THE MOTION OF THE MAGELLANIC CLOUDS*

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ABSTRACT

The proper motion of the Large (LMC) and Small (SMC) Magellanic Clouds are measured using data acquired with the Hipparcos satellite. Combination with two other independent measurements gives:

$\overline{\mu}_{\rm LMC} = 1.61 \pm 0.28\,{\rm mas/yr}$

$\overline{\mu}_{\rm SMC} = 1.67 \pm 0.92\,{\rm mas/yr}$

Within the measurement uncertainties both galaxies have parallel space velocity vectors and lead the Magellanic Stream.

Key words: Magellanic Clouds; Galaxies: kinematics and dynamics; Galaxies: interactions.

1. INTRODUCTION

The distances from the Galactic centre to the LMC and SMC are approximately 48 kpc and 54 kpc, respectively. The distance between the LMC and SMC amounts to about 21 kpc. The LMC is estimated to have a mass of about $2 \times 10^{10}\,M_\odot$, and the SMC is lighter by approximately an order of magnitude.

By inhabiting the Milky Way we are part of the interacting LMC–SMC–Galaxy system. Many of the processes affecting this system must have been important in shaping galaxies in the early universe. We are in an excellent position to observe the dynamical interaction of the collisionless, or stellar, components of the three galaxies. We can also investigate whether and how star formation is induced, and the underlying magnetohydrodynamical interaction. The closest galactic neighbours, the LMC and SMC, are thus windows into the early times of galaxy assembly, especially since some theoretical studies suggest that the LMC and SMC may have been one larger galaxy in the past, and that both may merge with the Galaxy in the future.

In order to relate the hydrodynamical, star formation, stellar kinematical and structural information which we have for the LMC, the SMC and the Galaxy, we need to know their relative motions. This can only be achieved by measuring the proper motion vectors of the LMC and the SMC. The radial velocities in the Galactic standard of rest are known to within about 1 km s^{-1}: $v_{\rm rad,LMC} = +80$ km s^{-1} and $v_{\rm rad,SMC} = +7$ km s^{-1}. The complete space velocity vectors of both galaxies are required to map their past orbit, and thus to probe the overall mass content of the triple system.

Details of the proper motion measurements of the LMC and the SMC using Hipparcos data, plus a detailed discussion of the results, including evidence for rotation of the LMC, and implications for the origin of the Magellanic Clouds and the associated gas stream, can be found in Kroupa & Bastian (1997).

2. THE DATA AND DATA REDUCTION

The Hipparcos satellite observed 36 LMC and 11 SMC stars. Of these, 33 LMC and 9 SMC members are used here. Three LMC stars are removed because their Hipparcos measurements are disturbed, and two SMC stars are removed because they lie in the region between the SMC and the LMC which is likely to be significantly affected by tides. The median standard error of the individual proper motion components for these stars is about 1.7 mas/yr, which is larger than the typical value of 1 mas/yr because the LMC and SMC stars are much fainter than the typical Hipparcos star.

In order to infer the mean proper motion of the LMC and SMC, data reduction must take account of the correlations between the measured quantities. These are significant for a group of stars that lie close to each other on the sky. Van Leeuwen & Evans (1997) describe a method which permits the full and consistent inclusion of the correlations.

*Based on data from the ESA Hipparcos astrometry satellite.

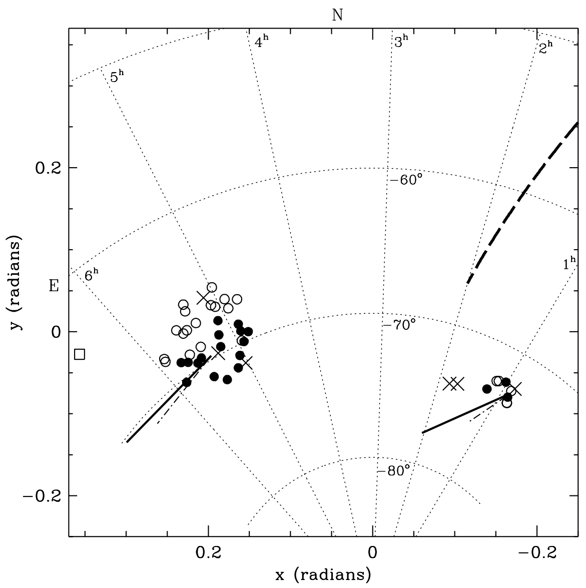

Figure 1. The figure shows a gnomonic sky plot of the Magellanic Cloud region. Open and solid circles are Hipparcos stars with positive and negative heliocentric radial velocities after subtraction of the Cloud's mean radial velocities of +274 km s^{-1} (LMC) and +148 km s^{-1} (SMC), respectively. Crosses are stars with unknown radial velocity. Bold lines indicate the proper motion vectors of the Clouds, as measured by Hipparcos; dash-dotted lines are the proper motions corrected for solar reflex motion. The bold dashed line roughly shows the location of the Magellanic Stream. The open square at left is the field centre used by Jones et al. (1994) to measure the LMC proper motion with respect to distant galaxies.

3. RESULTS

Using the method of van Leeuwen & Evans (1997), the Hipparcos data give:

$$\mu^{\rm Hip}_{\alpha,{\rm LMC}} \times \cos(\delta_{\rm LMC}) = +1.94 \pm 0.29\,{\rm mas/yr} \quad (1)$$

$$\mu^{\rm Hip}_{\delta,{\rm LMC}} = -0.14 \pm 0.36\,{\rm mas/yr} \quad (2)$$

and

$$\mu^{\rm Hip}_{\alpha,{\rm SMC}} \times \cos(\delta_{\rm SMC}) = +1.23 \pm 0.84\,{\rm mas/yr} \quad (3)$$

$$\mu^{\rm Hip}_{\delta,{\rm SMC}} = -1.21 \pm 0.75\,{\rm mas/yr} \quad (4)$$

Using 21 photographic plates spanning 14 yrs, Jones, Klemola & Lin (1994) measured:

$$\mu^{\rm JKL}_{\alpha,{\rm LMC}} \times \cos(\delta_{\rm LMC}) = +1.37 \pm 0.28\,{\rm mas/yr}$$

$$\mu^{\rm JKL}_{\delta,{\rm LMC}} = -0.18 \pm 0.27\,{\rm mas/yr}$$

for a field lying about 7.3 kpc from the LMC centre in the plane of the sky. A measurement of the mean proper motion of 35 stars distributed throughout the LMC, using proper motion measurements from the PPM Catalogue, gives (Kroupa, Röser & Bastian 1994):

$$\mu^{\rm KRB}_{\alpha,{\rm LMC}} \times \cos(\delta_{\rm LMC}) = +1.3 \pm 0.6\,{\rm mas/yr}$$

$$\mu^{\rm KRB}_{\delta,{\rm LMC}} = +1.1 \pm 0.7\,{\rm mas/yr}.$$

For the SMC they obtain, using 8 PPM stars:

$$\mu^{\rm KRB}_{\alpha,{\rm SMC}} \times \cos(\delta_{\rm SMC}) = +0.5 \pm 1.0\,{\rm mas/yr}$$

$$\mu^{\rm KRB}_{\delta,{\rm SMC}} = -2.0 \pm 1.4\,{\rm mas/yr}.$$

Improved estimates of the proper motion of both galaxies can be obtained by combining the above independent measurements:

$$\overline{\mu}_{\alpha,{\rm LMC}} \times \cos(\delta_{\rm LMC}) = +1.61 \pm 0.19\,{\rm mas/yr} \quad (5)$$

$$\overline{\mu}_{\delta,{\rm LMC}} = -0.06 \pm 0.21\,{\rm mas/yr} \quad (6)$$

$$\overline{\mu}_{\alpha,{\rm SMC}} \times \cos(\delta_{\rm SMC}) = +0.93 \pm 0.64\,{\rm mas/yr} \quad (7)$$

$$\overline{\mu}_{\delta,{\rm SMC}} = -1.39 \pm 0.66\,{\rm mas/yr} \quad (8)$$

4. DISCUSSION

According to Equations 5-8 and the resulting space motion vectors (Kroupa & Bastian 1997), the LMC and SMC are on approximately parallel trajectories heading the Magellanic Stream (see Figure 1). The Magellanic Stream is thus either a tidal tail, resulting from the interaction between the LMC, the SMC and the Galaxy, or a ram-pressure feature, or, what appears most likely, a combination of both. A review of the various models can be found in Kroupa & Bastian (1997).

The total galactocentric space velocity of the LMC amounts to 265 ± 65 km s^{-1}. This is comparable to the local circular velocity. However, the presently available information is not sufficient to conclude that the potential of the Galaxy extends to a distance of about 50 kpc with a flat rotation curve, or if the Magellanic Clouds are unbound to the Galaxy. This question, among others, can be answered if the distances to the gas clouds in the Magellanic Stream are measured, and if the proper motions of the LMC and the SMC are estimated to an accuracy of at least 0.1 mas/yr. This will be achieved with a future astrometric space mission, such as GAIA and/or DIVA.

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