Microlensing in the Small Magellanic Cloud: lessons from an $N$-body simulation

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Abstract

We analyse an $N$-body simulation of the Small Magellanic Cloud (SMC), that of Gardiner & Noguchi (1996) to determine its microlensing statistics. We find that the optical depth due to self-lensing in the simulation is low, $0.4 \times 10^{-7}$, but still consistent (at the 90% level) with that observed by the EROS and MACHO collaborations. This low optical depth is due to the relatively small line of sight thickness of the SMC produced in the simulation. The proper motions and time scales of the simulation are consistent with those observed assuming a standard mass function for stars in the SMC. The time scale distribution from the standard mass function generates a significant fraction of short time scale events: future self-lensing events towards the SMC may have the same time scales as events observed towards the Large Magellanic Cloud (LMC). Although some debris was stripped from the SMC during its collision with the LMC about 2 $\times$ $10^8$ yr ago, the optical depth of the LMC due to this debris is low, a few $\times 10^{-9}$, and thus cannot explain the measured optical depth towards the LMC.

1 Introduction

At the present time, the greatest mystery posed by microlensing is the cause of the lensing events towards the Large Magellanic Cloud (LMC). One of the original motivations for microlensing experiments was the search for halo dark matter constituents such as brown dwarfs. Based on the 6-8 events recorded during the first two years of their search, the MACHO group determined that if these events were caused by an intervening halo lensing population, this population would account for a good fraction of the mass of the halo. However, they also concluded that the mass of the lenses was greater than 0.1 $M_\odot$, ruling out a brown dwarf candidate (Alcock et al. 1997a). White dwarfs and other stellar remnants have been eliminated by a closed box model of halo chemical evolution (Gibson & Mould 1997) and through a more general model of cosmological chemical evolution (Fields, Freese & Graff 1998). Currently, there is no really viable candidate for a halo lensing population for the LMC.

A great limitation of using the LMC to probe the Galactic halo for microlensing events is that it only samples a single line of sight. In response, there have been attempts to look for halo microlensing along two other lines of sight, towards M31 (Crotts & Tomaney 1996; Ansari et al. 1997) and towards the Small Magellanic Cloud (SMC). Indeed, two events have so far been detected towards the SMC.

Both of these events proved to be different from the ensemble of other events observed towards the LMC. The first event, MACHO-97-SMC-1 (Alcock et al. 1997c, Palanque-Delabrouille et al. 1998) had a time scale of 120 days, much longer than those of the events seen towards the LMC. An event of such long duration should show a measurable parallax deviation from the standard light curve due to the circular motion of the earth around the sun, unless the mass of the lens is very large or the lens is in the SMC. The lack of a parallax deviation enabled the EROS group to show that this event is likely due to a lens within the SMC, although it may be due to a high mass lens in the halo. (Palanque-Delabrouille et al. 1998). The long time scale of this event also suggested that the lens was drawn from a different distribution from that of the LMC lenses.

The second observed SMC event, MACHO-98-SMC-1, was also unique. It was alerted by the MACHO group to be a caustic crossing event caused by a binary lens (Becker et al. 1998, Alcock et al. 1998). A caustic crossing allows an actual resolution of the spatial structure of the source star. Detailed observations every few minutes by the EROS collaboration (which observed the end of the caustic crossing) (Afonso et al. 1998) and by the PLANET collaboration (which observed the peak of the caustic crossing) (Albrow et al. 1999) and further photometry by MACHO/GMAN (Alcock et al. 1998) and by OGLE (Udalski et al. 1998) allowed all the collaborations to place limits or solve for the proper motion of the lens. For this paper, we will adopt PLANET model 1 with a proper motion of the lens with respect to the source of 1.26 km s$^{-1}$ kpc$^{-1}$, which gives the best fit to all the data (A. Gould, private communication). This proper motion is (as we will confirm) consistent with the lens being in the SMC: it is an order of magnitude smaller than the proper motion expected for a lens in the Galactic halo.

To sum up, while the SMC has been tapped as an alternative probe of the Galactic halo, both of the microlensing events observed so far towards the SMC are most likely due to lenses inside the SMC.

There have been no precise theoretical predictions of the microlensing statistics of the SMC be-
cause its structure is poorly understood. The SMC is known to be far from virial equilibrium (Staveley-Smith et al. 1997), having suffered from a recent encounter with the LMC as well as tidal stress from the Milky Way (Murai & Fujimoto 1980; Gardiner, Sawa & Fujimoto 1994). One can measure the stellar density in the plane of the sky, but there is no accepted three dimensional model for the distribution of stars in the SMC (Westerlund 1997). Mathewson, Ford & Visvanathan (1986) examined Cepheids in the SMC and found a total depth of 32 kpc. Caldwell & Coulson (1986) find a total depth for Cepheids in the SMC of 20 kpc, based on an inclined plane model. However, for microlensing, what is important is the line of sight dispersion in distance about that plane: Caldwell & Coulson (1986) find a dispersion about the plane of $0.10 - 0.13$ mag. Welch et al. (1987) find an rms thickness of 0.12 mag corresponding to a total width ($4\sigma$) of 13 kpc. Welch et al. (1987) suggest that the Mathewson, Ford and Visvanathan (1986) data suffered from additional unaccounted scatter in part because of poor phase coverage in their sample: many of the Cepheids were only observed during luminosity minima.

Since so little is known about the line of sight structure and transverse velocity distribution of the SMC, previous attempts to determine the microlensing statistics have relied on simple models of the SMC. Palanque-Delabrouille et al. (1998) assumed a double exponential SMC and considered a range of line of sight scale lengths to derive an optical depth of $1.0 - 1.8 \times 10^{-7}$. Sahu & Sahu (1998) examined a few simple models of the SMC, with a total line of sight width of $\sim 5$ kpc to derive an optical depth of $0.5 - 2.5 \times 10^{-7}$. Since there is no measurement of the transverse velocity distribution in the SMC, Palanque-Delabrouille et al. (1998), Albrow et al. (1999) and Sahu & Sahu (1998) assumed that the transverse velocity distribution should approximately resemble the line of sight distribution. However, as the SMC is elongated along the line of sight, and possibly consists of several distinct components, this can at best be a rough estimate.

As these models are not accurate in detail, or even in their basic parameters, they could only provide an order of magnitude estimate of the optical depth and time scales of microlensing events. Since there are only two detected events, no greater precision was needed to be consistent with the data. However, several more events would be detected by existing microlensing programs if the present event rate of one per year were to continue, and many more could in principle be detected (Gould 1999). There is still a need to make a more accurate prediction of the microlensing optical depth due to self-lensing in the SMC.

Both the line of sight dispersion and the transverse velocity dispersion of the SMC will strongly affect the number and character of the microlensing events due to self-lensing in the SMC. The optical depth, the probability that a particular star is being lensed, is directly proportional to the line of sight depth of the SMC, while the time scales of the SMC events are in part determined by the transverse velocity dispersions of the SMC. By studying an accurate model of the SMC, we can theoretically predict these quantities. Conversely, comparison of the microlensing statistics generated by a model with the data will provide additional information to constrain the structure of the SMC.

In several respects, the most realistic models of the SMC are the result of computer simulations. Such models can provide complete information on the 3-D structure and kinematics, which is difficult and in some cases impossible to obtain by other means. In this paper, we examine the N-body simulation by Gardiner & Noguchi (1996) (GN). This simulation represents, to date, the only published detailed self-gravitating simulation of the SMC conducted with N-body techniques; previous work (e.g., Murai & Fujimoto 1980) relied exclusively on test particle techniques. This simulation successfully reproduces a central bar of the SMC due to a spontaneous bar instability as well as other features generated as a result of the tidal interaction of the SMC with the LMC (represented by a fixed Plummer potential) and the Galaxy (represented by a fixed logarithmic halo potential). Such tidal features included a Wing of the SMC, an inter-Cloud bridge (both formed as a result of an SMC-LMC encounter $2 \times 10^8$ yr ago) and the Magellanic Stream (originating at the penultimate perigalactic passage of the Magellanic Clouds 1.5 Gyr ago). Regarding the internal structure of the SMC, the model produces large-scale features, namely a central bar and tidally induced spiral arms, which appear to be related to corresponding structures delineated by observations of Cepheids (Caldwell & Coulson 1986). The kinematics of the model correspond to the pattern seen in the velocity–right ascension plane delineated by HI and young stellar objects found by Mathewson et al. (1988), showing conclusively that this pattern is due to a bar structure viewed nearly end-on. On the basis of the successful reproduction of many of the observed characteristics of the SMC, we will conduct a detailed microlensing analysis of the simulation by GN.

In Section 2, we will examine this simulation to derive a map of the microlensing optical depth of the SMC from self-lensing, i.e., lensing of stars in the back of the SMC by stars in the front of the SMC. We will show that the optical depth is concentrated toward the centre of the bar, though some events should still be present towards the Wing. We will show that the GN simulation has a lower optical depth than the most likely value found.
by the EROS and MACHO experiments (Palanque-Delabrouille 1998, Alcock et al. 1998). However, with only one event in the EROS analysis and two in the MACHO analysis, our low optical depth is still consistent with the experiments at the 90% confidence level.

In Section 3, we will calculate the transverse velocities of the lenses with respect to the moving line of sight and use these velocities to calculate proper motions and, assuming a typical lens mass function, the time scales of the lensing events. The time scales and proper motion distribution in the simulation will be shown to be consistent with those observed.

The GN simulation also follows debris from the SMC thrown off by the interaction with the LMC and the Galaxy. In Section 4, we will show that this debris does not explain the observed microlensing optical depth towards the LMC. We conclude by presenting a discussion and summary in Sections 5 and 6.

2 Microlensing Analysis and Optical Depth

2.1 Calculation of the Microlensing Statistics

Our calculations of the microlensing statistics of the SMC are based on the “present day” snapshot of the GN simulation. The simulation is set up so that the SMC is initially represented as a disc galaxy with a halo of equal mass to the disc, and the simulation contains both “disc” and “halo” particles. At the present epoch, the disc and halo particles are somewhat mixed in spatial distribution, and the labels refer only to the initial positions of the particles. Under the assumption that the disc particles are stars and the halo particles are nonlensing dark matter, we define our principal model to be one in which only the disc particles participate in lensing. We also tested a model in which both halo and disc particles participate in lensing, but with one-half of the mass represented by both types of particles considered to be in non-lensing gas and dark matter. The two models gave qualitatively similar results.

We calculate the microlensing statistics of our N-body simulation by generating a statistical ensemble of microlensing “events”. A microlensing event is defined to occur when a lensing object lies within an Einstein radius of the line of sight to a background “source” star. This probability is generally quite low, which is why microlensing searches require observations of tens of millions of source stars to find a handful of events. To boost our statistics, we artificially increase the Einstein radius of our simulation by a boost factor $\sqrt{b}$ which increases the probability that a star will be lensed by a factor $b$. For each source particle in the simulation, we count how many lens particles lie within the boosted Einstein radius. The microlensing optical depth to a particular source particle is then just the number of lenses in front of that particle divided by the boost factor, $\tau = N/b$. All the microlensing statistics discussed below were extracted from this ensemble of events.

![Optical Depth (x 10^8)](image)

Figure 1: The optical depth as a function of position in the SMC. Isolated spikes are due to discrete particles.

2.2 SMC Optical Depth

A map of the optical depth of the SMC calculated for the simulation can be found in Fig. 1. The optical depth in the centre of the SMC is relatively high, with a peak of $1.6 \times 10^{-7}$, of the same order as that measured by the microlensing experiments.

As can be readily seen in Fig. 1, the optical depth of the SMC is not constant: it is highest in the centre of the bar and falls off towards the wings. Comparison with the projected mass surface density of our simulation shown in Fig. 2 shows that in the centre of the bar, the optical depth is roughly proportional to the projected mass density. Towards the edges of the bar, there are some regions with a relatively high optical depth where there is low mass density; these regions are due to the “wing” of material thrown tens of kpc behind the SMC by the most recent collision with the LMC. Isolated peaks in the optical depth in this region are due to individual particles in the wing lying well behind the SMC. Particle distribution plots showing the wing
and bar can be found in GN.

However, the microlensing groups do not measure the peak optical depth of the SMC. They report a single number which is an average optical depth over that portion of the SMC that is observed in their fields. In addition, different regions are weighted according to the local density of source stars in the reference images of the microlensing surveys, a complex function of the surface brightness, exposure time, and seeing of the individual experiments. The experimental optical depth will thus be

$$\tau = \frac{1}{N^*} \sum_{\text{resolved stars}} \tau_i$$

(1)

where \(\tau_i\) is the optical depth of star \(i\) and \(N^*\) is the total number of resolved stars in the experiment. There is an additional complication due to blending, which is more severe in the inner regions than the outer ones; however, Monte-Carlo simulations suggest that this should be at most a 20% effect (Palanque-Delabrouille 1997).

The optical depth parameter was originally designed to measure the rate of microlensing due to a foreground Galactic halo population, and was thought to be a slowly changing function of position. In that case, the derived optical depth would be relatively independent of the averaging, and all experiments should arrive at the same number. However, as can be seen in Fig.1, this is not the case: the SMC self-lensing optical depth rises rapidly to its peak value roughly as fast as the luminosity density of the SMC rises. Thus, it is possible that different experiments averaging over different fields will report discrepant values of the optical depth.

For example, the MACHO experiment has equal exposure times for all its fields. In comparison, the EROS experiment covers a wider projected area of the SMC, and has longer exposures and larger numbers of resolved stars in the outer fields. Thus, the EROS experiment places more weight on the outer fields with low optical depth than the MACHO experiment. We expect the EROS experiment to report a lower average optical depth for SMC self-lensing.

As an example of an experimental optical depth calculation from the GN simulation, we will determine the mean optical depth that would be reported by the EROS experiment with which one of us (DG) has worked. The source densities in the EROS fields can be found in Palanque-Delabrouille (1997). We reproduce the number of sources in each CCD in Fig.3. We then approximate equation (1) as an average over the individual CCDs in the EROS CCD array:

$$\tau \approx \frac{\sum_{\text{all CCDs}} N^*_\text{CCD} \tau_{\text{CCD}}}{\sum_{\text{all CCDs}} N^*_\text{CCD}}$$

(2)

Figure 2: The luminosity density of the SMC from the simulation, assuming a stellar mass-to-light ratio of 3. Compare with de Vaucouleurs (1957).

Figure 3: The number of source stars in thousands in each CCD in the EROS 2 experiment, from Palanque-Delabrouille (1997). Each CCD is 0.35° on a side.
to get $\tau = 0.4 \times 10^{-7}$.

If we assume that the density of source stars is equal to the density of lens stars, we get $\tau = 0.5 \times 10^{-7}$.

3 Proper Motions and Time Scales

Figure 4: Distribution of proper motions of the microlensing events in the simulation. The circle marks solution 1 for the proper motion of MACHO-98-SMC-1 from Albrow et al. (1999).

The proper motions of our ensemble of SMC events are shown in Fig. 4. The typical event in the simulation has a proper motion of $\sim 1$ km/sec/kpc. Also shown is the proper motion of the second SMC event. As can be seen from this figure, the simulation is easily consistent with the solution for the sole event with an accurately measured proper motion under the assumption that the lens is in the SMC.

We calculated the distribution of microlensing time scales (Einstein radius crossing times) by assuming that the lenses have a flat mass function, $dN/d\log M = \text{const}$ between the cut off masses of $0.09 M_\odot$ and $1 M_\odot$. In this distribution, the average mass of a lens is $0.35 M_\odot$. We find that the mean Einstein radius crossing time is 100 days while the median time scale is 78 days (see Fig. 5).

Figure 5: Distribution of Einstein radius crossing times of the microlensing events in the simulation assuming that the lenses have a flat mass function, $dN/d\log M = \text{const}$ between the cut off masses of $0.09 M_\odot$ and $1 M_\odot$. The open circle marks solution 1 for the proper motion of MACHO-98-SMC-1 from Albrow et al. (1999). The closed circle is for MACHO-97-SMC-1 from Palanque-Delabrouille et al. (1998). The crosses are the LMC events from Alcock et al. (1997a).

Of course, the mass function of the ordinary stellar population of the SMC is very poorly known, especially at the lower end. We tried an alternative mass function, $dN/d\log M = m^{-1}$ between the cutoff masses of $0.01 M_\odot$ and $1 M_\odot$. Note that half of the stellar mass due to this mass function is in brown dwarfs. For this model, the mean Einstein radius crossing time is 50 days while the median time scale is 30 days.

The long time scales measured in the SMC suggest that the mass function of the SMC is weighted towards stars of mass $0.3 M_\odot$, and is not dominated by brown dwarfs.

4 LMC Optical Depth

Zhao (1998) has proposed that debris lying in a tidal tail stripped from an ancient Magellanic progenitor galaxy by the Milky Way may explain the observed microlensing rate towards the LMC. Within this general framework, he suggests that the debris thrown off by the SMC-LMC tidal interaction
could also lead to a high optical depth for the LMC. There have been several observational attempts to search for this debris. Zaritsky & Lin (1997) report a possible detection of such debris in observations of red clump stars, but the results of further variable star searches by the MACHO group (Alcock et al. 1997b), and examination of the surface brightness contours of the LMC (Gould 1998) showed that there is no evidence for such a population. A stellar evolutionary explanation for the observations of Zaritsky & Lin (1997) was proposed by Beaulieu & Sackett (1998). However, possible evidence for debris within a few kpc of the LMC along the line of sight is reported by the SMC debris to give rise to a high optical depth for the LMC. But not enough to explain the observed microlensing events. The average optical depth of the LMC due to this background debris is only of order a few × 10^{-9}, two orders of magnitude below that observed. Even though the optical depth of the individual stars in the background debris may be high due to the foreground LMC, the observed optical depth will be low since the vast majority of observed stars will be in the foreground LMC, not in the background debris. Nor is this a matter of bad luck in the placement of the LMC with respect to the distribution of LMC debris in the simulation. Nowhere outside the SMC does the optical depth due to SMC debris rise above a ∼ few × 10^{-9}, orders of magnitude below that observed by the MACHO group. It seems unlikely, based on the GN simulation, that the SMC could have produced enough debris to give rise to a high optical depth for the LMC.

5 Discussion

5.1 Comparison with other results

The optical depth that we derive for the SMC, 0.4 × 10^{-7}, is much lower than the optical depths derived in the simple models of Palanque-Delabrouille et al. (1998) of 1.0 – 1.8 × 10^{-7} and Sahu & Sahu (1998) of 0.5 – 2.5 × 10^{-7}. We will examine their assumptions and show why their optical depths are larger than ours. The discrepancy arises because the SMC in the GN simulation has a lower line of sight distance dispersion than was assumed by Palanque-Delabrouille et al. (1998) and by Sahu & Sahu (1998).

Palanque-Delabrouille et al. (1998) assume that the density of source stars follows the density of light whereas in fact it is actually roughly constant. This is not a bad approximation however, and they only overestimate the optical depth by a factor of 1.3. We caution that if the EROS fields had been larger, the discrepancy would have been greater.

Sahu & Sahu (1998) derive an average mass density by dividing a fiducial value of the total mass of the SMC of 2 × 10^{9} M_{\odot} by a fiducial total area of 15 kpc^{2} to obtain a mass density of 133 M_{\odot}/pc^{2}. The use of an average mass density is appropriate in the limit that the source density is constant. This is roughly true for the EROS fields which had longer exposures for the outer fields (see Fig. 3), but is likely to be false for the MACHO fields which had constant exposures. In fact, given that the EROS source stars have roughly uniform density, the average mass density should be computed by dividing the mass within the EROS fields by the area of those fields. The EROS fields cover an area of about 10 kpc^{2} and a total mass of about 1 × 10^{9} M_{\odot} (Palanque-Delabrouille et al. 1998) so these estimates are not far off, yielding a total surface density of ∼ 100 M_{\odot}/pc^{2}, close to the values derived by Sahu & Sahu (1998).

Figure 6: Distribution of distances to particles in a small section of the SMC. Compare with Fig. 9 in GN. Even though the SMC has a large spatial extent in the simulation, the extent is due to the large tilt of the SMC plane with respect to the sky plane; nevertheless the particles are narrowly distributed about a two dimensional distribution.

We find that the core of the SMC bar in the GN simulation, where most of the microlensing takes place in the simulation, is actually rather narrow, with a line of sight rms dispersion of only 1 kpc (see Fig. 1). Sahu & Sahu (1998) and Palanque-Delabrouille et al. (1998) assume larger dispersions based on the Cepheid observations of Caldwell & Coulson (1986) and Mathewson, Ford & Visvanathan (1986). The discrepancy between the sim-
ulation and the Cepheid observations was discussed by GN who suggested that, being a young population, Cepheids may be influenced by gas-dynamics not present in the strictly N-body simulation. However, since there is no reason to believe that the lenses in the SMC are due to a particularly young population, they may in fact be better represented by the N-body particles of the simulation than by the (young) Cepheid population.

However, measuring the thickness of a Cepheid population is quite difficult (Welch et al. 1987). Caldwell & Coulson (1986) noted that their Cepheids were distributed along a plane inclined with respect to the sky plane; they are not all at the same distance, but neither are they in a thick distribution liable to generate microlensing. Graff et al. (in preparation), in an analysis of the EROS 2 Cepheid database, suggest that the extra dispersion in Cepheid magnitudes in the SMC may be due to a larger intrinsic dispersion for Cepheids in the SMC compared to the LMC (which had been used as a standard), or perhaps to larger differential reddening. The Cepheid samples may be heavily influenced by Cepheids in the Wing of the SMC. Although the Wing does indeed have a large line of sight distance dispersion, it is not substantial enough in the simulation to contribute strongly to the microlensing rate.

Our optical depth calculation of $0.4 \times 10^{-7}$ is nearly an order of magnitude lower than that calculated (from only 1 event, MACHO-97-SMC-1) by the EROS experiment of $3.3 \times 10^{-7}$ (Palanque-Delabrouille et al. 1998) and is also lower than the first order estimate by the MACHO collaboration of $2 - 3 \times 10^{-7}$ based on both events (Alcock et al. 1998). Since these optical depth calculations are based on only a few events, the discrepancy is at most marginally significant. The 90% lower limit on the EROS optical depth is only $0.35 \times 10^{-7}$; the corresponding MACHO value is $\sim 0.5 \times 10^{-7}$.

If, however, several more SMC events are detected, thereby confirming that the optical depth is larger than $\sim 0.4 \times 10^{-7}$, then we will have learned that the GN model contains deficiencies in its representation of the SMC. Either the bar is actually thicker than in the GN simulation, or the Wing is more substantial.

The length of the initial bar used in the simulation was about 8 kpc; if the bar had maintained its original configuration to the present day, it could be more highly inclined to the sky plane while preserving its projected dimensions, thereby giving a greater thickness along an individual line of sight. A more extended bar could be realized if the encounter between the Magellanic Clouds a few 10$^8$ yr ago was a less disruptive one. A lower mass for the LMC, a higher mass for the SMC, and greater separation between the Magellanic Clouds at closest approach would all serve to reduce the strength of tidal forces disrupting the edges of the bar. Another possibility to consider is that intense star formation occurred in the spiral arms generated by the tidal interaction, contributing to the optical depth towards the SMC centre. A hydrodynamical simulation which includes star formation would be needed to investigate this possibility.

5.2 Nature of the Lensing Population

The EROS group has suggested that measurements of microlensing in the SMC could be interpreted as showing that there is no foreground halo population of lenses (Afonso et al. 1998). They predicted that future SMC events would continue to have long time scales as observed in the first SMC event. In that case, since SMC events would have different time scales from those observed in the LMC, they could not be due to the same foreground halo population.

Our simulation suggests that the situation will not be so clear. As seen in Fig[4], the predicted range of time scales from a realistic velocity dispersion and a realistic mass function is broad enough to encompass short time scale events such as those found in the LMC (marked as crosses). Thus, some of the subsequent SMC events should have the short time scales seen towards the LMC. We expect that several SMC events will be needed before one can conclusively say that events towards the two galaxies come from different distributions.

This result is not specific to our simulation; any reasonably broad mass function and transverse velocity distribution should give rise to an equally broad distribution of Einstein radius crossing times.

In addition, if our low estimate of the optical depth of the SMC is correct, then current experiments will not provide a large enough sample of future events to analyze in this manner.

The GN simulation does not lend support to Zhao’s (1998) suggestion that tidal debris from the most recent collision of the SMC and the LMC could be responsible for the LMC microlensing events. Nevertheless, Kunkel et al. (1997) have suggested that repeated encounters between the SMC and the LMC could form a polar ring around the LMC; it is feasible that such a structure might be responsible for microlensing. Thus, a simulation with an earlier staring epoch (the GN simulation only considers the two most recent SMC-LMC encounters) might slowly build up debris bound to the LMC. Exploratory simulations that we have performed with up to four previous encounters do not support this hypothesis; any nascent ring structure tends to be disrupted by tidal interactions with the Milky Way. However, it is conceivable that the GN simulation may not accurately track the past history of the SMC-LMC interaction, and that a different orbital configuration may reproduce a large enough cloud of debris along the line of sight to the LMC to generate microlensing.
5.3 The Future

If we are correct in claiming that the self-lensing optical depth towards the SMC is low, then in the near future, present generation experiments will not detect a large number of self-lensing events. If there is a foreground Galactic halo population of lenses, then these lenses will be detected in significant numbers, and will tend to have the short time scales seen in the LMC events.

However, if we are incorrect, i.e., the optical depth towards the SMC is high, then there will be a large background of SMC self-lensing events. A good fraction of these events will have the short time scales seen in the LMC events, and will be indistinguishable from a putative population of foreground halo lenses.

Ultimately, improved observations (Stubbs 1998) may be necessary to resolve the question of the nature of lensing events in the Magellanic Clouds. Better seeing and larger telescopes will allow the detection of many more events. Better photometry will allow the detection of small changes in the shape of the microlensing light curve which will provide further information on the location of the lenses.

6 Summary

The GN model of the SMC is consistent with the hypothesis that the two microlensing events observed towards the SMC are due to self-lensing. The time scales and proper motions in the model are consistent with those observed towards the SMC. The optical depth in the model, $0.4 \times 10^{-7}$, is much lower than the most likely value suggested by the experiments, but still consistent at the 90% confidence level owing to the paucity of events. This low optical depth is due to the low line of sight thickness of the model. The GN simulation does not explain the observed microlensing towards the LMC. Nowhere in the simulation outside the SMC is the debris dense enough to generate a large optical depth. Tidal debris from the most recent SMC-LMC collision is unlikely to account for the LMC optical depth.

Owing to the low SMC optical depth, suggesting that the number of future events will be low, and the breadth of the time scale distribution, which suggests a high probability that at least some of these future events will have the same time scales as the LMC events, present generation experiments alone are unlikely to resolve the question of whether the SMC is lensed by a halo lensing population.
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