Stars within the Large Magellanic Cloud as potential lenses for observed microlensing events

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Abstract:

Massive Compact objects in the halo, known as MACHOs, have been postulated as the origin of a substantial fraction of ‘dark matter’ known to exist in the haloes of galaxies\(^1,2\). Paczyński\(^3\) has suggested that it might possible to detect these low-luminosity objects by their potential to act as gravitational lenses, causing a characteristic brightening when they cross the path of light from a star in a nearby galaxy. Very recently, two groups reported possible detections of microlensing of stars in the Large Magellanic Cloud (LMC)\(^4,5\). Here I show that microlensing by stars within the LMC itself can account for the observed events. It is further shown that if stars within the LMC are the lenses, the observed light curve can differ from the light curve due to a galactic lens even at relatively low magnifications. This provides a possibility of distinguishing between the galactic lenses and the LMC lenses. For a given number of monitored stars, the LMC induced events should be strongly concentrated towards the central region of the LMC, while the galactic events should be uniformly spread over the whole area of the LMC, so the two can also be distinguished statistically.

Based on a suggestion by Paczyński\(^3\), two groups involved in the monitoring of a few million stars in the LMC for more than a year, have reported the detection of three microlensing events as evidence for the presence of dark objects in the Galactic halo\(^4,5\). However, this has also been the cause for some concern: if these events are caused by such objects in the halo, it would lead to some problems in terms of stellar evolution and the theory of galaxy formation\(^6\). Recent work on deuterium abundance derived from the observations of a quasar suggests that the dark halos of galaxies may well be nonbaryonic\(^7\). Furthermore, the rate of microlensing events as observed seems to be lower than expected from the dark halo, and it is important to estimate the rate expected from the stars that are known to exist in our galaxy and in the LMC. The analyses for the galactic stars and the LMC halo have been done\(^8,9\), but the importance of the LMC stars has been overlooked so far. This paper presents the estimate of the rate of microlensing events to be expected from the LMC stars acting as gravitational lenses.

To calculate the probability of the microlensing being caused by a star in the LMC itself, we need to know the stellar mass density in the LMC. Let us first confine ourselves to the bar of the LMC. From the surface luminosity, it is estimated that the observed luminosity of the bar is about 10 to 12 % of the total observed luminosity of the LMC in the optical wavelengths\(^10,11\). To calculate the extinction, I have used the IRAS 100 \(\mu m\) maps\(^12,13\), the background galaxy counts\(^14\), and the observations of the most reddened stars in the
region\textsuperscript{15}, which give a consistent value of 1.5 magnitudes in $V$. To see how the extinction affects the mass, let us assume that the extinction is uniform in depth, and let $d$ be the total depth. Thus for any line of sight, if $A_v$ is the total extinction in the line of sight

$$\frac{L_{\text{obs}}}{L_{\text{true}}} = \frac{1}{d} \int_0^d 2.5^{-A_v l/d} dl = \frac{1 - e^{-0.916 A_v}}{0.916 A_v}$$  (1)

Using $A_v$=1.5 magnitudes for the bar, and $A_v$=0.3 to 0.4 magnitudes for the region outside, it is easy to show that the true luminosity of the bar is about 14 to 18% of the total luminosity of the LMC. The total mass of the LMC, as determined from various methods, ranges from $6 \times 10^9$ to $15 \times 10^9$ $M_\odot$.\textsuperscript{16,16} Assuming that the mass to light ratio in the bar and the outer parts are the same, we can take the mass of the bar as $2 \times 10^9$ $M_\odot$. Considering the fact that the LMC is gas poor and only about 5% of the LMC mass is neutral hydrogen\textsuperscript{16–18}, we will neglect the contribution of gas to the mass and assume that the entire mass is made up of stars.

To calculate the probability of microlensing, let us assume that there are $N_{\text{tot}}$ stars being monitored. To see the effect of extinction on the number of monitored stars at various depths, we note that the limiting magnitude of the current surveys are about 20 to 21, which at the distance of the LMC, corresponds to an absolute magnitude of 1.5 to 2.5. So the magnitude of the stars that can be observed at the near side is 1.5 to 2.5 while the limiting magnitude at the far end is 1.5 magnitudes brighter. If the distribution of stars among different spectral types is assumed to be similar to what is observed in the solar neighborhood, then the difference in the monitored number of stars per unit depth from front end to the back is about three\textsuperscript{19}. (As it turns out, the effect of extinction is small. If the extinction is 3 magnitudes instead of 1.5, the net probability decreases only by less than 50%.)

Hence, assuming the extinction to be uniform in depth, we can express the observed number of stars at any layer $dl$, at a depth of $l$, as

$$N_{\text{obs}}(l) = N_l 3^{-\frac{l}{d}} dl$$  (2)

where $N_l$ is the observed number of stars per unit depth in absence of extinction. If $N_{\text{tot}}$ is the total number of stars being monitored, then

$$N_{\text{tot}} = \int_0^d N_l 3^{-\frac{l}{d}} dl = 0.6 N_l d$$  (3)

Substituting eq. 3 in eq. 2, we get

$$N_{\text{obs}}(l) \simeq \frac{N_{\text{tot}}}{0.6d} 3^{-\frac{l}{d}} dl$$  (4)
The fraction of area covered by the Einstein rings af all the individual stars lying in the front of this layer can be expressed as

$$A_f(l) = \int_0^l \pi R_E^2(l)n(l)dl$$  \hspace{1cm} (5)$$

where $n(l)$ is the stellar number density at depth $l$ and $R_E$ is the Einstein radius. Note that $n = \rho/m$ and $R_E^2 \propto m$ where $\rho$ is the stellar mass density and $m$ is the mass of the star. Thus, assuming the stellar density to be uniform with depth

$$A_f(l) = \frac{2\pi G \rho l^2}{c^2}$$  \hspace{1cm} (6)$$

which is thus independent of the mass distribution. From Eq. 4 and 6, the optical depth to microlensing by stars within the bar can be expressed as

$$\tau_{bar} = \frac{1}{N_{tot}} \int_0^d N_{obs}(l)A_f(l)dl \simeq \frac{0.5\pi G \rho_{bar} d^2}{c^2}$$  \hspace{1cm} (7)$$

For the value of $\rho$, we can substitute,

$$\rho_{bar} = \frac{M}{LWd}$$  \hspace{1cm} (8)$$

where $L$, $W$, $d$ and $M$ are the length, width, depth and mass of the bar respectively. Assuming $L=3000pc$ and $W=d=600pc^{10,20,21}$, and substituting eq.8 in eq.7, we get,

$$\tau_{bar} \simeq 5 \times 10^{-8},$$  \hspace{1cm} (9)$$

with some uncertainties due to the uncertainties in the size and mass of the bar. Carrying out an identical analysis for the region outside the bar it is easy to see that, if the depth of the LMC disk is between 100 to 300pc$^{22}$, the optical depth in the region outside the bar is about 4 to 12 times smaller.

The MACHO event lies in the central region of the bar. Keeping in mind the uncertainties involved in the estimation of optical depth on the basis of a single event$^{8,23}$, we can only say that it seems to be well below the optical depth of $5 \times 10^{-7}$ expected from a dark halo made up entirely of MACHOs, and is consistent with the optical depth calculated above. In the case of EROS events, one lies in the outer region of the bar, the other is far from the bar, and the optical depth has been estimated to be higher ($\sim 2 \times 10^{-7}$, Ref. 8). But Gould et al.$^8$ also suggest that there may be some systematic effects and the detection efficiencies may be uncertain. The situation will be clearer as more events are observed, particularly events with higher magnifications (see below), and we must wait
for more events to be observed before making any direct comparison with the calculated optical depth.

If the microlensing is indeed caused by the LMC lenses, then one important consequence is that the sources can be resolved at much smaller magnifications. Let us see how.

The amplification sharply rises when the lensing object comes close to being perfectly aligned with the source. The physical reason for this is that when the lensing object and the source are perfectly aligned, the image becomes a ring (also called the Einstein ring) instead of two separate images. [For details, see ref. 3]. In the case of lensing by MACHOs, $R_E$ is of the order of $1.2 \times 10^{14} \sqrt{\frac{M}{M_\odot}}$ cm, which, at the source plane, is $\sim 10^{15} \sqrt{\frac{M}{M_\odot}}$ cm. If the lensing is caused by the objects in the disk of our galaxy, $R_E$ projected onto the source plane is $> 10^{15} \sqrt{\frac{M}{M_\odot}}$. But if the lens is in the LMC, for a typical distance $D$ of about 100pc between the source and the lens, $R_E \simeq 10^{13} \sqrt{\frac{M}{M_\odot}}$ cm, which is at least 2 orders of magnitude smaller. As an example, let us consider the source to be a red giant, and a 0.5 $M_\odot$ lens. In order that at least a part of the source is perfectly aligned with the lensing object in this case, the impact parameter $u$ has to be $\lesssim 0.001$ (i.e. magnification $\gtrsim 1000$) for a halo or disk lens whereas it has to be $\lesssim 0.1$ (i.e. magnification $\gtrsim 10$) for an LMC lens, which will make the light curve different from that of a point source$^{24-26}$. Considering the fact that the events are expected to be uniformly distributed in $u$, this provides a possibility to distinguish between the halo lenses and the LMC lenses as more events are observed.

As is clear from the optical depth estimates, for a given number of monitored stars, the LMC induced events should be strongly concentrated towards the central region of the LMC, while the galactic events (whether by disk or halo lenses) should be uniformly spread over the whole area of the LMC. So the two can be distinguished statistically in most cases and, as described earlier, individually in some cases from the light curves.

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