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DATA ANALYSIS OF MOA FOR GRAVITATIONAL MICROLENSING EVENTS WITH DURATIONS LESS THAN 2 DAYS BY USING BROWN DWARF POPULATION

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RESUMEN

Las microlentes gravitacionales son unos de los métodos más potentes para la detección de objetos de baja masa como exoplanetas y enanas marrones. El parámetro más importante que podemos extraer de un evento amplificado por microlente es el tiempo de cruce de Einstein. En este trabajo, hemos realizado simulaciones Monte-Carlo, obteniendo la distribución de los tiempos de cruce de Einstein para la población de enanas marrones. Mostramos que esta población puede ser una buena candidata para entender eventos de muy corta duración (inferiores a dos días). Los datos usados en este análisis fueron tomados en las sesiones de 2006 y 2007 por el Cartografiado MOA-II, con el telescopio de 1.8m MOA-II ubicado en el Observatorio de Mt. John en Nueva Zelanda.

ABSTRACT

Gravitational Microlensing is one of the most powerful methods of detecting very low mass objects like Exoplanets and Brown dwarfs. The most important parameter that we can extract from a microlensing event is the Einstein radius crossing time t_E. In this work, by performing Monte-Carlo simulation, we obtain t_E distribution for brown dwarf population. Then we show that this population can be a good candidate for very short microlensing events with $t_E < 2$ days. The data set used in this analysis was taken in 2006 and 2007 seasons by the MOA-II survey, using the 1.8-m MOA-II telescope located at the Mt. John University Observatory, New Zealand.

Key Words: brown dwarfs — gravitational lensing — planets and satellites: general — stars: low-mass

1. INTRODUCTION

Sumi et al. (2011) reported the discovery of an unbound planetary−mass population, based on Microlensing Observations in Astrophysics (MOA) collaboration during 2006−2007 towards the Galactic Bulge. This sample contains $\sim$ 1000 microlensing events, with an Einstein crossing time of $t_E < 200$ days. However, only 474 high quality microlensing events have been accepted. Ten of these events have $t_E < 2$ days and can point to a population of low mass objects. We simulate Einstein crossing time for brown dwarfs, and compare it with their results. Then we show that brown dwarfs can be good candidates for short duration lensing events of this sample. Our work is based on 2006−2007 MOA data set too.

2. GRAVITATIONAL MICROLENSING

When a foreground lens object passes close enough to the line of sight of a background source object, the light from the source is magnified. This phenomenon is called gravitational lensing. There are three classes of gravitational lensing: 1. Strong lensing, 2. Weak lensing, 3. Microlensing. Gravitational microlensing is one of the best methods in detecting low mass objects. Microlensing can detect faint objects such as planets and brown dwarfs. In the approximation of simple microlensing, the Einstein radius is given by

$$R_E = \sqrt{\frac{4GM}{c^2} D_s x(1-x)} \tag{1}$$

where M is the lens mass, D_s is the distance from the observer to the light source, and x is the ratio of the lens−observer distance to the source−observer distance (D_d). The Einstein crossing time is obtained from

$$t_E = \frac{R_E}{v_t} = \frac{\sqrt{\frac{4GM}{c^2} D_s x(1-x)}}{v_t} \tag{2}$$

Here v_t is the transverse lens−source velocity. We see that t_E depends on the lens mass, source−observer distance, transverse lens−source velocity, and the ratio of the lens−observer distance to the source-observer distance. Thus, to simulate Einstein crossing time, we need all these distributions. In addition, we must calculate the number

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of events. For this purpose, we define optical depth. The optical depth is the probability that at any given time a given star falls into the Einstein radii of the lenses. This statistical concept is expressed as

$$\tau = \int_0^{D_s} n(D_d)\pi R_E^2 dD_d \tag{3}$$

where n(D_d) is the number density of lenses, and the term πR_E^2 is the lensing cross-section. We can obtain event rate from the optical depth. This is the rate at which a given background star undergoes a microlensing event due to a foreground lens. By some calculations, the event rate equation reduces to

$$\Gamma = \frac{2}{\pi}\tau < \frac{1}{t_E} > \tag{4}$$

And the number of microlensing events is given by

$$N_{ev} = N_s T_0 \Gamma < \varepsilon > \tag{5}$$

where $< \varepsilon >$ is the detection efficiency, averaged over t_E, N_s is the total number of source stars monitored for microlensing, and T_0 is the duration of the survey in days. In the following, we simulate the distributions and determine the number of events.

3. SIMULATION

3.1. *Mass distribution*

Brown dwarfs have unlimited lifetimes. It means that regardless of their birth dates, they exist today. Thus, the present day brown dwarf mass function is the brown dwarf initial mass function (IMF). We use a power law mass function for brown dwarfs to obtain the mass distribution of the lens (Chabrier. 2002).

$$\xi(m) = \frac{dn}{dm} = Am^{-\alpha} \tag{6}$$

Where n is the number density of objects, and $\alpha = 1$ is the power index for the brown dwarf regime. The maximum and minimum mass for brown dwarfs are $0.072M_\odot$and $0.001M_\odot$, respectively. The key point is that there is no mass edge between planets and brown dwarfs. In other words, these two populations overlap. In this range, we cannot be sure whether the object is planet or brown dwarf. Figure 1 shows the brown dwarf mass distribution. The number of artificial events generated in our simulations is equal to 10,000.

3.2. *X distribution*

The next distribution function is the x distribution, the ratio of the lens−observer distance to

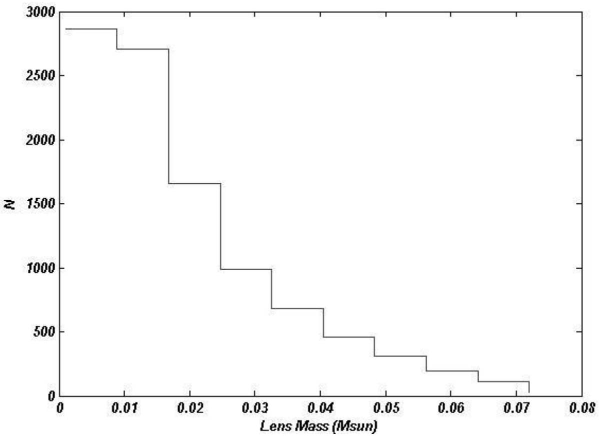

Fig. 1. The mass distribution of the lens.

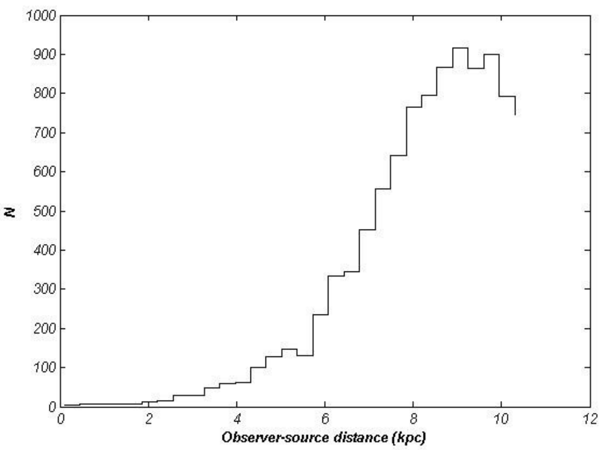

Fig. 2. Source distance distribution.

the source−observer distance. To obtain this distribution, we need the event rate of the microlensing events.

$$\frac{d\Gamma}{dx} \propto \sqrt{x(1-x)}\rho(R,z) \tag{7}$$

Here ρ is the disk density (Y.R. Rahal. 2009).

$$\rho(R,z) = \frac{\Sigma}{2H} e^{-\frac{R-R_\odot}{h}} e^{-\frac{|z|}{H}} \tag{8}$$

Where Σ is the column density of the disk at the Sun position $R_\odot$, $H = 0.325$ kpc is the height scale, and $h = 3.5$ kpc is the length scale of the disc. Since the source distance is more than the lens distance, we choose x as a random number between 0 and 1.

3.3. *Source distance distribution*

The next step is to determine the source distance distribution. Our sources belong to Galactic disk or bulge. The density distribution of the bulge is defined as follows

$$\rho_B = \frac{M_B}{6.57\pi abc} exp(-\frac{r^2}{2}) \tag{9}$$

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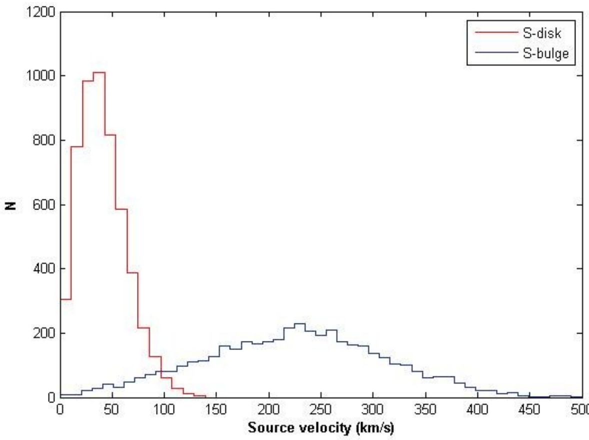

Fig. 3. Source velocity distribution. The red line indicates the objects that are in the disk, and the blue line represents the objects that are in the bulge. Total number of artificial events equals 10000. The number of sources that are in the bulge equal 4482, and the number of sources that are in the disk equals to 5518.

where M_B is the bulge mass, and a,b,c are the length scale factors, (a, b, c) = (1.49 kpc, 0.58 kpc, 0.40 kpc). figure 2 displays the distance distribution of the sources. By using the Monte Carlo method in the source distance, and x distribution, we can obtain the lens distance distribution, D_d.

3.4. *Transverse lens−source velocity distribution*

The last distribution we need is the transverse lens−source velocity distribution. Since the objects can belong to the galactic disk or bulge, depending on their positions, their velocity functions follow different types of distributions. First, we choose the object distance from the distance distribution and calculate the disk and bulge density at that distance. The next step is to calculate the ratio of the disk density to the total density. Now, to determine whether the object belongs to the disk or bulge, we select a random number between 0 and 1. If the number is less than this ratio, we consider that the object belongs to the disk. Otherwise, it belongs to the bulge. If the object belongs to the disk, its velocity includes two parts. The first part is the global velocity or the global rotation of the disk that depends on distance from the object to the Galactic center. This velocity is given by

$$v_{rot}(r) = v_{rot,\odot}(1.00762(\frac{r}{R_\odot})^{0.0394} + 0.00712) \quad (10)$$

where $v_{rot,\odot}$ = 220 km/s is the orbital velocity of our sun around the center of the galaxy. The second part is the dispersion velocity that has random direction, and its value follows the Gaussian distribution function.

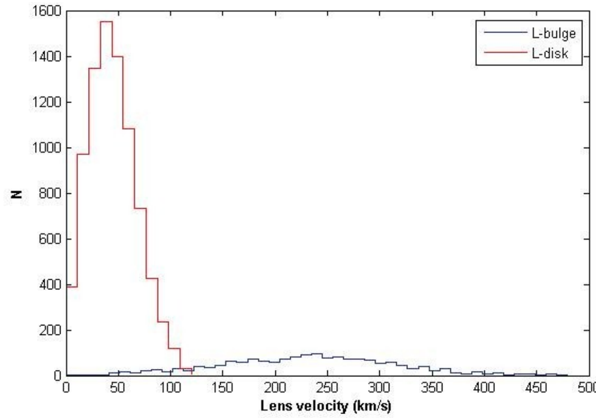

Fig. 4. Lens velocity distribution. The red line indicates the objects that are in the disk, and the blue line represents the objects that are in the bulge. Total number of artificial events equals 10000. Number of lenses that are in the bulge equals 8310, and the number of lenses that are in the disk is equal to 1690.

$$F(v) = \frac{1}{\sigma\sqrt{2\pi}} exp(-\frac{(v - v_0)^2}{2\sigma^2}) \quad (11)$$

where σ is the distribution parameter. While the v_0 parameter for the sources has a constant value about 30 km/s, this parameter varies from 30 km/s to 500 km/s for the lenses, in order to be able to investigate its effect on the number of events. If the object belongs to the bulge, its velocity distribution is given by

$$F(v) = \frac{1}{\sigma^2_{bulge}} v_T exp(-\frac{v_T^2}{2\sigma^2_{bulge}}) \quad (12)$$

with σ_{bulge} = 110 km/s. Figure 3 and 4 display the source and the lens velocity distributions, as well as the contribution of the disk and the bulge. As we see in these figures, half of the sources belong to the disk and half of them belong to the bulge. While, most of lenses belong to the disk. Now we can have transverse lens−source velocity.

3.5. *Optical Depth*

If we assume all the lenses have the same mass, then the optical depth depends only on the mass density along the line of sight and not on the mass function of lenses.

$$\tau = \frac{4\pi G}{c^2} D_s^2 \int_0^1 \rho(x)x(1 - x)dx \quad (13)$$

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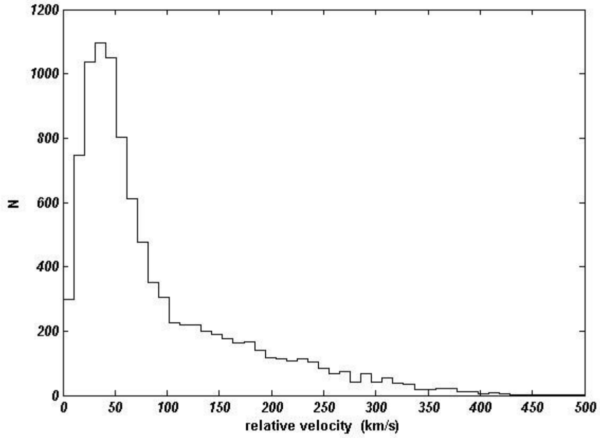

Fig. 5. Transverse lens-source velocity distribution (v_t).

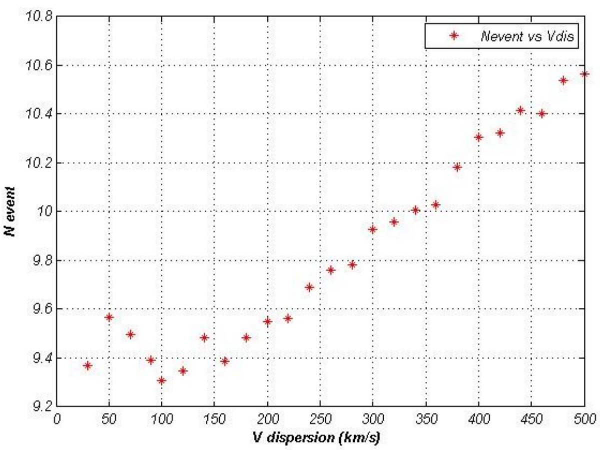

Fig. 6. The number-velocity diagram.

where $\rho(x)$ is the disk density. Solving this integral numerically, we find that the average microlensing optical depth for brown dwarfs is 0.1416×10^{-7}. Thus, the event rate is given by

$$\Gamma = \frac{2}{\pi}\tau < \frac{1}{t_E} >= 9.01 \times 10^{-9} < \frac{1}{t_E} > \qquad (14)$$

Now, we can discuss the number of microlensing events (equation (5)) for brown dwarf population.

4. CONCLUSION

The question that comes first to our mind is this: Regardless of brown dwarfs dispersion velocity, can this population be a good candidate for gravitational microlensing events with durations less than 2 days? To investigate this question, we first assume that the lens dispersion velocity equals the source dispersion velocity ($v_0 = 30$ km/s), and see how many events will be generated. The number of events we obtain

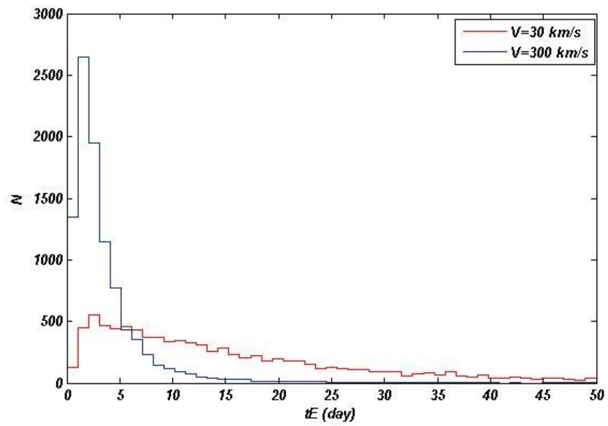

Fig. 7. Theoretical distributions of the event timescale, t_E , for two dispersion velocities 30 km/s and 300 km/s , regardless of the detection efficiency.

from our simulation is 9.37. According to MOA collaboration, the number of observed events equals 10. Since our result is between $10 \pm \sqrt{10}$, it is acceptable. Thus, it seems that brown dwarf population can be a good candidate for events lasting less than 2 days, regardless of its velocity. Now we want to know the effect of lens dispersion velocity on the number of events. For this purpose, we increase the dispersion velocity from 30 km/s to 500 km/s, and calculate the number of events. Figure 6 displays the number−velocity diagram. As shown in the figure, when the dispersion velocity increases, the number of events increases too.

In the following, we simulate the theoretical distributions of the event timescale, t_E, for two dispersion velocities 30 km/s and 300 km/s , regardless of the detection efficiency. Figure 7 shows these distributions.

Since we cannot see all the generated events, we have to consider detection efficiency in our calculations. First we determine the detection efficiency at the Einstein radius crossing time for every event. Then we select a random number between 0 and 1. If this number is less than the detection efficiency, the event is acceptable. It means that we can detect the event.

Figure 8 represents the observed distributions of microlensing event timescale, for two dispersion velocity 30 km/s and 300 km/s. To compare these two distributions with Sumi et al. (2011), we plot them on logarithmic scale. Figure 9 and 10 show these distributions. Figure 11 displays observed and theoretical distributions of event timescale, based on MOA survey during 2006−2007. In this figure, we can see Einstein crossing time distribution for main

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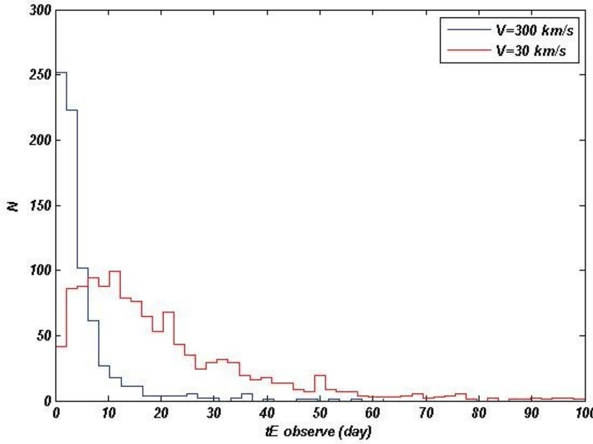

Fig. 8. Observed distributions of event timescale, for two dispersion velocities 30 km/s and 300 km/s.

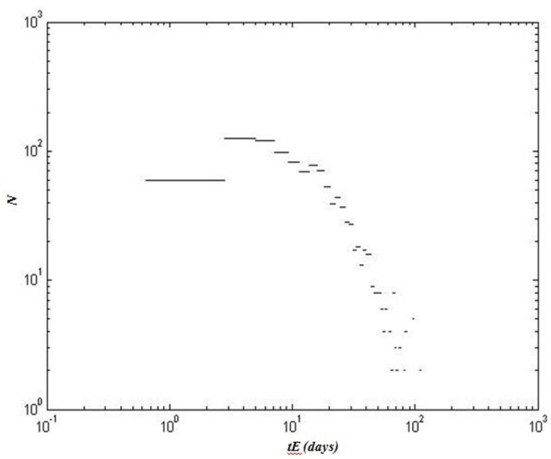

Fig. 9. Observed distribution of microlensing event timescale, dispersion velocity= 30 km/s.

sequence star, white dwarf, neutron star, black hole, brown dwarf, and planetary−mass populations. By comparing these figures, we find that when the dispersion velocity equals 30 km/s, our simulation is compatible with the brown dwarf distribution in Figure 11. While when the dispersion velocity increase, our simulation is similar to the planetary−mass distribution. Thus, it seems that high−velocity brown dwarf population can be a good candidate for very short microlensing events.

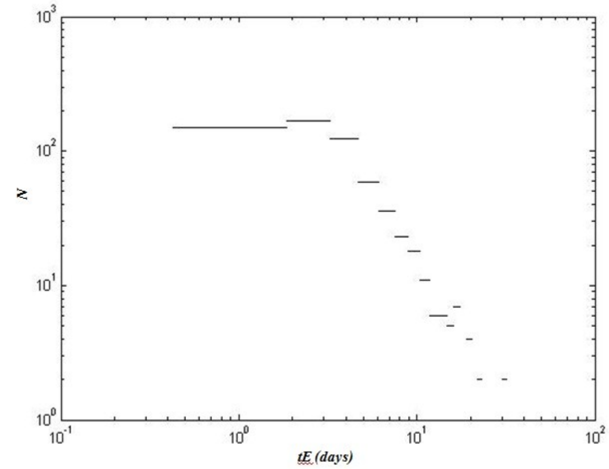

Fig. 10. Observed distribution of microlensing event timescale, dispersion velocity = 300 km/s.

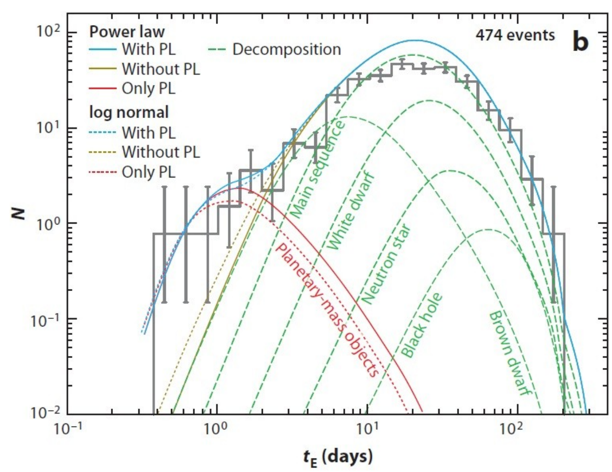

Fig. 11. Observed and theoretical distributions of event timescale, based on MOA survey during 2006−2007. The black line shows the number of observed events. The dashed green lines display Einstein crossing time distribution for main sequence star, white dwarf, neutron star, black hole, and brown dwarf. The solid and dotted red curves are models for planetary−mass population that is suggested by Sumi et al. (2011). The dark yellow solid and dotted curves are models with power−law and log normal mass functions, without planetary−mass objects. The solid and dotted blue curves show these models with planetary−mass populations (B. Gaudi. 2012).

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