Gravitational Microlensing by the MACHOs of the LMC

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Submitted to

The Astrophysical Journal

(Received )

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ABSTRACT

The expected microlensing events of the LMC by the MACHOs of the LMC itself are calculated and compared with analogue events by objects in the Galactic halo. The LMC matter distribution is modelled by a spherical halo and an exponential disk while a face-on exponential disk is used for the stellar distribution of the LMC. Among the microlensing events discovered by the MACHOs and EROS projects, a fraction of 22% could be caused by the lenses near the center of the LMC or 13% from lenses at 5° from the LMC center. Therefore, any statistical study of these microlensing events must take the LMC lenses into account.

Subject headings: gravitational lensing – galaxies: Magellanic Clouds
1. INTRODUCTION

The recent detection of microlensing of stars in the Large Magellanic Cloud (LMC) (Alcock et al., 1993; Aubourg et al., 1993) and in the direction of the Galactic bulge (Udalski et al., 1993) opens a new way to search for unseen matter in the halo and the disk of our Galaxy. Indeed, these discoveries show that it has become possible nowadays to use microlensing for the determination of mass range of compact objects (MACHOs) in the Galaxy. The above three experiments are still underway and a statistically significant sample of microlensing events in both the LMC and the Galactic bulge will hopefully be available in a few years.

It was realised a long time ago that nonstellar objects within the Galaxy can act as gravitational lenses (Liebes, 1964). However, the observational detection of these nonstellar population (MACHOs) in the massive halo of our Galaxy using the gravitational lensing effect had remained impossible until recent years when Paczyński (1986) proposed to monitor the brightness of several million stars in the LMC, as the gravitational effects of the MACHOs can temporarily magnify the light from stars of LMC. Griest (1991) further developed this idea by adopting a more realistic mass distribution model for the MACHOs of the Galactic halo. These two recent important papers have led people to believe that the three microlensing events detected in the LMC are due to the MACHOs in the halo of our Galaxy.

However, the contribution of unseen matter in the LMC itself, possibly in the form of the MACHOs, to the microlensing events has not been taken into account in the determination of mass for the MACHOs by the MACHO Project and the EROS collaboration, mainly because this effect is believed to be relatively small and can then be negligible. Gould (1993) has very recently considered the gravitational microlensing effect of MACHOs of the LMC halo and found that the LMC halo may lead to a variation of the optical depth to lensing as a function of sky position. However, it is unlikely that one can actually see such a variation without considering the distribution of stellar population of the LMC. Unlike the one by the Galactic halo, the optical depth to microlensing by the
LMC halo/disk increases dramatically along the line of sight passing through the LMC disk. Therefore, the expected microlensing events by the LMC cannot be estimated simply by multiplying the optical depth by the total number of stars of the LMC as for the case of the Galactic halo (Paczyński, 1986). In fact, the optical depth to lensing by the LMC halo/disk cannot provide valuable information about the fraction of microlensing events produced by the LMC in the experiments, and it has remained very unclear today how large the contribution of the LMC halo and/or disk is to the detected events in the LMC.

In light of the upcoming statistical study of microlensing and its significance for searches of dark matter in modern astrophysics, this paper presents calculations of the fraction of the expected microlensing events from the MACHOs of the halo/disk of the LMC by taking into account the distribution of stellar population of the LMC modelled by a face-on exponential disk. A direct comparison of microlensing contributions from the halo of our Galaxy and from the halo/disk of the LMC will be given.
2. OPTICAL DEPTH TO LENSING

2.1 Halo Model

A rotational analysis of various populations of the LMC (HI, planetary nebulae, clusters, LPVs, etc.) (Rohlfs et al., 1984; Meatheringham et al., 1988; Hughes et al., 1991; Schommer et al., 1992; etc.) indicates that the LMC rotation curve exhibits both solid body (out to \( \sim 2^\circ \)) and flat rotation (to \( 8^\circ – 15^\circ \)) components. To fit this rotation curve and also to simplify the calculation, a spherical isothermal halo with a definite core radius \( (r_c) \) is assumed for the LMC:

\[
\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2},
\]

Because such a halo extends to infinity and the mass diverges, it is necessary to truncate the halo at some radius \( R \) so that the total mass within \( R \) is

\[
M(R) = 4\pi \rho_0 r_c^3 \left( \frac{R}{r_c} - \arctan \frac{R}{r_c} \right),
\]

and the rotation velocity is

\[
v(R) = \left[ \frac{4\pi G \rho_0 r_c^3}{R} \left( \frac{R}{r_c} - \arctan \frac{R}{r_c} \right) \right]^{1/2}.
\]

The lensing cross-section by a pointlike mass \( (m) \) is simply

\[
\pi a_c^2 = \frac{4\pi G m}{c^2} \frac{D_dD_{ds}}{D_s},
\]

where \( a_c \) is the critical radius (the “Einstein radius”), and the other parameters have their usual meanings. The optical depth to microlensing is the probability of finding a source within \( a_c \), the microlensing tube. Assuming that the MACHOs in the LMC follow the distribution of eq.(1), one has the total optical depth

\[
\tau = \tau_0 \int_{x_h}^{x_s} \frac{x(x_s - x)dx}{x_s(1 + x_c^2 - 2x \cos \beta + x^2)}.
\]

Here

\[
\tau_0 = \left( \frac{v}{c} \right)^2 \frac{1}{1 - \frac{r_c}{R} \arctan \frac{R}{r_c}}
\]
and $\beta$ is the angle between the line of sight to the center and to the source (star) of the LMC. All distances are measured in unit of $D_c$, the distance to the center of the LMC, which is 50.6 kpc (McCall, 1993). The radius of the LMC ($x_R = R/D_c$) and the distance to the source ($x_s = D_s/D_c$) define the "edge" of the LMC halo at the direction of $\beta$,

$$x_h = \cos \beta - \sqrt{x_R^2 - \sin^2 \beta}.$$  

Integration of eq.(5) gives

$$\frac{\tau}{\tau_0} = \frac{x_h}{x_s} - 1 + \left(\frac{1}{2} - \frac{\cos \beta}{x_s}\right) \ln \frac{1+x_h^2-2x_s \cos \beta+x_s^2}{1+x_R^2-2x_s \cos \beta+x_s^2} + \frac{1+x_s^2+(x_s-2 \cos \beta) \cos \beta}{x_s \sqrt{x_h^2+\sin^2 \beta}} \left(\arctan \frac{x_s-\cos \beta}{\sqrt{x_h^2+\sin^2 \beta}} - \arctan \frac{x_h-\cos \beta}{\sqrt{x_s^2+\sin^2 \beta}}\right).$$

(8)

The variation of optical depth with the source positions, $D_s$ and $\beta$, is shown in Figure 1 for a halo radius of $15^\circ$ (see Schommer et al, 1992). The rotation velocity has been taken to be 79 km/s. The corresponding result for the MACHOs of the Galactic halo (Paczyński, 1986; Griest, 1991) is also plotted for comparison.

The contribution of the LMC halo to the optical depth depends sharply on the positions of stars in the LMC: The stars within a projected angular distance of $2^\circ$ from the center of the LMC may be significantly affected by the microlensing of foreground MACHOs of the LMC, especially if the stars are behind the disk plane. A larger probability (as high as $10^{-6}$) than the one ($5 \times 10^{-7}$) by the MACHOs in the Galactic halo appears to be possible. For stars in the disk plane but within $2^\circ$ of the center of the LMC, the optical depth is $(1$ to $2) \times 10^{-7}$, making the total optical depth be $(6$ to $7) \times 10^{-7}$ in combination with the value for the halo of our Galaxy. Even for the stars with a projected angular distance of $5^\circ$ from the center but behind the disk, the optical depth could still reach $10^{-7}$.

2.2 Disk Model

The kinematic analysis shows that the dynamics of the LMC are dominated by a single rotating disk. The foreground MACHOs in the disk of the LMC may then affect the background stars. Recall that the LMC is very close to face-on despite the uncertainties
in measurement of the tilt \( i \approx 27^\circ \). Matter distribution of the LMC can be assumed to be an isothermal self-gravitating disk having density

\[
\rho = \rho_0 e^{-R/h} \text{sech}^2\left(\frac{z}{z_0}\right)
\]

with an exponential disk of the scale length \( h \) in the radial direction and an isothermal sheet of the scale height \( z_0 \) in the \( z \)-direction (van der Kruit & Searle, 1981). The central mass density \( \rho_0 \) can be related to the maximum rotational velocity by (Freeman, 1970)

\[
\rho_0 = \frac{1}{4\pi G h z_0} \left(\frac{V_m}{0.62}\right)^2.
\]

For simplicity, the inclination is taken to be \( 0^\circ \), i.e., a face-on distribution of the disk matter. Repeating the procedure of the above calculation by using the matter distribution of eq. (9), one has the total optical depth to microlensing by the LMC disk

\[
\tau = \tau_0 \int_0^{x_s} \frac{x(x_s - x)}{x_s} e^{-x_0^2/2} \text{sech}^2 \left( \frac{1 - x \cos \beta}{(z_0/D_c)} \right) dx,
\]

where

\[
\tau_0 = \left(\frac{V_m}{0.62c}\right)^2 \left(\frac{D_c^2}{h z_0}\right).
\]

The distance parameters, \( x \) and \( x_s \), and the position of the sources, \( D_0 \), and \( \beta \), have the same definitions as in the above section. The numerical results are shown in Figure 2 by choosing \( V_m = 79 \) km/s, \( h = 1.6 \) kpc and \( z_0 = 0.43 \) kpc for the LMC (Freeman, Illingworth & Oemler, 1983; Hughers, Wood & Reid, 1991).

Foreground Stars are nearly unaffected by the microlensing of the MACHOs in the LMC because there are very few intervening lensing objects. However, larger optical depths to microlensing for the stars behind disk are found in the central region of the LMC, resulting mainly from the higher number density of the MACHOs in the disk. A probability as high as \( 10^{-6} \) appears for stars at a distance of \( z = 5 \) kpc behind the central disk. In general, the stars within an angle of \( \sim 3^\circ \) from the center of the LMC and a distance of \( z \sim 4 \) kpc behind the disk would have a probability for microlensing \( \sim 10^{-7} \).
comparable to the one for the MACHOs of the halo of our Galaxy. Except for the sharp
decrease for the foreground stars, the optical depth by the MACHOs in the disk varies
with $D_s$ in a manner similar to that calculated for the MACHOs in the halo of the LMC.
3. EXPECTED MICROLENSING EVENTS

Microlensing experiments of monitoring the brightness of stars of the LMC provide the microlensed stars and their positions, which cannot be related directly to the optical depth to lensing. The totally expected microlensing events can be found by convolving the optical depth with the stellar population of LMC and then integrating along the line of sight.

A disk model similar to eq.(9) can be applied to the distribution of stellar population of the LMC, except that $\rho_o$ cannot be determined by the dynamical analysis of eq.(10). The density of these stellar objects along the line of sight is shown in Figure 3. The expected events per solid angle ($d\Omega$) and per line of sight distance ($dD_s$) in the direction of $\beta$ from the center of the LMC are then

$$\frac{dN}{d\Omega dD_s} = \tau(\beta, D_s)\rho(\beta, D_s)D_s^2$$  \hspace{1cm} (13)

The variations of the expected events with $D_s$ are shown in Figure 4(a) and Figure 4(b) using the optical depth by the LMC halo and the disk, respectively. The result by the Galactic halo is also displayed for comparison, which mainly follows the distribution of stellar population due to its nearly constant probability ($\tau$) at the LMC position (see Figure 1 and Figure 2). Although both the LMC halo and the disk exhibit large optical depths at large distances behind the disk as shown in Figure 1 and Figure 2, the expected events are sharply confined within the disk since very few stars can be found at that large distance behind the disk.

The totally expected events in the LMC per solid angle in the direction of $\beta$ are plotted in Figure 5(a) for the contributions of the Galactic halo, the LMC halo, the LMC disk and the LMC halo + disk, respectively. Moreover, Figure 5(b) illustrates the ratio of the expected events by the LMC to the ones by the Galactic halo. The decrease of the expected events with the angular distance $\beta$ that results from the distribution of stellar population of the LMC is well demonstrated by the curve of the Galactic halo because of its nearly unchanged optical depth at the LMC position. The steeper slopes of the curves for the LMC halo, in particular the LMC disk, are then due to the fewer populations of
the MACHOs with the increase of angular distance $\beta$. This leads to a decrease function of the ratio of $dN_{\text{LMC}}/dN_{\text{Galaxy}}$ with $\beta$.

Define a parameter that describes the fraction of contributions by the LMC in the experiment of searching for the microlensing events of the LMC:

$$q = \frac{N_{\text{LMC}}}{N_{\text{Galaxy}} + N_{\text{LMC}}}.$$  \hspace{1cm} (14)

Figure 6 shows the variation of $q$ against the angular distance $\beta$ by summing the contribution of the LMC halo and that of the disk. It turns out that the LMC is capable of producing 22% to 13% of the totally detected microlensing events from the center to the distance of $\beta = 5^\circ$ of the LMC. This implies that one out the five events to be observed within $\sim 2^\circ$ of the LMC center may be created by the MACHOs of the LMC itself.
4. CONCLUSIONS

The MACHOs of the LMC itself are shown to be able to act as gravitational microlenses for stars of the LMC, responsible for as high as 22% of the microlensing events detected and to be detected in the LMC. Thus, it is necessary to take the LMC microlensing events into account in the statistical study of the recent microlensing experiments (the MACHOs and EROS projects) for monitoring the brightness of stars of the LMC. The expected microlensing events vary with sky position, due to both the distribution of stellar population and the contributions of the MACHOs of the halo/disk of the LMC. It is then argued that the recently reported microlensing events near the center of the LMC should be considered seriously if they all have a Galactic halo origin. The distinction of the events by the LMC itself from the observed ones, though it is difficult, would be of importance for the mass determination of the MACHOs making up the halo of our Galaxy.

The present conclusions are based on a spherical halo and an exponential disk model for matter distribution and a face-on exponential disk model for the distribution of stellar population of the LMC. It would be necessary in the future to have a better estimate of the expected events by adopting a more realistic model involving the tilt of the disk of the LMC although it is unlikely that the small angle of inclination of the LMC disk would significantly change the present conclusion. Nevertheless, the idea of involving the distribution of stellar population of the “target” galaxy suggested in this paper should be also applied to SMC, M31 and M33 for the estimates of their own contributions to the microlensing events to be detected in the future experiments.

ACKNOWLEDGMENTS

I have benefited from my discussion with Alain Bouquet, Yannick Giraud-Héraud, Jean Kaplan and Charling Tao. I am also grateful to Marshall L. McCall and Laurent Nottale for reading the manuscript and for helpful comments, and CNRS and K.C.Wong Foundation for financial support.
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Figure Captions

Figure 1  Variation of the optical depth to microlensing by the MACHOs in the LMC halo with the positions of sources of the LMC: the distance $D_s$ and the angular distance $\beta$ from the center of the LMC. The core radius of the LMC is taken to be $2^\circ$ and the whole size is truncated at the radius of $15^\circ$. The optical depth by MACHOs of the Galactic halo is shown by the dotted line.

Figure 2  The same as in Figure 1 but for the disk model. The dynamical parameters are: $V_m = 79$ km/s; $h = 1.6$ kpc and $z_0 = 0.43$ kpc.

Figure 3  Variation of stellar population of the LMC along the line of sight.

Figure 4  Variations of the expected microlensing events along the line of sight per solid angle and per line of sight distance by the LMC halo (a) and by the LMC disk (b). The contribution of the Galactic halo is plotted as dotted lines.

Figure 5a  The expected microlensing events per solid angle in the direction of $\beta$. The contributions of the Galactic halo, the LMC halo, the LMC disk and the LMC halo + disk are shown.

Figure 5b  The ratios of the expected microlensing events by the LMC (halo, disk and halo+disk) to the ones by the halo of our Galaxy.

Figure 6  The fraction of the microlensing events by the LMC (halo+disk) in the microlensing experiments: $q = N_{\text{LMC}}/(N_{\text{Galaxy}} + N_{\text{LMC}})$. 

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