Kinematic outliers in the Large Magellanic Cloud: constraints on star–star microlensing

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ABSTRACT

Although a decade of microlensing searches towards the Large Magellanic Cloud (LMC) has detected 13–25 possible microlensing events, the nature and the location of the lenses, being either halo MACHOs or LMC stars, remains a subject of debate. The star–star lensing models generically predict the existence of a small population (more than ∼5 per cent) of stars with a spatial and kinematic distribution different from the thin, young disc of the LMC. Here we present the results of a large spectroscopic survey of the LMC, consisting of more than 1300 radial velocities measured accurately with the 2dF instrument. In this large sample, no evidence is found for any extraneous population over the expected LMC and Galactic components. Any additional, kinematically distinct, population can only be present at less than the 1 per cent level. We discuss the significance of this finding for the LMC self-lensing models.

Key words: gravitational lensing – galaxies: haloes – Magellanic Clouds – galaxies: kinematics and dynamics – dark matter.

1 INTRODUCTION

About a decade of searches for microlenses along the line of sight to the Magellanic Clouds (MCs) by MACHO/OGLE/EROS and a number of follow-up surveys have found more than 13 candidate microlensing events towards the Large Magellanic Cloud (LMC) and two towards the Small Magellanic Cloud (SMC). The MACHO collaboration (Alcock et al. 2000) conclude that the lenses are mostly massive compact objects (MACHOs) residing in the halo of the Galaxy, perhaps in the form of ancient white dwarfs (WDs). These WDs would make up 10–20 per cent of the halo dynamical mass, with the remaining 80–90 per cent in some other component. The detection of high proper motion white dwarfs (Hambly, Smartt & Hodgkin 1997; Hodgkin et al. 2000; Ibata et al. 2000; Oppenheimer et al. 2001) supports this interpretation.

The assertion that WDs make up at least 3 per cent of the expected local dark matter density Oppenheimer et al. (2001) has been hotly contested (see the review by Richer 2001). Some argue very strongly that these WDs trace the thick disc kinematics instead (Reid, Sahu & Hawley 2001). If the thick disc interpretation is true, then the halo would have very few WDs, but the big question remains: what objects are responsible for microlensing the LMC stars?

The answer is perhaps the LMC stars themselves. From the very beginning there have been many variations of star–star self-lensing proposals as first advocated by Sahu (1994). Star–star lensing models typically invoke an unvirialized component of the LMC and the SMC (e.g. a puffed up disc or a hot stellar halo with a surface brightness of only a few per cent of the LMC disc, a wrapped-around tidal ring, an offset bar, etc., all because of tidal shocking among the LMC, SMC and the Galaxy) because of low optical depth of a virialized, thin LMC disc (Gould 1995). Any unvirialized component of the LMC can then lense with stars in the thin disc of the LMC. Some recent theoretical models (e.g. Zhao & Evans 2001) argue that there could be enough stellar lenses in the LMC bar and disc to account for from half to all of the observed events. These models generally predict that the events should have peculiarities in photometry, kinematics and spatial distribution because the lensing optical depth is higher in some regions than others. These are highlighted in at least five of the dozen observed events: the LMC near-clump event MACHO-LMC-1 and LMC binary events MACHO-LMC-9 and MACHO-LMC-14, the SMC caustic event MACHO-98-SMC-1 and long-duration event MACHO-97-SMC-1. Although there is no strong direct evidence, it is reasonable to expect that all of the dozen observed lenses belong to the same LMC or SMC population as for these exotic events because ordinary single stars should be at least as common as binary stars in a given LMC or SMC stellar population, and they all have similar lensing cross-sections and detection efficiencies.

Zhao (1999a,b) discussed a number of observational tests to differentiate the two competing classes of lensing models. In particular,
stars in any proposed unvirialized component should be identifiable as kinematic outliers, meaning that they deviate from the rotation curve of the LMC, as traced by the majority of LMC disc stars and by H I gas. The objective of the present contribution is to analyse the kinematics of a large sample of stars towards the LMC to investigate whether outliers can be singled out. These kinematic outliers may reveal the presence of any hot component around the LMC, or any cold halo stream either in the Galactic halo or the LMC halo (Graff et al. 2000). We aim to be able to detect a kinematically distinct population (polar ring or thickened disc) in the LMC present at the ~5 per cent level. If such a population is identified its relation to the microlensed sources can be studied.

We foresaw two possible outcomes of this experiment.

(i) The LMC microlensed sources and the randomly selected LMC field stars have disc kinematics: this would imply that the lenses are in the halo, supporting the MACHO interpretation of a dark baryonic component in the halo in the form of white dwarfs and consistent with the high-velocity, blue, old white dwarfs in the solar neighbourhood detected by Ibata et al. (2000) and Oppenheimer et al. (2001).

(ii) The sample of microlenses or the sample of field stars contain many outliers from the LMC rotation curve, implying that the Galactic dark halo is almost entirely made of a non-compact component. The solar neighbourhood white dwarfs are merely a local peculiarity.

2 OBSERVATIONS

A sample of ~6000 stars was selected from an LMC colour-magnitude diagram (CMD) produced from UKST photographic plates measured on the APM facility (see Fig. 1). These stars were randomly selected for magnitudes and colours in the ranges 16 < $B - R$ < 2.5, in order to have as few biases as possible on the sample selection. The fields were chosen centred on each previously microlensed star.

The present data set is the result of three observing campaigns from 1999 to 2002, using the 2dF (2-Degree Field) instrument at the 3.9-m Anglo-Australian Telescope. This instrument is a fibre spectrograph coupled to a robot positioner that is capable of observing the spectra of up to 400 sources simultaneously over a 2° diameter circular field. Owing to adverse weather conditions only five field setups were obtained, all in UK Schmidt Telescope field 56, for a total of 1576 target stars observed. Fig. 2 shows the distribution of these sources over the face of the LMC. Table 1 provides a summary of the observing log. The 1200-V grating was used, giving spectra with dispersion of 1.1 Å pixel$^{-1}$ over the wavelength range 4625 < $\lambda$ < 5765 Å. For each fibre setup, three 1800-s exposures were combined.

The spectral images were debiased, flat-fielded and wavelength calibrated using the excellent 2dF pipeline software. The spectrum of the night sky was monitored with ≥20 fibres in each setup, and the mean sky spectrum was subtracted from the object spectra. Judging from the residuals at the position of the bright [O i] 5577-Å sky line, the sky subtraction process is accurate to better than ~1 per cent. After combining the three exposures, the average quality of the spectra of our survey stars gave a signal-to-noise (S/N) ratio greater than S/N = 10. The wavelength calibration was checked by fitting the peak of the [O i] 5577-Å sky line. We estimate that the typical velocity error is ~$15 \pm 10$ km s$^{-1}$.

Owing to the wide colour range of the stars observed ($-1 < B - R < 2.5$), the cost of observing a sufficient number of radial velocity standard stars of spectral types covering this colour range would have been prohibitive with 2dF. Instead we chose to use survey stars as radial velocity standards, picking 10 high signal-to-noise ratio stars from a box of 16 < $R$ < 18 and $-1.0 < B_1 - R < 2.5$, with dispersion of 1.1 $\pm 10$ km s$^{-1}$.

![Figure 1](https://academic.oup.com/mnras/article-abstract/339/3/701/971327/1)

**Figure 1.** The left-hand panel shows a Hess diagram of the LMC field. The right-hand panel shows the portion of the CMD where our sample stars are selected from a box of 16 < $R$ < 18 and $-1.0 < B_1 - R < 2.5$. The targets are marked according to their radial velocities, as in Fig. 1.

- **Table 1.** Summary of observations.

| Date     | Field | RA   | Dec.  | Epoch |
|----------|-------|------|------|-------|
| 2000 Nov 24 | F056 Conf 05 | 05 04 03 | -69 33 18 | 2000 |
| 2002 Jan 5 | F056 Conf 01 | 05 14 44 | -68 48 01 | 2000 |
| 2002 Jan 5 | F056 Conf 02 | 05 17 14 | -70 46 58 | 2000 |
| 2002 Jan 5 | F056 Conf 04 | 05 26 14 | -70 21 14 | 2000 |
| 2002 Jan 5 | F056 Conf 21 | 05 24 03 | -68 49 12 | 2000 |

![Figure 2](https://academic.oup.com/mnras/article-abstract/339/3/701/971327/2)

**Figure 2.** The location of the target objects in the LMC. The stars are marked according to their radial velocities, as in Fig. 1.

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stars at roughly even intervals of $B-J$ colour over the above range. Each survey star was cross-correlated against each template star, giving a relative velocity measurement, the corresponding uncertainty, and Tonry–Davis cross-correlation ‘$R$’ parameter (Tonry & Davis 1979). The template spectrum that gave the highest ‘$R$’ value was considered to provide the best cross-correlation match with a particular survey star, and the resulting radial velocity difference was used to compute the heliocentric radial velocity of the survey star. The zero-point velocity of one of the (K-type) LMC radial velocity ‘standards’ was measured with respect to a genuine radial velocity standard of the same spectral type. The radial velocity offsets of the remaining nine LMC radial velocity ‘standards’ were calculated by fitting the peak of the numerous LMC population (where we assume that there is no systematic offset in velocity between stars of different spectral types in the LMC).

To ensure a good quality sample, we applied three parameter cuts to the data set: we require the Tonry–Davis cross-correlation parameter to be $R > 5$; the heliocentric radial velocities are constrained to have $|v_h| < 1000$ km s$^{-1}$ and the radial velocity uncertainties (determined from the fit of the cross-correlation peak) were set to be $\delta v_h < 50$ km s$^{-1}$. The resulting data set, cleaned of low signal-to-noise ratio spectra and spectra that were not well matched by our library of 10 ‘standard’ stars, comprises 1347 objects. The velocity histogram of this sample is displayed in Fig. 3. A scatter diagram is also shown in Fig. 4 for the velocity and the colour of our sample stars.

3 The Expected Galactic and LMC Populations

The LMC is located at $\ell = 280^\circ$, i.e. roughly towards the direction of antitrotation, and is below the disc at $b = -33^\circ$. Since the Sun rotates about the Galactic Centre 10 km s$^{-1}$ faster than the local standard of rest (LSR) (Dehnen & Binney 1998), most local stars will be seen towards lower heliocentric radial velocities. However, the main effect is that the projection of the circular velocity vector of the disc decreases beyond the tangent point. Thus, the majority of Galactic disc stars seen along the line of sight towards the LMC will be seen with $v_h < 0$ km s$^{-1}$. In Figs 4 (lower-panel) and 5 we display a kinematic star-counts model, which contains disc, thick disc and spheroid populations. The expected number of sources per deg$^2$ within our magnitude range is 1012 (disc, dashed), 620 (thick disc, dot-dashed) and 370 (spheroid, dotted) (Ibata 1994).

Note that, of the stars with $v_h < 100$ km s$^{-1}$, most have intermediate colours $B - V \sim 1$, and are therefore typically solar-luminosity main-sequence stars with $M_B \sim 6$ (e.g. Binney & Merrifield 1998). The distance range corresponding to our magnitude selection range $16 < R < 18$, is then $\sim 1 < d < 2.5$ kpc. Given the Galactic latitude of the fields, these disc stars are located several scaleheights below the disc, and mostly beyond the tangent point. Nearby, intrinsically fainter and redder disc dwarfs hardly make it into the magnitude selection region.

The simplest explanation of our data is as follows.

(i) The 40 stars with $v_h < 100$ km s$^{-1}$ are normal disc dwarfs, and display an expected radial velocity distribution.

(ii) The 1291 stars with $170 < v_h < 380$ km s$^{-1}$ are drawn from a single simple Gaussian distribution, with intrinsic dispersion $\sigma_v = 24$ km s$^{-1}$.

(iii) The three stars with $100 < v_h < 170$ km s$^{-1}$ and $B_J - R < 0$ have suspect velocities because their radial velocities as derived from different (but similar) templates do not agree.

(iv) The 11 stars with $100 < v < 170$ km s$^{-1}$ and $B_J - R > 0$ are spheroid stars.

(v) The two stars with $v > 380$ km s$^{-1}$ are halo stars.

According to the model displayed in Fig. 5, the number of stars in the velocity range $100 < v_h < 170$ km s$^{-1}$ should number only 5 per cent of the number in the velocity range $-100 < v_h < 100$ km s$^{-1}$. The observed number is 35 per cent. Is the excess of $\sim 11$ stars caused by an extraneous unexpected population that could account for the observed microlensing? This population,

![Figure 3](https://academic.oup.com/mnras/article-abstract/339/3/701/971327)

**Figure 3.** The heliocentric radial velocity distribution of stars in the sample.

![Figure 4](https://academic.oup.com/mnras/article-abstract/339/3/701/971327)

**Figure 4.** Heliocentric radial velocity as a function of star colour. Upper panel: data. Lower panel: predictions of the Galaxy model with a colour conversion $B_J - R = 1.25(B - V)$. Note the outliers in the data cannot be explained by the Galaxy model.
however, would only represent a small fraction of the mass required to account for the observed frequency micro-lensing. Hence this data effectively rules out the existence of an extraneous kinematic population that exceeds 1 per cent of the LMC.

4 COMPARISON WITH PREVIOUS WORK

The distribution of radial velocities of LMC stars has been studied by many authors. The kinematical properties of the LMC have been studied with many different tracers, including HI (e.g. Kim et al. 1998), star clusters (Freeman, Illingworth & Oemler 1983; Schommer et al. 1992), planetary nebulae (Meatheringham et al. 1988), H II regions and supergiants (Feitzinger, Schmidt-Kaler & Isserstedt 1977). Recently, van der Marel et al. (2002) have combined the carbon stars data set of Kunkel, Irwin & Demers (1997), which covers the periphery of the LMC at all position angles, with a rotation of stars in the LMC centred on $\delta$ CM $= 5^\circ 27.6'^\circ \pm 3.9'^\circ$ and $b_{\text{CM}} = -69^\circ 52' \pm 25'$, which is approximately $1.2^\circ \pm 0.6'$ away from the gas kinematical centre. The kinematics of stars are roughly described by a flat rotation of 50 km s$^{-1}$ outside 4$'$ with an inclination $i = 34.7^\circ \pm 6.2^\circ$ and a position angle $\Theta = 129.9^\circ \pm 6^\circ$. The velocity dispersion for the carbon stars is $20-22$ km s$^{-1}$ between 1 and 3.5 kpc from the centre, followed by a decline to $16-17$ km s$^{-1}$ between 3.5 and 1 kpc from the centre, and a subsequent increase to $21-22$ km s$^{-1}$ between 7 and 9 kpc. The velocity dispersion increases with age (e.g. Gyuk, Dalal & Griest 2000), with a range from $\sigma \approx 6$ km s$^{-1}$ for the youngest populations (e.g. supergiants, H II regions, H I gas) to $\sigma \approx 30$ km s$^{-1}$ for the oldest populations (e.g. old long-period variables, old clusters). The carbon stars are part of the intermediate-age population that is believed to be fairly representative for the bulk of the mass in the LMC. Our sample appears to be consistent with the carbon star sample of van der Marel et al. (2002). Fig. 6 is made to examine the question of whether there is any significant velocity variation with spatial position. Given the sparseness of our sample, we do not see any strong systematic variation across our fields. Our fields are also mostly on the short axis of the LMC disc, hence the signature arising from rotation is also very weak. This supports our treatment of our sample as a whole.

5 ANALYSIS

We now investigate the question of whether we could have detected a significant population superimposed on the LMC.

Fig. 4 is a diagram similar to the Hess diagram, but shows the Galactic model projected in the radial velocity and colour plane. We normalize the Galactic model using those neighbouring field histograms. Compare this with the distribution of possible Galactic stars in our sample, e.g. the four blue stars with 50 $< v < 150$ km s$^{-1}$. It is difficult for a standard Galactic model to account for the velocity distribution we are observing even for the redder objects in the $0 < v < 150$ km s$^{-1}$ range.

We also test the Galactic model by comparing it with a colour histogram from our plate data in that region in the $16 < R < 20$.
On the other hand, it is very unlikely that the hypothetical (Milky Way) halo white dwarfs account for the lensing in the LMC. Zhao (2002) argues that any violent galactic winds following an early epoch of starbursting would significantly weaken the potential wells of galaxies. The Milky Way galaxy would have been disintegrated if more than half of its dynamical mass were blown off violently in a wind generated by the formation of numerous MACHO progenitors. Since the Milky Way galaxy is very tightly bound, and there is no sign of any globular cluster escaping from the Milky Way either, these should imply an upper limit on the baryons participating in the early starbursts and baryons locked in stellar remnants, such as white dwarfs. The white dwarfs should not make up more than 1–5 per cent of the total mass of the Galaxy. Similar arguments also imply upper limits for the amount of neutron stars and stellar black holes, in galaxy haloes. This dynamical upper limit is exceeded by the amount of halo white dwarfs claimed in recent proper motion searches and in earlier microlensing observations (Alcock et al. 2000) in the Galactic halo, suggesting that these interpretations of observations are problematic theoretically.

We propose that the most likely of the existing models for microlensing in the LMC is perhaps the ‘mutual-lensing’ model of Zhao & Evans (2001), where the LMC stars are on two distinct planes with different inclinations or warped so that stars on the front plane could lens those in the plane ~1 kpc behind. One of the planes may be the LMC disc, and the other may well be the irregular bar of the LMC, which is known to be offset from the LMC disc. Such an unvirialized configuration could only be a transient phase of the general process of merging, after perhaps recent interactions with the SMC and the Milky Way. In this type of model we do not expect the stars in the two planes to share the same rotation around the LMC disc, but the differences in systematic velocities should be small because they share a common potential well. Our data can exclude any systematic offset of \( \geq 70 \text{ km s}^{-1} \) safely, but do not yet exclude the possibility of smaller velocity distortions arising from different inclinations in the LMC. A larger sample with more accurate velocity would be needed to reveal small differences among disc or bar stars of the LMC, and set stronger limits on star–star lensing in the LMC.

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The LMC disc is known to have a poorly defined inclination observationally, and is perhaps warped (e.g. Olsen & Salyk 2002).

Figure 7. From top to bottom colour histograms for UKST fields nos 54, 56 and 58. Field no 58 is toward the Galactic plane at approximately \((l, b) = (281^{\circ}, -25^{\circ})\) and no 54 at \((286^{\circ}, -42^{\circ})\) with \(E(B-V) = 0.11\) and 0.04, respectively. The middle panel is for the reference field no 56, which is roughly centred on the LMC at \((281^{\circ}, -34^{\circ})\) with \(E(B-V) = 0.23\). We used a colour cut that removes the stars in the blue and late M in the red.

18 mag range. With plausible assumptions concerning completeness, Fig. 7 shows the colour histograms in a few UKST fields (nos 54, 56 and 58). Except for the reference field no 56, which is on the LMC, these fields are sufficiently away from the LMC to represent the Galactic distribution in the general direction of the LMC. While there are significant differences between nos 54 and 58, the overall distribution resembles the prediction from our Galaxy model (cf. Fig. 5), i.e. most of Galactic stars in the LMC direction have a largely bimodal colour distribution peaked around \(B_1 - R = 1.25\) \((B - V) = 1\) and 1.5. Our Galaxy model, albeit simple, should not significantly bias our conclusion.

6 CONCLUSIONS

If the microlensing in the LMC is indeed caused by self-lensing, then kinematic outliers are expected towards the LMC in their distributions of radial velocity, proper motion, projected distance from the centre of the LMC, distance modulus and reddening (Zhao 1999a,b). The lack of features in our radial velocity sample argues tentatively for a relatively smooth and uniform distribution of stars in the LMC with very few outliers. Our data does not support the notion that there is a large fluffy stellar halo around the LMC (e.g. Evans & Kerins 2000).

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