Expected EAGLE Event Rate towards the Magellanic Clouds

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We propose to search for MACHOs by observing EAGLE (Extremely Amplified Gravitational Lensing) events of a majority of dim stars. This search is independent of the usual one. For the detection limit of EAGLE ($\sim 20$ mag), $\sim 100 f (\tau_{\text{LMC}}/3 \times 10^{-7}) (100 \text{ days}/\langle \ell \rangle)$ EAGLE events/y are expected to result from all the dim stars in LMC. Here $\tau_{\text{LMC}}$ and $\langle \ell \rangle$ are the optical depth and the average duration of microlensing events, respectively, while $f$ ($0 < f < 1$) is a parameter depending on the unknown stellar luminosity function. The observed mean duration of EAGLE events also depends on the luminosity function and is $0.01 \sim 0.4$ times the usual duration of microlensing events, which corresponds to $1 \sim 30$ days. The follow-up observation using larger telescopes may enable us to determine the impact parameter and the true duration of the event. If $f$ is determined by another independent method, we can also determine $\tau_{\text{LMC}}$. Even if $f$ is undetermined, the detection of EAGLE events strongly suggest that MACHOs are not due to variable source stars, since EAGLE events are due to the dim main-sequence stars. Although for the SMC, the event rate is smaller by a factor of $\sim 7$, it is still a substantial number ($\sim 13 f (\tau_{\text{SMC}}/3 \times 10^{-7}) (100 \text{ days}/\langle \ell \rangle)$ events/y).

§1. Introduction

The analysis of the first 2.1 years of photometry of 8.5 million stars in the Large Magellanic Cloud (LMC) by the MACHO collaboration suggests that the optical depth $\tau_{\text{LMC}}$ is $2.9^{+1.4}_{-0.6} \times 10^{-7}$ and the mass of MACHOs is $0.5^{+0.3}_{-0.2}M_\odot$ in the standard spherical flat rotation halo model. At present, however, we do not know where MACHOs are, what the fraction of MACHOs in the halo is, and what MACHOs are. The basic reason why we do not know the locations and the fraction of MACHOs is that the spatial distribution function of MACHOs is not known in spite of many arguments concerning the mass distribution of halo dark matter. What we can say from the present observations is that the minimum total mass of MACHOs is $5.6 \times 10^{10}M_\odot \tau_{\text{LMC}}/2 \times 10^{-7}11$ if the density distribution of MACHOs is spherical and a decreasing function of the galactocentric radius. This means that the fraction of MACHOs up to the LMC is at least 10 %.

The estimated mass of MACHOs is just the mass of red dwarfs. However, the contribution of the halo red dwarfs to MACHO events should be small, since the observed density of the halo red dwarfs is too low. As for the white dwarf MACHOs, the mass fraction of white dwarfs in the halo is less than 10 %, since the existence of too many white dwarfs with bright progenitors is in conflict with the number counts of distant galaxies. At present we should consider the possibility that MACHOs may be black holes or boson stars, although their origin of existence is completely unknown.
In this situation the first urgent matter we must consider is increasing the statistics of MACHO events along the LMC to confirm the optical depth, since the total mass of MACHOs becomes smaller than $5 \times 10^{10} M_\odot$ (i.e. $\sim 10\%$ of the mass of the halo inside the LMC) only if the density distribution of MACHOs is unusual or $\tau_{\text{LMC}} \ll 2 \times 10^{-7}$. An independent observation which can confirm the existence of MACHOs and determine the optical depth is also desirable, since MACHO candidates may be variable stars after the follow-up observation. In reality, the EROS 2 event proved to be a variable star.

Secondly, from the determination of the optical depth only toward the LMC, for a general non-symmetric density distribution of MACHOs, what we can say is that the minimum column density of MACHOs along the LMC ($\Sigma_{\min}^{\text{MACHO}}$) is $25 M_\odot \text{pc}^{-2} \tau_{\text{LMC}}/2 \times 10^{-7}$. If the clump of MACHOs exists only halfway between LMC and the sun, $M_{\text{min}}^{\text{MACHO}}$ is $\sim 1.5 \times 10^9 M_\odot$. If this is the case, the optical depth in other directions should be quite different, and the inhomogeneity of the distribution of MACHOs could be checked. Therefore to know the spatial distribution of MACHOs, observation in other directions, such as the Small Magellanic Cloud (SMC), is indispensable.

In observations of MACHOs toward the LMC and the SMC, millions of bright stars with apparent magnitude smaller than $\sim 21$ are observed daily. However, there are plenty of stars dimmer than this magnitude limit (i.e. apparent magnitude larger than $\sim 21$). In this paper we propose to search for MACHOs by observing EAGLE events (Extremely Amplified Gravitational LEnsing events = microlensing event with an impact parameter $u \ll 1$) of a majority of dim stars. This search is independent of the usual one. In §2 we show how to compute the rate and the duration of EAGLE events. In §3 we will show the results for the LMC and the SMC. Section 4 is devoted to discussion.

§2. Event rate of EAGLE

EAGLE events in general and for Bulge sources have been discussed. Here we discuss EAGLE events for the LMC and the SMC. The amplification factor $A$ is given by

$$A = \frac{u^2 + 2}{u \sqrt{u^2 + 4}},$$  \hspace{1cm}(1)$$

$$u = \frac{\theta_s}{\theta_E},$$  \hspace{1cm}(2)$$

where $\theta_s$ and $\theta_E$ are the angular distance to the source and the angular size of the Einstein radius, respectively. For EAGLE events, $A \approx 1/u$ is a good approximation. Now, for a given observation threshold of $m_{\text{obs}} = 21 \sim 22$ in the apparent magnitude for MACHO project), if the apparent magnitude ($m_0$) of a star in the LMC (SMC) is larger than $m_{\text{obs}}$, it is so dim that it cannot be identified as a star in the LMC (SMC). However, if it is amplified by a MACHO with an impact parameter $u$ smaller than $u_{\text{obs}}(= 10^{-0.4(m_0 - m_{\text{obs}})})$, the image of the star can be identified as a star in the LMC (SMC) by CCD camera. In practice we can identify an EAGLE event as a
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microlensing candidate when the light curve is well determined so that the detection threshold magnitude of the EAGLE event $m_{th}$ should be a little smaller than $m_{obs}$. We assume in this paper that $m_{th} = m_{obs} - \Delta m$, where $\Delta m (\sim 1)$ is a constant. Then the threshold impact parameter is given by

$$u_T = 10^{-0.4(m_0 - m_{th})}.$$  \hfill (3)

We refer to this as an EAGLE event in this paper for definiteness. EAGLE events will be detected just like new stars, and the observational technique is simple. Thus, this method is entirely different from the so-called pixel lensing method: monitoring the pixels rather than the stars. \hfill (20)-(22)

The event rate of EAGLE for a source star is given by

$$\Gamma = \frac{\tau}{\langle t \rangle} u_T,$$  \hfill (4)

$$\simeq 1.1 \times 10^{-6} \left( \frac{\tau}{3 \times 10^{-7}} \right) \left( \frac{\langle t \rangle}{100 \text{ days}} \right)^{-1} u_T \text{ events/year},$$  \hfill (5)

where $\tau$ and $\langle t \rangle$ are the optical depth and the average duration ($u \leq 1$) of microlensing events, respectively. Note that $\Gamma$ is proportional to the luminosity of the source star. With $n_L(m_0)$ and $m_T$ being the stellar luminosity function and the total apparent magnitude of the LMC (SMC), respectively, we have the total event rate ($\Gamma_E$) of EAGLE by all stars in the LMC (SMC) as

$$\Gamma_E = \int_{m_{obs}}^{\infty} \Gamma n_L(m_0) dm_0,$$  \hfill (6)

$$\simeq 1.1 \times 10^{-6} f 10^{-0.4(m_T - m_{th})} \left( \frac{\tau}{3 \times 10^{-7}} \right) \left( \frac{\langle t \rangle}{100 \text{ days}} \right)^{-1} \text{ events/year},$$  \hfill (7)

$$\sim 100 f \left( \frac{\tau}{3 \times 10^{-7}} \right) \left( \frac{\langle t \rangle}{100 \text{ days}} \right)^{-1} \text{ events/year for LMC (} m_T = 0.1),$$  \hfill (8)

$$\sim 13 f \left( \frac{\tau}{3 \times 10^{-7}} \right) \left( \frac{\langle t \rangle}{100 \text{ days}} \right)^{-1} \text{ events/year for SMC (} m_T = 2.3),$$  \hfill (9)

where $f$ is the fraction of the luminosity by the stars below the observation threshold ($m_0 > m_{obs}$) to the total luminosity of the LMC (SMC). We assume $m_{th} = 20$.

Since the surface brightenesses of the LMC and the SMC are not so large, even for the central part of these galaxies the surface brightenesses are $B(0) = 21.17$ mag arcsec$^{-2}$ for the LMC and $B(0) = 22.71$ mag arcsec$^{-2}$ for the SMC. \hfill (23) This means in ordinary fields $m_{obs}$ is $\sim 21$ mag. In reality the MACHO project monitors many stars of magnitude $\sim 21$ mag. Thus, the magnitudes for the EAGLE events can be detected similar to the usual MACHO events.

Since there is no available luminosity function for the LMC and the SMC except for fairly brighter stars, we estimate $f$ using the following two methods:

Model 1: We use the luminosity function for our Galaxy to estimate $f$.

Model 2: We assume a power law stellar initial mass function with the power index $\alpha$ and a constant star formation rate.

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2.1. Model 1

The luminosity function of Scalo\(^{24}\) can be approximated as

\[
\log \phi(V) = \begin{cases} 
\frac{3}{5} V - 4.2 & (V \leq 2) \\
\frac{1}{8} V - 3.25 & (2 \leq V \leq 10) \\
-2 & (10 \leq V),
\end{cases}
\]

where \(V\) is the stellar absolute visual magnitude. Then, we have

\[
f = \frac{\int_{m_{\text{obs}}}^{\infty} L_0(V) \phi(V) dV}{\int_{-\infty}^{\infty} L_0(V) \phi(V) dV},
\]

where \(\mu\) is the distance modulus and \(L_0\) is the absolute luminosity of the star. The results are shown in Tables I to IV as \(G\).

2.2. Model 2

We adopt the power law initial mass function as

\[
n(M) = C M^{-\alpha}, \quad (M_l < M < M_u)
\]

where \(M_l\) and \(M_u\) are the lower and the upper mass limit of the stars, respectively. The mass-luminosity relation of the main sequence star is expressed by\(^{25}\)

\[
L_0(M) = L_\odot \left(\frac{M}{M_\odot}\right)^\eta,
\]

\[
\eta \sim 3,
\]

where \(M\) is the mass of the star. The observation of the color distribution suggests that neither the LMC nor the SMC is likely experiencing a star-formation "burst" at the present epoch, both galaxies have formed a bulk of their stars for the last 5 Gyr,\(^{23},26\) and the star formation rates are fairly constant.\(^{27},28\) Thus, for simplicity, we assume that the star formation rates of these galaxies have been constant for the last 5 Gyr and was zero before 5 Gyr ago. Assuming that the lifetime of the sun is 10 Gyr, we obtain the present day mass function as

\[
n_p(M) \simeq C M^{-\alpha} (M < 1.4 M_\odot),\]

\[
\simeq 2 \left(\frac{M}{M_\odot}\right)^{-2} C M^{-\alpha} (1.4 M_\odot \leq M).
\]

Initial mass functions of massive stars of the LMC and the SMC are not so different from that of the Galaxy,\(^{29}\) and the slopes for OB associations are found to be essentially the same as Salpeter IMF.\(^{30}\) However, for field stars, the slope is very steep as \(\alpha \sim 5\). Taking account of these data, we assume a single power law and use the two extreme values of \(\alpha = 2.35\) and \(5\) to know the range of \(f\) which is given by

\[
f = \frac{\int_{M_l}^{M_{\text{obs}}} M^n n_p(M) dM}{\int_{M_l}^{M_u} M^n n_p(M) dM},
\]
where $M_{\text{obs}}$ is the mass of the star whose apparent magnitude is $m_{\text{obs}}$.

We next discuss the duration of an EAGLE event ($t_E$). In a microlensing event, the apparent luminosity as a function of time ($l(t)$) is expressed as

$$l(t) = \frac{R_E l_0}{\sqrt{b^2 + v_\perp^2(t-t_0)^2}},$$

where $R_E, b, v_\perp$ and $t_0$ are the Einstein radius, the impact parameter, the transverse velocity and the time of the maximum luminosity, respectively, and $l_0 = 10^{-0.4}m_0$. From the observational data, we can determine the values of $t_0$ and $R_E l_0/b$. By a follow-up observation using large telescopes, we may determine $l_0$ so that $R_E/b = u_{\text{min}}^{-1}$ may be determined. $t_E$ is defined to be the duration for which the apparent magnitude ($m$) of the source star satisfies $m < m_{\text{obs}}$. This quantity is given by

$$t_E = t_{\text{dur}} \sqrt{\frac{l_0^2}{l_{\text{obs}}^2} - \frac{b^2}{R_E^2}},$$

$$t_{\text{dur}} = \frac{2R_E}{v_\perp},$$

where $l_{\text{obs}}$ is the apparent luminosity corresponding to the observation threshold magnitude $m_{\text{obs}}$ and $u_{\text{obs}} = 10^{-0.4(m_0 - m_{\text{th}})}$. From the observed values of $t_E, m_0$ and $b/R_E$, we can determine the true duration of microlensing event $t_{\text{dur}}$. The mean value of $t_E(m_0)$ for given $u_T(m_0)$ is derived as

$$\langle t_E(m_0) \rangle = t_{\text{dur}} \frac{1}{u_T} \int_0^{u_T} \sqrt{u_{\text{obs}}^2 - u_{\text{min}}^2} du_{\text{min}},$$

$$\simeq 0.97 t_{\text{dur}} u_{\text{obs}}(m_0),$$

where we assume $\Delta m = 1$. The mean value of $\langle t_E(m_0) \rangle$ for different $m_0$ is given by

$$\langle t_E(m_0) \rangle = \frac{1}{\Gamma_E} \int_{m_{\text{th}}}^{m_0} \langle t_E(m_0) \rangle \Gamma_{\text{L}}(m_0) dm_0.$$

§3. Results

We computed $f$ and $\langle t_E(m_0) \rangle$ for the LMC and the SMC using the Galactic stellar luminosity function (marked as $G$) as well as using the power law stellar model with $\eta = 3, M_u = 50M_\odot, M_I = 0.1M_\odot$, and the power index $\alpha = 2.35$ and $5$ for two cases of the detection threshold as

Case A) $m_{\text{obs}} = 21$ mag, $m_{\text{th}} = 20$ mag and $\Delta m = 1$ mag.

Case B) $m_{\text{obs}} = 19$ mag, $m_{\text{th}} = 18$ mag and $\Delta m = 1$ mag.

As for $\mu$ and $m_T(V)$, we adopt $\mu = 18.5$ mag and $m_T(V) = 0.1$ mag for the LMC and $\mu = 18.9$ mag and $m_T(V) = 2.3$ mag for the SMC.
The results are shown in Tables I to IV. Using these tables, we display the expected number of EAGLE events for all MACHO spherical halo in the standard flat rotation curve ($\tau_{\text{LMC}} \sim 5 \times 10^{-7}$ and $\tau_{\text{SMC}} \sim 7 \times 10^{-7}$)\(^3\) with $\langle \ell \rangle = 70$ days since all MACHO halo is still possible from the observational data.\(^1\) Then, for Case A, we have $I_{E\text{LMC}} = 240 \ f \text{ events/year and } I_{E\text{SMC}} = 31 \ f \text{ events/year}$, so that even for the smallest value of $f$, we expect $I_{E\text{LMC}} = 77 \ f \text{ events/year and } I_{E\text{SMC}} = 13 \ f \text{ events/year}$.

Are there possible EAGLE events in already existing data? This is certainly possible. One example is LMC event 12 of the MACHO project, which may be an EAGLE event.\(^1\) Thus it is necessary to search EAGLE events systematically and estimate the detection efficiency even using existing observational data. However, the duration of EAGLE events is usually short (1 day $\sim$ 30 days), especially for Case B, so that the usual observational mode (1 or 2 observation/night) is not adequate. In this sense the observational mode used by the MOA collaboration (Japan-New Zealand collaboration of Microlensing Observation for Astronomy),\(^31\) for example, seems to be suitable. There working on this project have been trying to observe microlensing events by planet MACHOs since May 1996 at Mt. John, so that they have been observing stars in the LMC and the SMC as frequently as possible. This year they are planning to observe 1.5 million stars in the LMC 12 times/night in the winter and 6 times/night in the summer.\(^32\) If 8 microlensing events reported by the MACHO collaboration are not due to variable source stars but due to MACHOs, a substantial number of EAGLE events should be observed in the observation mode taken such as by the MOA collaboration.

§4. Discussion

In the actual observation of microlensing events, only a fraction of the LMC and/or the SMC are observed. The LMC and the SMC are too large to be monitored frequently since half light radii are estimated to be $3.03 \pm 0.05$ degree (LMC) and $0.99 \pm 0.03$ degree (SMC),\(^23\) respectively. This means that the detection rate of EAGLE should be multiplied by $g = (\text{luminosity of the observed area})/(\text{luminosity of LMC})$. Although for the LMC, $g$ is small ($g \sim 0.2$), the event rate of...
EAGLE is substantial (∼ 20 events/year). For the SMC $g$ can be large ($g \sim 0.5$) since the SMC is smaller than the LMC, so that the event rate of EAGLE is also substantial (∼ 10 events/year).

From the observational event rate of EAGLE, we know the quantity $f\tau$ from Eqs. (8) and (9). To estimate $f$ we used the stellar luminosity function of the Galaxy as marked $G$, and Salpeter IMF ($\alpha = 2.35$) to obtain similar results. If the star formation history and/or stellar initial mass functions of the LMC and the SMC are different from those of the Galaxy, the luminosity functions should be different from the Galaxy. However, the initial mass functions of massive stars of these galaxies are fairly similar to that of the Galaxy, and the current star formation is not very active, so that the deviation of $f$ from that of case $G$ may not be large. This is a completely independent determination of $\tau$ from the usual method.

For EAGLE events we observe extremely amplified dim stars, which are mostly main sequence stars. Since the intrinsic variabilities of these stars are expected to be small, we can pick up microlensing events efficiently. Moreover, the EAGLE event rate toward the LMC estimated in this paper, ∼ 20 events/year, may be much larger than the usual non-EAGLE MACHO event rate, ∼ 4 events/year. If $\tau^{\text{LMC}} \sim 3 \times 10^{-7}$, numerous EAGLE events must be observed toward the LMC so that the observation of EAGLE events will give us an independent method to confirm the existence of MACHOs. As for the SMC, the EAGLE event rate is also substantial, and the observation of EAGLE events toward the SMC may determine the optical depth toward the SMC, which is needed to know the spatial distribution of MACHOs.

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References

17) A. Milsztajn, talk at the 3rd Microlensing Workshop (March 6-8, 1997, Notre Dame University).