 5 26 29.125 | -69 27 02.99 | -02            | +04          | 274*                 | 269542 |
| 354761 | -68 082 | 10.1  | B  | 5 26 45.325 | -68 49 52.63 | +02            | +00          | 298                  | 269546 |
| 354771 | -67 122 | 9.5   | B  | 5 27 56.054 | -67 20 46.15 | +00            | +05          | 303*                 | 269577 |
| 354798 | -67 145 | 9.6   | B  | 5 30 15.676 | -67 32 21.76 | +02            | +04          | 336                  | 269644 |
| 354800 | -69 165 | 9.4   | B  | 5 30 22.535 | -69 19 38.95 | -02            | +02          | —                    | 269649 |
| 354803 | -69 170 | 10.4  | B  | 5 30 50.052 | -69 31 29.26 | -03            | +02          | 260                  | 269661 |
| 354815 | -67 162 | 9.3   | G0 | 5 31 38.421 | -67 28 11.49 | +02            | +02          | 310*                 | 269697 |
| 354818 | -68 114 | 9.4   | B  | 5 31 52.269 | -68 32 38.57 | -02            | +03          | 252                  | 269700 |
| 354852 | -67 208 | 9.5   | A3 | 5 35 00.190 | -67 01 12.50 | -03            | +08          | 307                  | 269807 |
| 354885 | -69 243 | 9.6   | Pd | 5 38 42.399 | -69 06 02.81 | -03            | +08          | 273                  | 38268  |
| 354888 | -69 246 | 9.5   | Oa | 5 38 53.341 | -69 02 00.94 | -02            | +03          | —                    | 38282  |
| 354892 | -69 253 | 9.5   | B  | 5 39 29.163 | -69 27 12.23 | +02            | -01          | 287*                 | 269936 |
| 354939 | -67 260 | 9.4   | G0 | 5 45 00.627 | -67 10 34.26 | -11            | +02          | 310*                 | 270111 |
| 354945 | -69 299 | 9.4   | B0 | 5 45 16.609 | -68 59 51.57 | -03            | +09          | 253                  | 270086 |
| 368614 | -70 029 | 9.6   | Pe | 4 59 22.752 | -70 11 45.80 | -03            | -03          | 244                  | 32763  |
| 368629 | -71 003 | 10.4  | B  | 5 02 07.377 | -71 20 13.07 | +00            | -03          | 197*                 | 269006 |
| 368674 | -71 014 | 9.2   | B5 | 5 09 38.919 | -71 24 02.25 | -01            | +00          | 231                  | 269172 |

 $V_R$ : Feast, Thackeray & Wesselink (1960);  $V_R^*$ : Barbier-Brossat & Petit (1990).**Table 2.** SMC stars with proper motion measurements.

| PPM    | San | $m_V$ | Sp | RA          | DEC          | $\mu_\alpha^*$ | $\mu_\delta$ | $V_R$                | HD   |
|--------|-----|-------|----|-------------|--------------|----------------|--------------|----------------------|------|
|        |     |       |    | 2000        |              | mas            | mas          | km sec <sup>-1</sup> |      |
|        |     |       |    | hh mm ss    | ° ' "        | per year       |              |                      |      |
| 367066 | 027 | 9.7   | B  | 0 49 02.969 | -73 21 41.11 | +01            | -04          | 152                  | 4862 |
| 367088 | 056 | 9.8   | Pe | 0 53 04.865 | -72 38 00.09 | +02            | -04          | 158                  | 5291 |
| 367141 | 106 | 9.7   | B8 | 1 02 49.584 | -72 10 14.48 | -03            | -01          | 143                  | —    |
| 367169 | 130 | 9.5   | B  | 1 07 18.217 | -72 28 03.68 | +03            | -06          | 181                  | 6884 |
| 367183 | 137 | 9.9   | B  | 1 09 03.983 | -72 32 17.42 | +03            | -01          | 247                  | 7099 |
| 367207 | 152 | 10.2  | B  | 1 13 30.473 | -73 20 10.01 | -03            | +04          | 175                  | 7583 |
| 367381 | 193 | 10.2  | —  | 1 44 03.973 | -74 40 49.60 | +06            | +03          | 184                  | —    |
| 367388 | 194 | 10.6  | —  | 1 45 03.828 | -74 31 32.49 | +05            | +03          | —                    | —    |

 $V_R$ : Feast, Thackeray & Wesselink (1960).

allow the determination of the transverse velocity, which leads to a gradient in radial velocity across the LMC if the direction of motion is assumed. This approach was pioneered by Feitzinger, Isserstedt & Schmidt-Kaler (1977), who derived a heliocentric transverse velocity of approximately 275 km s<sup>-1</sup>. Using the same approach Meatheringham et al. (1988) found a heliocentric transverse velocity of 275 ± 65 km s<sup>-1</sup>, Prévot, Rousseau & Martin (1989) reported a galactocentric transverse velocity of 150 km s<sup>-1</sup>, and Hughes, Wood & Reid (1991) derived a galactocentric

transverse velocity of about 200 km s<sup>-1</sup>. This method, however, requires the assumption of circular symmetry, which may not be correct for the LMC given the tidal effects which may be significant (see Sections 2.2 and 5).

A preliminary result of an independent study of the proper motion of the LMC has been reported by Tucholke & Hiesgen (1991). They found  $\mu_\alpha^* = 0.91 \pm 2.34$  mas yr<sup>-1</sup> and  $\mu_\delta = -0.23 \pm 2.77$  mas yr<sup>-1</sup> by measuring absolute proper motions relative to background reference galaxies. Tucholke & Hiesgen measured 498 galaxies on photographic plates

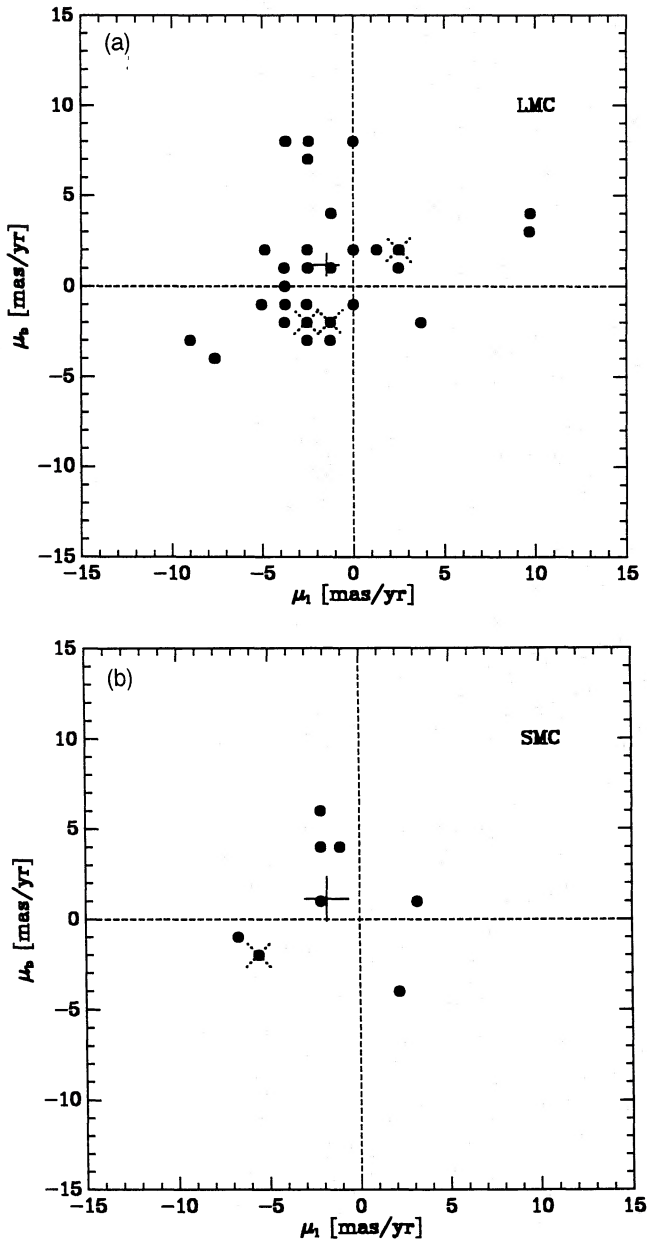


**Figure 1.** The distribution of proper motions is plotted in Galactic coordinates,  $\mu_l$  and  $\mu_b$ , for LMC (a) and SMC (b) members. Data crossed out with dotted lines represent stars for which we do not know the radial velocity. The solid plus sign is the mean proper motion, its size corresponding to the standard deviation of the mean. The mean proper motion for the LMC is  $\mu_l = -1.5 \pm 0.7$  mas yr $^{-1}$ ,  $\mu_b = +1.2 \pm 0.6$  mas yr $^{-1}$ . For the SMC we obtain  $\mu_l = -1.8 \pm 1.2$  mas yr $^{-1}$  and  $\mu_b = +1.1 \pm 1.2$  mas yr $^{-1}$ . Excluding San 193 and 194 in Table 2 (see Section 2.2), we obtain for the SMC  $\mu_l = -0.4 \pm 1.0$  mas yr $^{-1}$  and  $\mu_b = +2.0 \pm 1.4$  mas yr $^{-1}$ . A proper motion of 1 mas yr $^{-1}$  due east corresponds to  $\mu_l = -0.2$  mas yr $^{-1}$ ,  $\mu_b = +0.9$  mas yr $^{-1}$  for the LMC, and  $\mu_l = -0.9$  mas yr $^{-1}$ ,  $\mu_b = +0.1$  mas yr $^{-1}$  for the SMC.

subdivided into 24 subplates with an epoch difference of 15 yr, but did not explicitly define their sample of LMC members. Although only preliminary, it is interesting to note that Jones, Klemola & Lin (1989) also reported a proper motion, the magnitude of which 'is less than half of that predicted' by Lin & Lynden-Bell (1982; see Section 5). Their

**Table 3.** Measured motions of LMC and SMC.

|                  | $\overline{\mu_\alpha^*}$ | $\overline{\mu_\delta}$ | $\mu$          |
|------------------|---------------------------|-------------------------|----------------|
|                  | mas yr $^{-1}$            | mas yr $^{-1}$          | mas yr $^{-1}$ |
| LMC              | $+1.3 \pm 0.6$            | $+1.1 \pm 0.7$          | $1.8 \pm 0.9$  |
| SMC              | $+1.7 \pm 1.1$            | $-0.8 \pm 1.3$          | $1.9 \pm 1.7$  |
| SMC <sup>1</sup> | $+0.5 \pm 1.0$            | $-2.0 \pm 1.4$          | $2.1 \pm 1.7$  |

<sup>1</sup>San 193 and 194 excluded (Section 2.2).

project is now mostly complete, and very recently Lin (1993) briefly announced the measurement of the motion of the LMC with respect to background galaxies using 251 LMC member stars and 92 galaxies on 21 photographic plates covering an epoch span of 14 yr and centred on a field about 9° to the north-east of the centre of the LMC. After applying corrections for the rotation of the LMC, Lin reported for the LMC a galactocentric transverse velocity of 236 km s $^{-1}$ , which corresponds to a proper motion of 1.5 mas yr $^{-1}$ . Extended galaxy images make the definition of an inertial reference frame somewhat difficult. Another problem the above two approaches face is that a proper motion can only be measured in a field far enough from the LMC centre to allow detection of background galaxies. If the rotation of the LMC extends to distances of about 10 kpc then rotational corrections may become very important because the maximum measured circular speed lies between 0.2 and 0.3 mas yr $^{-1}$  (see Section 6). Furthermore, the outer regions of the LMC are expected to be tidally affected (Gardiner et al. 1993), making the application of corrections to the measurement of the proper motion in an outlying region of the LMC rather uncertain.

In summary, all six studies above yield  $\mu \approx 1\text{--}1.5$  mas yr $^{-1}$  due east. Our measurement (Table 3) agrees with these results. Adoption of a different constant of precession (Section 2.1) does not have a significant effect on the proper motion of the LMC.

#### 4 THE SPACE MOTION OF THE MAGELLANIC CLOUDS

Ideally, we would like to have very accurate measurements of the proper motions and radial velocities of a statistically meaningful large number of LMC and SMC members. This would allow a detailed analysis of the rotation and orbit of the two galaxies. Our LMC sample contains 35 stars, whereas our SMC sample contains merely eight stars. The radial velocity measurements are precise to about 15 km s $^{-1}$ . The individual proper motion values, on the other hand, have a typical uncertainty of about 3 mas yr $^{-1}$ , which translates to an uncertainty of 700 km s $^{-1}$  at a distance of 50 kpc. The maximum rotational velocity of the LMC is about 60–80 km s $^{-1}$  (Meatherington et al. 1988; Prévot et al. 1989).

We assume that the position vector of the Sun is  $(-8.5, 0, 0)$  kpc with origin at the Galactic Centre, and that the Sun orbits the Galactic Centre with a circular velocity of  $(0, +220, 0)$  km s $^{-1}$  and has a peculiar velocity of  $(u_\odot, v_\odot, w_\odot) = (9, 12, 7)$  km s $^{-1}$  (Mihalas & Binney 1981), where positive  $u$  is in the direction towards the Galactic Centre at the position of the Sun. We compute the velocity vector for each entry in Tables 1 and 2. The mean galactocentric

position vectors, which we take to be the positions of the LMC and SMC, are  $51 \times (-0.03, -0.83, -0.56)$  kpc and  $60 \times (0.25, -0.65, -0.72)$  kpc, respectively. For the stars for which we have no radial velocity, we adopt the mean radial velocity of their Cloud. The mean galactocentric space motion vectors of both clouds in units of  $\text{km s}^{-1}$  are

$$u_{\text{LMC}} = (-279 \pm 165, -218 \pm 79, +85 \pm 122),$$

$$u_{\text{SMC}} = (-276 \pm 322, -353 \pm 284, +126 \pm 264).$$

The heliocentric and galactocentric radial and tangential velocities ( $\overline{v_{r,h}}$ ,  $v_{r,g}$ ,  $v_{t,h}$ ,  $v_{t,g}$ , where  $\overline{v_{r,h}}$  is the mean heliocentric radial velocity obtained from Tables 1 and 2) for the LMC and SMC are given in Table 4 for a comparison with model predictions in Section 5.

In Section 2 we noted that the two stars San 193 and 194 may belong to a different kinematic group on grounds of their spatial location. Excluding these stars we obtain, for the galactocentric position of the SMC,  $60 \times (0.25, -0.64, -0.73)$  kpc, and for the galactocentric space motion vector of the SMC,  $u_{\text{SMC}} = (+177 \pm 169, -309 \pm 385, +310 \pm 222) \text{ km s}^{-1}$ .

Gardiner et al. (1994) predict  $u_{\text{LMC}} = (-5, -225, 194) \text{ km s}^{-1}$  and  $u_{\text{SMC}} = (40, -185, 171) \text{ km s}^{-1}$ .

## 5 MODELS AND PREDICTIONS

In this section we briefly review some models of the Magellanic System, with the intention of discussing the accuracy that the astrometrist must achieve when measuring the proper motion of the Magellanic Clouds in order to distinguish between scenarios.

The future and past histories of the Magellanic Stream and the LMC and SMC remain unknown. Tremaine (1976) considered the effect of dynamical friction on the motion of the LMC and derived an orbit that leads to accretion on the Galaxy within  $2 \times 10^9$  yr. However, the Andromeda galaxy will probably merge with the Milky Way at about the same time, as its current distance is 670 kpc and its galactocentric radial velocity is  $-297 \text{ km s}^{-1}$  (Lynden-Bell & Lin 1977). The increasingly close proximity of Andromeda will thus affect the future dynamics of the Magellanic Clouds.

### 5.1 Tidal models

An early computer simulation of the Magellanic Stream by Lin & Lynden-Bell (1977) modelled the Galaxy as a point mass and the Magellanic Clouds as one circular disc of test particles which is disrupted at perigalacticon to form the

**Table 4.** Measured radial and tangential velocities of the LMC and SMC.

|                  | $v_{t,h}$<br>km sec <sup>-1</sup> | $\overline{v_{r,h}}$<br>km sec <sup>-1</sup> | $v_{t,g}$<br>km sec <sup>-1</sup> | $v_{r,g}$<br>km sec <sup>-1</sup> |
|------------------|-----------------------------------|----------------------------------------------|-----------------------------------|-----------------------------------|
| LMC              | 420 ± 220                         | 279 ± 32                                     | 335                               | 142                               |
| SMC              | 567 ± 504                         | 177 ± 34                                     | 460                               | 70                                |
| SMC <sup>1</sup> | 627 ± 504                         | 176 ± 38                                     | 472                               | 15                                |

<sup>1</sup>San 193 and 194 excluded (Section 2.2); the uncertainties in  $v_{r,g}$  and  $v_{t,g}$  are dominated by the uncertainty in  $v_{t,h}$ .

Magellanic Stream, the LMC and the SMC. They took the Magellanic Stream to be a tidal bridge advancing ahead of the LMC and SMC, i.e. the position angle of the proper motion is  $\theta \approx 270^\circ$ . Lin & Lynden-Bell found orbital solutions with a perigalacticon of about 11 kpc and a period of about 1 Gyr, making survival of the Magellanic Clouds for  $10^{10}$  Gyr unlikely.

A much more detailed analysis of the LMC-SMC-Galaxy triple was performed by Murai & Fujimoto (1980). By integrating into the past the motion of the LMC-SMC system in an extended isothermal Galactic halo with a circular velocity of  $250 \text{ km s}^{-1}$  (corresponding to a mass within 50 kpc of about  $7 \times 10^{11} M_\odot$ ), they constrained orbital solutions by requiring that the LMC-SMC binary system be bound for the past  $10^{10}$  yr. They found that the LMC and SMC suffered a recent close collision about  $2 \times 10^8$  yr ago when they approached to within a distance of 2–3 kpc of each other. They modelled the tidal origin of the Magellanic Stream by studying the motion of test particles distributed on the discs of the LMC and SMC during the last two periods. The model stream follows the motion of the two Magellanic Clouds and was tidally stripped from the SMC about  $1.5 \times 10^9$  yr ago whilst it had a close encounter with the LMC near perigalacticon. To take account of the dynamics of the LMC-SMC system relaxes the necessity that the tidal force due to the Galaxy must be responsible for tearing the Clouds to form the Magellanic Stream. The orbit of the Magellanic Clouds that Murai & Fujimoto deduced is thus less eccentric (with peri- and apogalactic distances of 50 and approximately 100 kpc, respectively) than the solution that Lin & Lynden-Bell (1982) found.

Lin & Lynden-Bell (1982) reconsidered this problem through a thorough study of all available observational constraints on the inclinations and orbits of the LMC and SMC about each other, and deduced that the Magellanic Stream is a tidal tail. Applying the same numerical procedures as previously, they obtained an orbit of one greater Magellanic Cloud about the Galaxy. The Magellanic Stream results from the tidal interaction of the greater Magellanic Cloud with the Galaxy, and the SMC is represented by one of the test particles originally situated on the disc of the greater Magellanic Cloud. The Magellanic Stream was torn off at the last perigalactic passage about  $2 \times 10^9$  yr ago, and not at the current one. The perigalacticon of this orbit lies at about 50 kpc, and the period is approximately 3 Gyr with an apocentric distance from the Galactic Centre of about 200 kpc. Lin & Lynden-Bell inferred that, in order to get the large infall velocity at the tip of the Magellanic Stream, the Galactic halo must have a circular velocity of  $244 \pm 20 \text{ km s}^{-1}$  to a distance of at least 70 kpc. The mass of the Galaxy within 50 kpc that they required is thus about  $7 \times 10^{11} M_\odot$ . They also computed a model without a Galactic halo, but had to postulate non-gravitational forces to fit the Magellanic Stream.

In view of the persistent discrepancy in mass found for the Galaxy from studies of the Magellanic Stream and as found from studies of Galactic satellites, Shuter (1992) proposed an alternative interpretation of the Stream. Assuming that the Galactic mass within 50 kpc is  $3.6 \times 10^{11} M_\odot$ , obtained from satellites of the Galaxy (Fich & Tremaine 1991), and using an isothermal halo with a circular velocity of  $176 \text{ km s}^{-1}$  reaching to a distance of 190 kpc, Shuter computed the

orbits of a larger Magellanic Cloud not bound to the Galaxy. This dwarf galaxy takes part in the Hubble flow initially, and suffers a close passage past M31 where it is tidally disrupted and accelerated towards the Milky Way. The galactocentric velocity vector is fitted in such a way that the model tidal debris best approximates the observed Magellanic Stream.

Gardiner et al. (1994) relaxed the constraint that the Magellanic Clouds need to have formed a binary system for the past 10 Gyr. By integrating backwards in time the motion of the Magellanic Clouds in an isothermal Galactic halo with a circular velocity of  $220 \text{ km s}^{-1}$ , and extending to a distance of 200 kpc, they identified solutions for which the LMC–SMC pair has remained bound for at least the past 3 Gyr. The orbits extend from a perigalactic distance of between 40 and 45 kpc to an apogalactic distance of about 200 kpc. They found that for these a collision between the Clouds occurred 0.2 Gyr ago when they approached to within a distance of 7 kpc of each other. By introducing test particles for the most recent 2 Gyr, the simulations showed that the best representation of the Magellanic Stream is obtained for an orbit in which the LMC–SMC system has formed a bound pair for the past 15 Gyr. Using a large number of test particles, the authors investigated in detail the kinematic properties of matter surrounding the Magellanic Clouds. The LMC remains mostly unperturbed, but the SMC kinematics are qualitatively chaotic, in agreement with observations. The position of the test-particle stream is, however, offset by about  $10^\circ$  from the Magellanic Stream as viewed from the Sun.

## 5.2 Hydrodynamic models

The halo of our Galaxy contains gas, so that hydrodynamic effects may be important for the motion of the Magellanic Stream in which no stars have been found (Irwin 1991). To date, no model exists that combines the motions of collisionless and dissipative matter in the Magellanic System, and it is quite conceivable that a thin but hot halo gas can exert sufficient ram pressure to separate the gas in the Magellanic Stream from the stars. Wayte (1991) discussed existing non-tidal models and the weaknesses of these and of tidal models. The latter are far easier to implement, and all lead to an approximate representation of the position of the Magellanic Stream and distribution of radial velocities along it, but generally leave many aspects of the Magellanic Stream unanswered (e.g. the distribution of the column density of hydrogen gas and of velocity dispersions, and the position of the gas concentrations in the Magellanic Stream), whereas the former address these issues. The debate concentrates on whether the Magellanic Stream is primarily a tidal feature or a ram-pressure feature. If hydrodynamics is predominantly responsible for the Stream, then the above tidal approaches cannot be used to constrain the halo of the Galaxy.

The discovery of six gas concentrations, MS I to MS VI, in the Magellanic Stream by Mathewson, Schwarz & Murray (1977) led them to propose that the concentrations are now sinking thermal instabilities in the wake of the Magellanic Clouds as they move through a hot Galactic halo. The observed density enhancements are not reproduced by this model, leading Mathewson et al. (1987) to propose that the gas concentrations MS I to MS VI are a result of collisions between high-velocity hydrogen clouds orbiting in the halo

of the Galaxy and the LMC–SMC intercloud gas. This model has the drawback that the Magellanic Stream is continuous and not discrete, and that the high-velocity clouds in the halo are required to follow a particular distribution (see Wayte 1991 for a further discussion).

Recently, Liu (1992) investigated a model in which a long, thin column of gas moves in a quasi-steady state in the gravitational fields of the Magellanic Clouds and the Galaxy. By fitting the observed radial velocity distribution along the Stream by adopting a galactocentric transverse velocity of the Clouds, he found the circular velocity of the halo to be  $160 \text{ km s}^{-1}$  between about 45 and 100 kpc. The Magellanic Clouds move on an orbit with a perigalactic distance of 48 kpc and an apogalactic distance of about 320 kpc. Liu derived the variation of column density along the stream and showed it to be in good agreement with observations, and also deduced the density of the halo gas to be  $10^{-4}$ – $10^{-3} \text{ cm}^{-3}$  if it has a temperature of about  $5 \times 10^6 \text{ K}$ . Liu argued that two processes probably act together, namely the formation of a wake behind the Magellanic Clouds in the hot halo gas and the stripping of cold gas from the region between the LMC and SMC. The conditions are likely to be such that the motion of the Magellanic Clouds through the hot halo gas produces a turbulent wake along the orbit, from which vortices are shed periodically. He showed that this results in a chain of concentrations of cold hydrogen gas at the approximate positions of the MS I to MS VI clouds.

## 5.3 Discussion

The above describes the very different model ideas concerning the motion and origin of the Magellanic Stream, the LMC and SMC, which various past studies obtained. All of these are quite successful in explaining the distribution of radial velocities along the Stream. Non-tidal models offer the advantage of addressing other observed features of the Magellanic Stream.

We compile the existing model predictions in Table 5, where we explicitly state the Galactic parameters that the above authors adopted: the circular velocity of the Sun about the Galactic Centre,  $V_C$ , and the distance of the Sun from the Galactic Centre,  $R_\odot$ . The models predict a proper motion of between  $1.5$  and  $2.0 \text{ mas yr}^{-1}$ . If we compare the entries in Tables 3, 4 and 5, we see that the measurement of the proper motion of the LMC using PPM Catalogue stars is consistent with all the models. On the other hand, the six other determinations of the proper motion of the LMC discussed in Section 3 all derive  $\mu = 1$ – $1.5 \text{ mas yr}^{-1}$ .

We also note from Table 5 that the predictions from similar models show an appreciable range [e.g. Murai & Fujimoto (1980) predicted  $\mu = 1.7 \text{ mas yr}^{-1}$ , and Lin & Lynden-Bell (1982) predicted  $\mu = 2.0 \text{ mas yr}^{-1}$ ], and that models in which the Magellanic Clouds are assumed to be bound in an extended heavy halo predict a proper motion of between  $1.7$  and  $2.0 \text{ mas yr}^{-1}$ , whereas a model without a halo predicts  $\mu = 1.5 \text{ mas yr}^{-1}$  (Lin & Lynden-Bell 1982). A model that assumes the Magellanic Clouds to be not bound predicts a proper motion *within* the above range (Shuter 1992).

The conclusion that we draw here is that, even if we have an excellent measurement of the proper motion of the LMC, the uncertainties in the model parameters are sufficiently

**Table 5.** Model motions of the LMC.

| model                                      | $\mu$                | $\theta$ | $v_{t,h}$            | $v_{t,g}$            |
|--------------------------------------------|----------------------|----------|----------------------|----------------------|
|                                            | mas yr <sup>-1</sup> |          | km sec <sup>-1</sup> | km sec <sup>-1</sup> |
| Murai & Fujimoto (1980) <sup>1</sup>       | 1.7                  | 90°      | 424                  | 288                  |
| Lin & Lynden-Bell (1982) <sup>2</sup>      | 2.0                  | 90°      | 500                  | 373                  |
| Lin & Lynden-Bell (1982) <sup>3</sup>      | 1.5                  | 90°      | 370                  | 240                  |
| Shuter (1992) <sup>4</sup>                 | 1.9                  | 90°      | 480                  | 355                  |
| Liu (1992) <sup>5</sup>                    | 1.7                  | 90°      | 430                  | 310                  |
| Gardiner <i>et al.</i> (1994) <sup>6</sup> | 1.8                  | 80°      | 412                  | 287                  |

<sup>1</sup>  $V_C = 250$  km s<sup>-1</sup>,  $R_\odot = 10$  kpc; listed here is their model ' $i=0^\circ$ ',  $D_L = 50$  kpc,  $L'$  in their table 3.

<sup>2</sup> Heavy halo,  $V_C = 244$  km s<sup>-1</sup>,  $R_\odot = 9$  kpc.

<sup>3</sup> No halo.

<sup>4</sup> Motion is for the barycentre of LMC-SMC; the approximate heliocentric transverse velocity has been obtained from  $v_{t,h}$  by correcting for solar motion using  $V_C = 220$  km s<sup>-1</sup>;  $R_\odot = 8.5$  kpc.

<sup>5</sup> The approximate heliocentric transverse velocity has been obtained as for note 4.

<sup>6</sup>  $V_C = 220$  km s<sup>-1</sup>;  $R_\odot = 8.5$  kpc; the authors also predict the motion of the SMC:  $\mu = 1.6$  mas yr<sup>-1</sup>,  $\theta = 150^\circ$ .

large to preclude a unique choice of the model of the Magellanic Stream. If, however, we can find independent arguments to tie down the type of model (bound or unbound, tidal or non-tidal), then a precise and accurate measurement of the proper motion of the LMC will be very helpful in constraining the mass distribution in the outer parts of the Milky Way.

#### 5.4 Required accuracy in the measurement of $\mu$

The question that we address here is: what accuracy does future astrometry need to achieve when measuring the proper motion of the LMC in order to constrain significantly the distribution of matter in the Galactic halo?

In both the tidal and ram-pressure-stripping models of the Magellanic Stream, it is true that the particles of the Stream follow nearly the same orbit as the Magellanic Clouds but with slightly smaller orbital velocity. We thus expect the Magellanic Stream to be a better approximation of the past orbit of the Magellanic Clouds the further we go on the sky along the Stream, starting at its tip about  $100^\circ$  away from the LMC and going towards the LMC.

The mass within a sphere of radius  $R$  is for an isothermal halo  $M(<R) = 5.7 \times 10^{11} (V_C/220 \text{ km s}^{-1})^2 (R/50 \text{ kpc}) M_\odot$ , and is conveniently parametrized by the circular velocity  $V_C$ . We compute the orbit of the LMC backwards in an isothermal halo with circular velocity  $V_C$  assuming an initial (current) heliocentric radial velocity  $v_r = +274$  km s<sup>-1</sup> and a heliocentric proper motion  $\mu$ . By correcting these for a circular velocity of the Sun of 220 km s<sup>-1</sup>, we obtain 90 km s<sup>-1</sup> and  $\mu - 0.5$  mas yr<sup>-1</sup> as the initial radial and tangential velocity components of the LMC, whereby we neglect the peculiar motion of the Sun and its offset position from the Galactic Centre and assume that for our purpose the motion of the LMC sufficiently approximates the motion of the LMC-SMC system. We compute a series of orbits defined by a pair of  $V_C$  and  $\mu$  values. For each orbit we compute the radial velocity  $V_R$  as a function of angle  $\theta$  along the orbit and we find the  $V_C$ ,  $\mu$  pair that best represents the observed

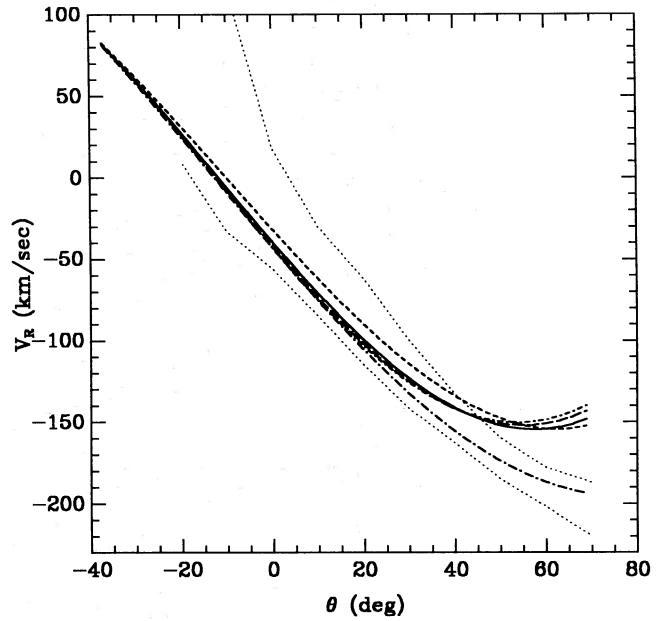


**Figure 2.** Radial velocity as a function of angle along the Magellanic Stream, which is denoted by the dotted lines (Mathewson *et al.* 1974). We show four of the many models (see Fig. 4 and Section 5.4) that best represent the Magellanic Stream: short-dash-dotted curve ( $V_C = 500$  km s<sup>-1</sup>,  $\mu = 2.9$  mas yr<sup>-1</sup>), long-dashed curve ( $V_C = 345$  km s<sup>-1</sup>,  $\mu = 2.3$  mas yr<sup>-1</sup>), solid curve ( $V_C = 220$  km s<sup>-1</sup>,  $\mu = 1.8$  mas yr<sup>-1</sup>) and short-dashed curve ( $V_C = 120$  km s<sup>-1</sup>,  $\mu = 1.4$  mas yr<sup>-1</sup>). A linear trajectory with no halo ( $V_C = 0$  km s<sup>-1</sup>,  $\mu = 1.2$  mas yr<sup>-1</sup>) leads to the long-dash-dotted curve which best represents the Magellanic Stream in velocity and angle space. Orbits corresponding to the five  $V_C$ ,  $\mu$  pairs shown here are plotted in Fig. 3.

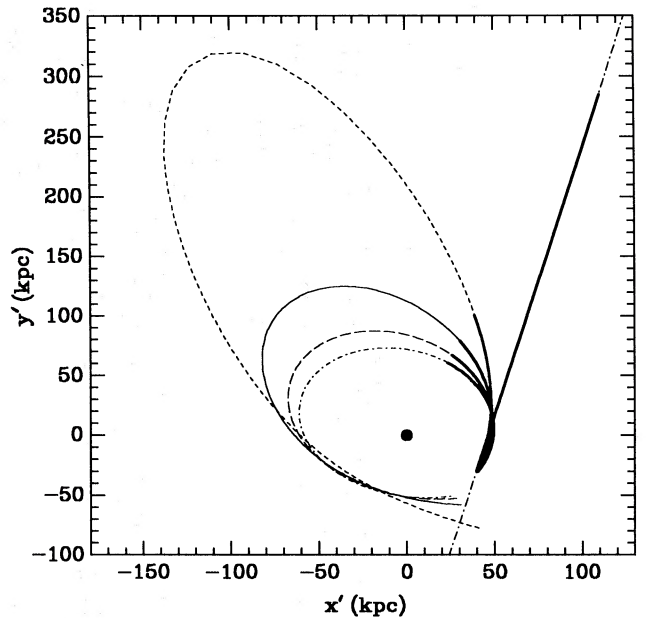


**Figure 3.** The orbits corresponding to the models shown in Fig. 2 are shown using the same symbols. The thick solid sections of each orbit approximately represent the length of the Magellanic Stream. All orbits converge at the current position of the LMC. The rectangular coordinate system used in the main text has been rotated so as to allow computation in the  $x'$ ,  $y'$ -plane.

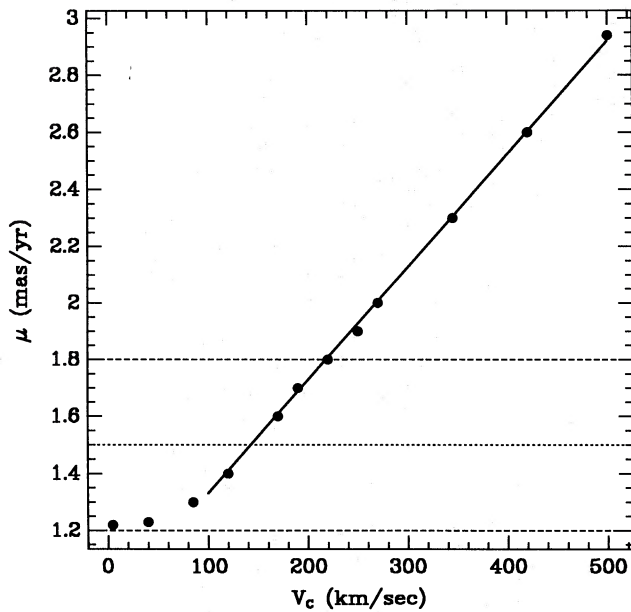


**Figure 4.** The heliocentric proper motion,  $\mu$ , that is required to give the best agreement with the Magellanic Stream is plotted as a function of the circular velocity,  $V_c$ , of the isothermal halo (Section 5.4). The solid line is the fit  $\mu = 0.93 + 0.0040 V_c$ . If a measurement of the proper motion of the LMC yields  $\mu = 1.5 \pm 0.1 \text{ mas yr}^{-1}$  then the  $3\sigma$  significance range, signified by the dashed lines, allows  $V_c = 0\text{--}220 \text{ km s}^{-1}$ .

variation of radial velocity along the Magellanic Stream. This is demonstrated in Fig. 2, and in Fig. 3 we show the corresponding orbits. A summary of  $V_c$ ,  $\mu$  pairs is given in Fig. 4.

It is interesting to note from Fig. 4 that if  $\mu = 1.5 \pm 0.1 \text{ mas yr}^{-1}$  then we cannot make a significant (i.e.  $3\sigma$ ) distinction between no halo, in which case the Magellanic Clouds are simply on a linear trajectory, and a massive halo with  $V_c = 220 \text{ km s}^{-1}$ . Also, we note that this very simple modelling requires for  $V_c = 220 \text{ km s}^{-1}$  a proper motion of  $\mu = 1.8 \text{ mas yr}^{-1}$ , which is precisely the value predicted by the much more detailed model of Gardiner et al. (1994).

## 6 CONCLUSIONS

We have measured the proper motions of the LMC and SMC in the PPM Catalogue reference frame. The results are given in Table 3. For the LMC we obtain  $1.7 \pm 0.9 \text{ mas yr}^{-1}$ . This measurement of the motion of the LMC is consistent with that predicted by Murai & Fujimoto (1980), Lin & Lynden-Bell (1982), Shuter (1992), Liu (1992) and Gardiner et al. (1993). All these models predict a proper motion of the LMC of between 1.5 and  $2 \text{ mas yr}^{-1}$  (Table 5). The smallest proper motion ( $1.5 \text{ mas yr}^{-1}$ ) results from a model with no Galactic halo, in which case non-gravitational forces are required to explain the Magellanic Stream (Lin & Lynden-Bell 1982). Models of the same type allow proper motions of the LMC that differ by up to  $0.3 \text{ mas yr}^{-1}$ . Tidal and non-tidal models of the Magellanic Stream predict essentially the same proper motion of the LMC. Other evidence (the presence or lack of stars, hydrogen column density, distance) is required to decide between models of the Magellanic Stream. Six other independent measurements of the proper

motion of the LMC discussed in Section 3 suggest that  $\mu \approx 1\text{--}1.5 \text{ mas yr}^{-1}$  due east. We emphasize that, in order to help to distinguish between models of the mass distribution in the outer parts of the Galaxy, the proper motion of the LMC (and preferably also of the SMC) has to be known to about  $0.1 \text{ mas yr}^{-1}$ . That is, the transverse velocity of the LMC has to be measured with an accuracy of about  $25 \text{ km s}^{-1}$ , which is about one-third to one-half of the maximum rotational velocity of the LMC (Meatheringham et al. 1988; Prévot et al. 1989), complicating the task even further. Measurements of the proper motion of the LMC based on data from the outer regions of the LMC need to be interpreted carefully, owing to the likely tidal perturbation of the outer regions of the LMC by the SMC.

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