GRAVITATIONAL MICROLENSING EVENTS AS A TARGET FOR THE SETI PROJECT

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ABSTRACT

The detection of signals from a possible extrasolar technological civilization is one of the most challenging efforts of science. In this work, we propose using natural telescopes made of single or binary gravitational lensing systems to magnify leakage of electromagnetic signals from a remote planet that harbors Extraterrestrial Intelligent (ETI) technology. Currently, gravitational microlensing surveys are monitoring a large area of the Galactic bulge to search for microlensing events, finding more than 2000 events per year. These lenses are capable of playing the role of natural telescopes, and, in some instances, they can magnify radio band signals from planets orbiting around the source stars in gravitational microlensing systems. Assuming that the frequency of electromagnetic waves used for telecommunication in ETIs is similar to ours, we propose follow-up observation of microlensing events with radio telescopes such as the Square Kilometre Array (SKA), the Low Frequency Demonstrators, and the Mileura Wide-Field Array. Amplifying signals from the leakage of broadcasting by an Earth-like civilization will allow us to detect them as far as the center of the Milky Way galaxy. Our analysis shows that in binary microlensing systems, the probability of amplification of signals from ETIs is more than that in single microlensing events. Finally, we propose the use of the target of opportunity mode for follow-up observations of binary microlensing events with SKA as a new observational program for searching ETIs. Using optimistic values for the factors of the Drake equation provides detection of about one event per year.

Key words: gravitational lensing: micro

1. INTRODUCTION

Are we alone in the universe? This is one of the deepest questions of mankind and in recent years there have been a lot of efforts to answer this question. The Search for Extraterrestrial Intelligence (SETI) is one of the projects trying to answer this question and since the 1960s no confirmed signal from extraterrestrial life has been detected (Wilson 2001). Another important effort started with direct and indirect observations of extrasolar planets after the discovery of the first exoplanet by Mayor & Queloz (1995). Nowadays, projects like Kepler1 have increased the number of extrasolar planets to more than one thousand candidates (Batalha & Kepler Team 2014) and an important question still remains: does any intelligent life exist in one of the discovered planets?

In order to detect Extraterrestrial Intelligence (ETI), we need to listen for leakages from the telecommunication signals of advanced technology civilizations. The transmitting signals can be either particles or photons. The properties of transmitting particle have been discussed extensively by Oliver & Billingham (1996) with the following properties: (a) each transmitting particle has minimum energy per quantum, (b) each particle has a large velocity, (c) particles must easily generate and be focused, and finally (d) the particles have not been easily absorbed by the interstellar medium. The best candidate that satisfies these four properties is the electromagnetic waves in radio or microwave wavelengths. The main challenge of detection of signals from an advanced civilization is that in the large astronomical scales signals are faded out. Also, in the radio waves for frequencies smaller than 100 MHz (larger than 3 m), the free–free absorption becomes important and for frequencies larger than 1 THz (smaller than 300 μm) absorption becomes increasingly important.

Assuming that the electromagnetic signals are transmitted by an advance civilization, these signals should have the specific property of violating the natural transmission mechanism to be distinguished from the natural sources (Tarter 2001). Moreover, we expect that transmission by the intelligent life has to be done in narrow band by the artificial sources with the minimum amount of Δλ/λ, similar to what our civilization is doing for transmitting signals. With our primitive technology, we can produce Δλ/λ ∼ 10−12 compare to nature, which is around 10−4−10−3 in astrophysical systems, and water masers with limiting values of 10−6. Assuming that Earth-like advanced civilizations using the same range of electromagnetic waves for telecommunications that we use, the present radio telescopes can eavesdrop on their radio transmissions (Loeb & Zaldarriaga 2007).

The aim of this work is to use gravitational microlensing as a natural amplifier to magnify the leakage of signals from remote planets at Galactic scales. The gravitational lenses can magnify electromagnetic waves from distant sources by converging light beams from the source star. This light magnification can be done either by single or binary lenses. At the present time, there are two main observational campaigns of OGLE and MOA that use wide-field telescopics to monitor the center of the Galaxy for gravitational microlensing detections. In 2014, OGLE could detect over 2000 microlensing events (Gaudi 2012; Sumi et al. 2013). The next generation of microlensing surveys, the Korean Microlensing Telescope Network, is going to cover a larger area and discover more microlensing events than present experiments (Park et al. 2012).

The main purpose of this work is the follow-up observation of microlensing events with radio telescopes to detect transmitting signals from planets hosting ETI and orbiting around the source stars in the microlensing systems. During the gravitational microlensing, electromagnetic waves independent

1 http://www.nasa.gov/kepler
of their wavelengths are magnified from both the parent source star and a planet orbiting around it. However, since the source star and the associated planet are separated with the distance in the order of astronomical units, their magnifications do not peak at the same time. This method increases the depth of the SETI observation from a few parsecs up to the center of the Galaxy. This technique in the visible band also has been proposed for detecting hot Jupiters by illuminating planets around the parent stars (Sajadian & Rahvar 2010).

The organization of this paper is as follows. In Section 2, we introduce the radio sources on an Earth-like planet similar to our transmitters on the Earth and study the possibility of detecting these sources with the present instruments that are used in cosmological observations. In Section 3, we introduce the basic formalism of gravitational microlensing as a natural amplifier of signals from an Earth-like planet by single and binary lensing systems. In Section 4, we perform a Monte-Carlo simulation and estimate the number of high magnification microlensing events of planets by follow-up radio observations for both single and binary lensing systems. In this section, we also investigate the wave optics effects of gravitational microlensing in our observation and the suppression of very high magnified singles in the radio light curve. Details about this effect are given in the Appendix. In Section 5, after introducing the Drake equation, we investigate the number of expected candidates with signals from the planets with intelligent life. The conclusion is given in Section 6.

2. RADIO SOURCES FROM AN EARTH-LIKE CIVILIZATION

Let us imaging an Earth-like civilization that is producing electromagnetic waves at the same frequency range and the same power that we are producing on Earth. We note that according to the classification of advanced civilizations by Kardashev, these planets may produce stronger transmissions compared to Earth (Kardashev 1964) or due to improved fibre optics communication on their planet, and thus they produce less man-made noises compare to ours. The transmitted signals might be either in beacon mode or they might be the unintentional leakage of signals. Here we use the later mode of transmission in our study (Loeb & Zaldarriaga 2007). As we discussed before, the artificial signals are narrow band and encoded signals contain more information compare to the natural signals. The complexity of signals from intelligent civilizations can be measured by various mathematical methods.

Different types of radio sources as a target for intelligent civilization have been discussed in Sullivan et al. (1978). According to Table 1, which is adapted from Sullivan et al. (1978) and Loeb & Zaldarriaga (2007), military radars with maximum power per transmitter \( P_{\text{max}} \approx 2 \times 10^{11} \text{ W} \) are the strongest sources that radiate radio waves isotropically. Television and FM stations are the second and third ranks in the power of radiation. Moreover, the Arecibo telescope has four radars that transmit with the power of \( 2 \times 10^{13} \text{ W} \) (Tarter 2001).

In recent years, the cosmological experiments have been designed to observe 21 cm emissions of H II regions from redshifts of \( z \approx 6–12 \), corresponding to 200–400 MHz (Becker et al. 2001). These cosmological observations are aiming to observe the reionization history of the universe. Fortunately, this range of frequency overlaps with the frequency range of telecommunications on the Earth (see Table 1), and it can be used for the observation of Earth-like planets in our Galaxy (if intelligent life uses the same range of frequency). While military transmitters are the strongest radio sources, TV and FM radio sources with 10–100 kW can outshine the Sun up to almost 100 times, meaning that radio emission from the parent star does not blend with signals from an Earth-like planet. Thus, the main limitation on the observation is the threshold of the signal-to-noise ratio of receivers that we are using on the Earth. The signal-to-noise increases by increasing the square root of the exposure time of the observation; however, exposures longer than the spinning period of the planet or orbital period of the planet around the parent star causes broadening of emission signals and erases the modulation effect. On the other hand, for long exposures, we cannot detect complex signals from the radio flux by accumulating signals. Here, we study the sensitivity of the Mileura Widefield (MWA)–Low Frequency Demonstrators (LFD) and the Square Kilometre Array (SKA) for the detection of signals from the intelligent life.

For the case of MWA–LFD, the point source sensitivity at 200 MHz is\(^2\)

\[
F_{\text{PSS}} = 0.4 \text{ mJy} \left( \frac{\Delta \nu}{8 \text{ kHz month}} \right)^{-1/2},
\]

\(^2\)The value of FPSS for other frequencies can be found at http://mwa-lfd.haystack.mit.edu/.

| Service (1) | Freq. (2) (MHz) | Transmitters (3) (No.) | Max. Power (4) per Tr. (W) | Bandwidth (5) (Hz) | Power (6) (W) | Power Hz\(^{-1}\) (7) (W Hz\(^{-1}\)) |
|------------|----------------|------------------------|---------------------------|-------------------|--------------|-------------------------------|
| Military   | ~400           | 10                     | \( 2 \times 10^4 \)      | \( 10^7 \)        | \( 2 \times 10^5 \) | \( 2 \times 10^9 \)            |
| FM         | 88–108         | 9000                   | \( 4 \times 10^3 \)      | 0.1               | \( 4 \times 10^8 \) | \( 4 \times 10^8 \)            |
| TV         | 40–850         | 2000                   | \( 5 \times 10^5 \)      | 0.1               | \( 10^4 \)    | \( 10^{10} \)                 |

\(\Delta \nu\) is the frequency bandwidth of the receiver, and \(t_{\text{obs}}\) is the observation time.
where \( t_{\text{obs}} \) is the total exposure time and \( \Delta \nu \) is the bandwidth. For a source with a minimum power of \( P_{\text{min}} \) located at the distance of \( D \) and emitting with the bandwidth of \( \Delta \nu \), the threshold of observability from Equation (1) is

\[
P_{\text{min}} = 1.99 \times 10^{13} W \times \left( \frac{D}{100 \text{ pc}} \right)^2 \times \left( \frac{\Delta \nu}{8 \text{ kHz}} \right)^{1/2} \left( \frac{t_{\text{obs}}}{10 \text{ minutes}} \right)^{-1/2}.
\]

(2)

Let us assume that we perform observations with the exposure time of 10 minutes. This strategy of observation enables us to monitor the modulation of frequency within a few hours from the spin of an Earth-like planet. Comparing the minimum flux of detection to the power of military transmitters in Table 1 as well as the Arecibo transmitter, we can detect them up to 10 pc and within this volume there are almost a thousand stars available. This volume can be increased by increasing the exposure time of observation; however, we will miss the sensitivity to the modulation.

The other important telescope in our desired range of frequency is the SKA telescope. This telescope is also designed for astrophysical and cosmological studies. It has a threshold sensitivity of \( 10^{-28} \text{ W m}^{-2} \) and is able to monitor sources with high cadences. This will enable us to monitor the time variation of source flux and search for possible meaningful signals from an Earth-like planet. By using a narrow bandwidth of detection, it is possible to improve the threshold sensitivity to \( 10^{-29} \text{ W m}^{-2} \) (Lazio et al. 2004). Using the strongest transmitter on an Earth-like planet from Table 1, we can put a limit on distance that can be detected with SKA. The result from Figure 1 is \( D_0 \approx 1.26 \text{ kpc} \).

In the following sections, we will introduce gravitational microlensing as the natural amplifiers of signals from remote planets. We will provide an observational strategy based on observational mode of microlensing surveys and estimate the number of planets that are illuminated with the gravitational microlensing in the radio band.

3. GRAVITATIONAL LENSING AS NATURAL TELESCOPES

The gravitational lensing of a star by another star in the Milky Way galaxy, for the first time, was introduced by Einstein (1936) and since the angular resolution of an optical telescope is less than the Einstein ring. Einstein noted in his paper that “There is no great chance of observing this phenomenon” Einstein (1936). On the other hand, the probability of detecting gravitational lensing inside the Galaxy is of the order of \( 10^{-7} \). After five decades, Paczyński in 1986 revisited the question of gravitational microlensing and estimate the observability of this phenomenon inside the Galaxy and propose the application of it for searching compact dark matter objects inside the Galactic halo (Paczyński 1986).

In the gravitational lensing inside the Milky Way, while the angular separation between the images is small and the ground-based telescope images are unresolvable, the magnification of light from the source star during the transit of the lens is a measurable quantity. The magnification depends on the angular separation between the source and lens stars. The overall magnification from single lensing is given by

\[
A(t) = \frac{2 + u(t)^2}{u(t)\sqrt{4 + u(t)^2}},
\]

where \( u \) is the impact parameter normalized to the Einstein ring. The impact parameter is a dynamical parameter and for a single lens changes by time as \( u(t)^2 = u_0^2 + (t - t_0)^2/t_E^2 \), where \( u_0 \) is the closest distance from the lens, \( t_0 \) is the moment of maximum magnification and \( t_E \) is the Einstein crossing time (Paczyński 1986; Rahvar 2015).

We imagine that, in addition to the source star, there is a planet with intelligent life orbiting around the source star. The projected orbit of the planet on the lens plane and relative distance of these three objects is shown in Figure 2. We take \( \tilde{r} \) as the orbital radius of the planet projected on the lens plane, normalized to the Einstein radius of the lens (i.e., \( \tilde{r} = \frac{D_{\odot} r}{D_E r_L} \)), \( \omega \) as the angular velocity of planet, and \( \phi \) as the initial phase of planet. The equation of motion of the planet in this coordinate system is given by

\[
\begin{align*}
X_p &= \tilde{r} \cos(\omega t + \phi), \\
Y_p &= \tilde{r} \sin(\omega t + \phi) \sin \beta,
\end{align*}
\]

where \( 90 - \beta \) is the angle between the \( Y \)-axis and the orbital plane and the orbital plane goes through the \( X \)-axis. The parent star is located at the center of the coordinate system and the trajectory of the lens is given by

\[
\begin{align*}
X_L &= \left( \frac{t - t_0}{t_E} \right) \cos \alpha - u_0 \sin \alpha, \\
Y_L &= \left( \frac{t - t_0}{t_E} \right) \sin \alpha + u_0 \cos \alpha,
\end{align*}
\]

Figure 1. Logarithm of power per area (in W m\(^{-2}\)) from a Military-like source adapted from Table 1 transmitted from Earth-like intelligent life as a function of distance from the source (in parsec). The horizontal dashed line (i.e., \( P/S = 10^{-29} \text{ W m}^{-2} \)) is the limiting value at which SKA can observe signals, which means that the source is detectable up to a distance of \( D \approx 1.26 \text{ kpc} \).
coherent light, the magnification is a finite value. Figure 3, on the right panel shows a typical light curve of a binary lens, magnifying signals from a planet orbiting a source star. Here, we consider the geometric optics in the calculation of magnification (Dominik 2007).

In the next section, we estimate the number of planets for which signals from intelligent civilizations can be illuminated by single or binary lensing up to the observational threshold of the SKA telescope.

4. STATISTICS OF PLANET ILLUMINATION

In this section, we estimate the number of Earth-like planets for which signals can be amplified with gravitational microlensing (as a natural telescope). The observation of microlensing events is done in two steps: (a) survey mode, where survey groups are monitoring stars in the direction of the Galactic Bulge and, by ongoing analysis of light curves, alert the microlensing events and (b) follow-up mode, where telescopes around the globe observe microlensing candidates with high cadence and better photometric precision. The map of the survey for the OGLE experiment is shown in Figure 4 toward the direction of the Galactic Bulge. In this section, we will estimate the statistics of high amplification of Earth-like planets by single and binary lensing systems.

4.1. Single Lens

One of the crucial parameters in the simulation of this effect in single and double lensing is the determination of \( \bar{r} \) as the projected orbit of the planet on the lens plane, normalized to the Einstein radius as follows.

\[
\bar{r} = \frac{r_H(M_2)}{5.7 \text{ au}} \left( \frac{M_L}{0.5 M_\odot} \right)^{-1/2} \left( \frac{D_S}{8 \text{ kpc}} \right)^{-1/2} \left( \frac{x}{1-x} \right)^{1/2},
\]

where \( x = D_L/D_S \) represents the ratio of observer-lens to the observer-source distances, \( M_L \) is the mass of the lens and \( r_H \) is the orbital radius of a planet, assuming that it is located at the habitable zone of a source star. We note that \( r_H \) is a function of mass and the age of the source star that the planet orbits around. For the main-sequence stars, it is given by \( r_H(M_2) = (0.8-1.5) \times (M_2/M_\odot)^2 \) au (Kasting et al. 1993; Koppapapu et al. 2013). For the red giants, these types of stars are unstable; however, for a solar-type star they stay at the first stages of the post main-sequence evolution. The temporal transit of the habitable zone is estimated to be of several \( 10^9 \) years at 2 au and around \( 10^8 \) years at 9 au (Lopez et al. 2005).

Fortunately, from studying the color–magnitude distribution of source stars in OGLE III microlensing events, we can estimate the statistics of stars in the main-sequence and in the red giant area. For OGLE III, in the direction of the Galactic bulge, we adapt statistics of microlensing events from the observations in the period of years 2001–2009. Analyzing the distribution of stars in Figure 5, the fraction of red-clump source stars to the overall number of stars is 16%. We use the same combination for the population of source stars in our Monte-Carlo simulation, associating a habitable zone to the source stars.

Taking into account that the limiting distance for detection of a military transmitter from an Earth-like planet with the SKA telescope is \( D_0 = 1.26 \) kpc (for details refer to Section 2), the
minimum magnification factor from microlensing is related to detectability with the SKA telescope at the distance of $D$ as follows.

$$A_{\text{min}} > \left( \frac{D_S}{D_0} \right)^2.$$  \hspace{1cm} (8)

For the case of microlensing events in the direction of the Galactic bulge, if we assume, for instance, a source star located at $D_S \approx 7$ kpc, the minimum magnification for the planet detection is $A_{\text{min}} > 30$. For the microlensing events in the direction of the Galactic Bulge, the source stars are not located at a fixed distance, rather they are distributed along our line of sight from the position of the observer to the center of the Galaxy. The main-sequence stars mainly belong to the disk and red clumps belong to the Galactic bulge.

In order to estimate the fraction of events with a magnification that satisfies the condition in expression (8), we perform a Monte-Carlo simulation where the geometrical parameters of the lens are chosen uniformly in the range of $u_0 \in [0, 1], \alpha \in [0, 2\pi], \beta \in [0, \pi], \phi \in [0, 2\pi]$. The other physical parameters, the Einstein crossing time $t_E$ and $\tilde{r}$, are taken according to the distribution of matter, the dynamics of the Galaxy, and the mass function of lens stars in the Galaxy. The mass functions, including the main sequence, brown dwarfs, and compact stars, are given with $\xi (\log m) = dn/\log m$, as follows (Chabrier 2003)

$$\xi (\log m) = 0.093 \times \exp \left[ -\frac{(\log m - \log 0.2)^2}{2 \times (0.55)^2} \right],$$  \hspace{1cm} m \leq m_\odot$$

$$\xi (\log m) = 0.041 \times m^{-1.35}, m > m_\odot.$$  \hspace{1cm} (9)
On the other hand, for simulating the source of the microlensing events, we adopt a complete sample from the *Hipparcos* catalog (Turon et al. 1995) and enhance the contribution of red clumps to be comparable to the observation in the Galactic center.

For the distribution of matter in the Galaxy, the density of lenses composed of the density of the disk and the bulge is described with a thin disk and a central bar structure. The disk is an exponential model adapted from the Besancon model (Robin et al. 2003)

\[
\rho_d(r, z) = \rho_0 \left[ \exp \left( - \frac{a^2}{h_R^2} \right) - \exp \left( - \frac{a^2}{h_R^2} \right) \right]
\]

where \( h_R = 5.0 \) kpc and \( h_R = 3.0 \) for age < 0.15 Gyr and \( h_R = 2.53 \) kpc and \( h_R = 1.32 \) for age > 0.15 Gyr, \( a^2 = r^2 + \left( \frac{z}{\epsilon} \right)^2 \), \( \epsilon \) and \( \rho_0 \) for different ages of stars are given in detail in Robin et al. (2003).

The bar is described in a cartesian frame positioned at the Galactic center with the major axis \( x \) tilted by \( \Phi = 13^\circ \) with respect to the Galactic center-Sun direction. The number density of stars in the bulge is also given by Robin et al. (2003)

\[
n_b(x, y, z) = n_0 e^{-r^2/2},
\]

\[
\sqrt{x^2 + y^2} < R_c,
\]

\[
n_b(x, y, z) = n_0 e^{-r^2/2} e^{-2(z/R_c)^2},
\]

\[
\sqrt{x^2 + y^2} > R_c,
\]

where \( R_c = 2.54 \) kpc are the scale length factors.

For the dynamics of the Galaxy, we apply the dynamics of stars in the disk and bulge separately. The global rotation of the disk is given as a function of the galactocentric distance by

\[
v_{rot}(r) = v_{rot, \odot} \times 1.00762 \left( \frac{r}{R_\odot} \right)^{0.0394} + 0.00712,
\]

where \( v_{rot, \odot} = 220 \) km s\(^{-1}\) (Brand & Blitz 1993). The peculiar velocity of the disk stars is described by an anisotropic Gaussian distribution with the following radial, tangential, and perpendicular velocity dispersions of \( \sigma_r = 34 \) km s\(^{-1}\), \( \sigma_\theta = 28 \) km s\(^{-1}\), and \( \sigma_z = 20 \) km s\(^{-1}\) (Rahal et al. 2009). The distribution of the transverse speed of stars in the bulge is also given by

\[
f_T(v_\perp) = \frac{1}{\sigma_{\text{bulge}}^2} v_\perp \exp \left( - \frac{v_\perp^2}{2\sigma_{\text{bulge}}^2} \right),
\]

where \( \sigma_{\text{bulge}} \approx 110 \) km s\(^{-1}\).

The relative transverse speed of the source and the lens on the lens plane is given by

\[
v_\perp = x(v_S - v_L) - y(v_L - v_S),
\]

where all the vectors are defined in two dimensions parallel to the lens plane and perpendicular to the line of sight. The rate of events, taking into account that each lens spans a tube with the diameter of \( 2R_c \) and the length of \( v_\perp \times T_{\text{obs}} \) is given by

\[
d\Gamma \propto M_S x(1 - x) \rho_s(x) \xi (\log M_L) v_L f_S(v_S) \times f_L(v_L) dxdv_Sdv_L d \log M_L,
\]

where \( \rho_s(x) \) is the stellar density of the Galaxy, \( \xi \) is the mass function of stars in logarithmic scale, \( f_S(v_S) \) and \( f_L(v_L) \) are the velocity distribution functions of source and lens in two dimensions. The important observable of microlensing events is the duration of the event that is given by \( t_\text{E} \) and the detectability of an event is directly related to this parameter. In our simulation, we adapt the detection efficiency function (i.e., \( \epsilon(t_\text{E}) \)) from the OGLE survey (Wyrzykowski et al. 2015).

For single-lens microlensing events in the direction of the Galactic bulge, assuming a planet orbiting at the habitable zone of the source star, almost 2.5% of the overall observed microlensing events satisfies the condition of expression (8). Figure 6 represents the distribution of microlensing events in terms of distance of the source stars (i.e., \( D_s \)) for overall microlensing (in solid line), and the distribution of microlensing events satisfies the condition of expression (8) (dashed line).
The average distance of the observer to the source stars for all the events is 8.36 kpc and for those with positive signals from the planet is 7.49 kpc. While the observation of microlensing events with nearby sources improves receiving strong signals from the planets, estimation of the distance of source stars in the ongoing microlensing events is a challenging problem.

To estimate the distance of the source star, the color–magnitude of stars around the source star within the radius of 60” is measured (as an example, see Street et al. 2016). Assuming that all the stars in the field are affected by the same amount of extinction, using the position of the center of red clumps in the color–magnitude diagram and the position of red clump stars in the Hipparcos catalog (Paczyński & Stanek 1998), we can calculate the extinction of the field. Then the dereddened color and magnitude of the source star (i.e., \( I_0, (V - I)_0 \)), measuring its offset with the red clump, can be calculated. The result would be an estimation from the distance modulus of the source star as well as the angular size of the source star. Due to uncertainty in the distance measurement, we propose performing the radio follow-up observation for all the microlensing candidates regardless of their source distances.

In this section, we have introduced the gravitational microlensing as a natural amplifier to enhance signals from planets, which will enable us to detect them up to distances of 10 Kpc. In other words, the depth of our observation with SKA could be extended up to the center of the Galaxy. With the present technology, microlensing surveys almost 2000 microlensing events per year. Regarding the fact that the efficiency for planet illumination from single lensing in the Monte-Carlo simulation is about 2.5%, we would expect to detect almost 50 high magnifications of planets around the microlensing source stars. For these events the average value of orbital size of habitable planets normalized to the Einstein radius is \( \langle \tilde{\alpha} \rangle = 0.18 \), compare to \( \langle \tilde{\alpha} \rangle = 0.19 \), which is the average value of this parameter for all the microlensing events regardless of planet detection. In the next section, we will estimate the number of high magnification planets by the binary lensing. The probability of these planets hosting intelligent communicating life will be discussed later.

### 4.2. Binary Lensing

In the binary lensing, the lensing system is composed of two objects. These objects can be either (a) a binary star, (b) a star with its companion planet, or (c) any other combination of sufficiently high mass objects, such as black holes, brown dwarfs, etc. Increasing the number of lenses from one to two or more objects dramatically increases the complication of the lensing equation. One of the features of having multiple lensing is the caustic lines on the source plane. Once a source crosses these lines, in theory, we have infinite magnification and in the observation, we can get sparks of light from the source object. In the case of binary lensing, either the source star or the planet orbiting around it, or both objects, can cross the caustic lines. The advantage of using binary lensing for detecting planet is that with an early warning system, from the deviation of the light curve from the single lensing, we can identify an ongoing binary microlensing event before the light curve peaks. We will show that the probability of high magnification of the planet in binary lensing is more than a typical single lens.

![Figure 7. Distribution of distance between lenses of 15 binary microlensing events from the OGLE 2002–2003 microlensing list (Jaroszynski et al. 2004). The distance between the lenses are normalized to the Einstein radius of the overall mass of lenses.](image-url)
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stars from Equation (7), we plot in Figure 8 the distribution of \( r \) where the microlensing events have been triggered with the microlensing surveys. The average value of this parameter is obtained as \( \langle r \rangle = 0.19 \). Y-axis is in the logarithmic scale.

Now we compare the size of \( r \) with the distance between the binary lenses (i.e., \( d \)). The average value of \( d \) from the observations of 15 binary lenses in the OGLE 2002–2003 season is \( \langle d \rangle = 1.26 \). The comparison of these two length scales provides the probability of crossing the planet’s orbit with the caustic lines of binary lenses. We note that due to the binary feature of the microlensing light curve from the source star, the source star crosses the caustic lines. Also for the case of equal mass binary lenses, in the intermediate regime where the distance of lenses is in the range of \( 1/\sqrt{2} < d < 2 \), the caustic lines are a connected bar shape on the lens plane (Dominik 1999), where comparing the intermediate regime for the caustic structure with Figure 7 means that almost all the cases of binary lenses are in this regime.

In order to estimate the probability of caustic crossing of a planet, we take a simple face-on orbital configuration of the planet around the source star and consider the relative motion of the planet’s orbit on the lens plane with respect to the binary lens. Since \( \bar{r} \ll d \), the probability of caustic crossing of planet can be estimated by

\[
P \approx \frac{d - \bar{r}}{d},
\]

where using the numerical values for \( \bar{r} \) and \( d \) result in \( P \approx 0.85 \). Considering that 1.75% of microlensing events in our sample are binary lenses, the probability of caustic crossing of a habitable planet in the binary lenses would be 1.5% of all the microlensing events.

Our calculation is based on geometric optics; however, having a point mass source with the longer wavelength emission from the source produces wave optics features from the microlensing magnification and the result is the suppression of the magnification and avoidance of the singularities. In the Appendix, a detailed calculation on the wave optics and its effect on the result of this section is discussed. We show that even using the gravitational lensing in the wave optics formalism does not change the results of this section.

5. STATISTICS OF INTELLIGENT LIFE DETECTION IN FOLLOW-UP MICROLENSING OBSERVATIONS

We have seen in the previous section that the number of planet illumination from the the single lensing is almost one order of magnitude more than that in the binary lensing. However, from the the analysis of the Monte-Carlo simulation, for almost 85% of the binary lensing there will be caustic crossing of the planet, which means that there will be high magnification by illuminating signals from the planet. Using binary lensing events for the follow-up observations has two practical advantages: (a) in the binary microlensing events, from the deviation of light curve, we can identify the binary microlensing systems in advance where the probability of illumination of habitable planet is almost 85%, and (b) since the probability of caustic crossing of the planet is high, the SKA telescope can be used in target of opportunity mode for the follow-up observation.

In what follows, we estimate of number of intelligent communication life in our observation method. We use the Drake equation, which provides the probability of a Communicating Intelligent Life (CIL) existing in our Galaxy. This equation is given by

\[
N_{\text{CIL}} = N_s f_p n_{\text{E}} f_L f_I f_C L/L_\odot,
\]

where \( N_s \) is the number of stars in our galaxy, \( f_p \) is the fraction of stars with planets, \( n_{\text{E}} \) is the number of Earth-like planets in the habitable zone, \( f_L \) is the fraction of planets on which life is developed, \( f_I \) is the fraction of those planets that evolve intelligent life, and \( f_C \) is the fraction of that intelligent life that can have radio communication. \( L \) is the timescale that intelligent civilizations exists and \( L_\odot \) is the overall age of the star in the stable position.

There are optimistic and pessimistic estimations for different factors in the Drake equation. We adapt updated estimations for each element. Observations of extrasolar planets with microlensing reveals that stars can have more than 1.6 Earth-like planet, which means that \( f_p \) is at least one (Cassan et al. 2012). On the other hand, recent analyses of the Kepler satellite showed that about 20% of all Sun-like stars have Earth-sized planets orbiting within the habitable zone (Petigura et al. 2013) (i.e., \( n_{\text{E}} = 0.2 \)). Also, the HARPS team estimated that almost 30% of solar-type stars have planets with an Earth mass or Super Earth mass (Pepe et al. 2011). If we assume that in these planets life eventually develops, then the probability of formation of life is one, and we can write \( f_I f_C L/L_\odot \approx 0.2 \).

The later factors of \( f_L \) and \( f_C \), and \( L \) are unclear since we only have data from one case that exists on the Earth. We do not know what fraction of life supporting planets eventually develop to harbor intelligent life. Does it have a fixed point of life evolution? With the probability of unity, there will be intelligent life, otherwise the probability of intelligent life is rare. Does emerging intelligent life need a long time, in the orders of billions of years, or it can happen in a short timescale? Also how long can intelligent life exist? Would it disappear by
self-destruction or live a long time, spreading over other planets, even in the form of artificial intelligent life. We recall the multiplications of these factors by $R = f_{\text{f}} f_{\text{C}} L/L_5$.

Now we can rewrite the Drake equation for the observation of a CIL with microlensing and apply the numerical values for some of the Drake factors. The result is

$$N_{\text{CIL},\mu} \simeq R \times N_{\mu},$$

where subscript $\mu$ represents microlensing events. For the parameter of $R$, we take an optimistic value assuming that every planet that supports life will eventually develop intelligent life (i.e., $f_{\text{f}} = 1$) and all intelligent life eventually develops an intelligent civilization (i.e., $f_{\text{C}} = 1$). For the lifetime of an intelligent civilization (i.e., $L$), while no signal from an intelligent civilization has been detected, we can assume that the present epoch of cosmology (after finishing the star burst epoch and present calm situation), there might be a burst of intelligent civilization in the universe. So let us take $L$ in the order of a hundred million years, while there are pessimistic estimations of the order of 200 years (Lemarchand 2009). The hypothetical longer timescale for the lifetime of an intelligent civilization could be due to developing and spreading of artificial intelligent life in larger areas of the Galaxy. Then let us take $L/L_5$ in the order of $10^{-2}$. Substituting numerical values for all the parameters, the number of intelligent life detections with SKA follow-up microlensing observations would be $N_{\text{CIL},\mu} \simeq 10^{-2} \times N_{\mu}$.

We can estimate $N_{\text{CIL},\mu}$ events for two cases of single and binary lensing. Assuming 2000 microlensing observations per year, we would expect to have $N_{\mu} = 30$, illuminating events from the binary and $N_{\mu} = 50$ illuminating events from the single lensing where the binary lensing $N_{\text{CIL},\mu}$ is of the order of 0.3 events per year and for the single lensing, it is of the order of 0.5 events per year. The next generation of microlensing events will certainly increase the number of microlensing candidates per year by probing larger areas, including the spiral arm directions and lowering the limiting magnitude of observations. So, in the near future, we may reach one microlensing event with a possible signal from intelligent life from the binary lensing events (taking into account optimistic values for the parameters of the Drake equation).

As we noted before, while the probability of detecting an intelligent civilization with binary lensing is less than that of single lensing, using the early warning system, we can be aware of caustic crossing of planets and as we discussed before; the probability of this event is about 85%. This creates the possibility of using the strategy of the target of opportunity in the observation of intelligent life with the SKA telescope.

6. CONCLUSION

In this work, we proposed using the gravitational microlensing as a natural telescope for magnifying signals from intelligent life at the Galactic scale. Microlensing can illuminate signals of a planet with the single or binary lensing mode for a short period of time and if in this period we observe these target with a radio telescope, these signals can be detected. We assumed that intelligent life is using the same wavelengths that we are using in our telecommunications. Telescopes such as SKA, which is designed for cosmological observation, are suitable for the observation of these signals.

We assumed an Earth-like military transmitter on a planet with an intelligent civilization and used the SKA telescope to detect transmitted signals. Then we simulate the number of microlensing events with enough illuminations from the planets orbiting the habitable zone that can be detected by the SKA telescope. In order to estimate the number of events, we performed a Monte-Carlo simulation and obtained the number of high magnification events in both single and binary lensing channels. We have shown that taking into account the wave optics effects in the gravitational lensing does not change the results of geometric optics. The result of the simulation is that for single-lens microlensing events, for 2.5% of the overall event, we will observe the illumination of the planet around the source star and for the binary lensing that is about 1.5% of all the events.

Finally, we used the Drake equation in our study and adapted the factors of this equation from the recent observations to estimate the number of intelligent life detections. For the factor of probability of intelligent life formation (i.e., $f_{\text{f}}$) and communicating civilizations (i.e., $f_{\text{C}}$), we adopt the optimistic values. Also, we assumed that intelligent life might be developed in the form of artificial intelligent civilizations and spread in the local areas of the Galaxy. The annual number of events, performing follow-up observations of microlensing events with the SKA telescope and getting a positive signal, is about 0.5 for illuminating events of single lensing and 0.3 for the case of binary lensing. While the number of binary lensing events is less than single lensing, the probability of the illuminating effect for the binary lensing is almost 85%. One of the advantages of binary microlensing events is that it can be identified long before the caustic crossing, using an early warning system of surveys. On the other hand, having binary lensing events, it can be observed by SKA as a target of opportunity mode, which make this program feasible. Increasing the number of microlensing events in the direction of the Galactic bulge as well as the spiral arms of the Galaxy is achievable with the next generation of microlensing surveys, using a wider field of view and increasing the sensitivity of detectors. This method of SETI observations would be a new item for the astrophysical applications of gravitational microlensing observations (Rahvar 2015).

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APPENDIX

WAVE OPTICS EFFECT AND SUPPRESSING OF SIGNALS

A point-like astronomical object produces a flat wave front at large distances from the source. Let us assume that we put a Young double slit experiment in front of this wave front. Slits at suitable separations result in fringes on the observer plane. The gravitational lensing system can play the same role as the Young double slit experiment by producing double or multiple images on the lens plane. The result would be interference on the observer plane where slits are located at astronomical scales far from the observer. The wave optics property of light in gravitational lensing is extensively discussed in Schneider et al. (1992). This method is also a complimentary observation for the detection of planets around the lenses (Mehrabi & Rahvar 2013).
In geometric optics, the caustic lines on the source plane are singular lines where the Jacobian of the determinant between the source plane and the image plane is zero. However, in the wave optics since the intensity of light is distributed in the diffraction fringes, the singularity is resolved. The magnification factor from a point-like source near the caustic line is given by

\[
\mu(y) = \frac{\mu_{\text{max}}}{Q^2} \left[ A_i \left( \frac{y}{y_0} \right) \right]^2,
\]

(20)

where \( y \) is the distance of the source from the caustic line, \( A_i(x) \) is the Airy function, and \( Q \approx 0.5357 \) is the maximum value of Airy function. The maximum magnification of the fringes as well as the wavelength of the Airy function depends on the Fermat potential as

\[
\mu_{\text{max}} = \frac{2^{5/3}\pi f^{1/3}}{\phi_1 \phi_{222}^{2/3} Q^2}, \quad y_0 = \left( \frac{\phi_{222}}{2f^2} \right)^{1/3},
\]

(21)

where \( \phi \) is the Fermat potential for a binary lens at the position of the images, the subscript is the spatial derivative in two directions, and \( f \) is the multiplication of the wavenumber to the Schwarzchild radius of lens \( f = 2kR_s \). For binary lenses, the Fermat potential is given by

\[
\phi(x, y) = \frac{1}{2}(x - y)^2 - q_1 \ln(|x - x_1|) - q_2 \ln(|x - x_2|),
\]

(22)

where \( q_1 \) and \( q_2 \) are the relative mass of lenses to the total mass of the system. \( x \) is the position of the image normalized to the overall Einstein radius, \( y \) is the position of the source normalized to the projected Einstein radius of binary system, and \( x_1 \) and \( x_2 \) are the position of lenses. The lens equation from the Fermat potential obtained by the extremum condition of this function (i.e., \( \partial \phi(x, y)/\partial x = 0 \)).

A detailed calculation of Fermat potential provides \( |\phi_{222}|^{-2/3}|\phi_{11}|^{-1} \approx q^{1/3} \) and the denominator of Equation (21) for the equal mass lens is of the order of 0.8. For the numerator of Equation (21), we adapt one meter size electromagnetic wavelength for an intelligent life transmitter, also one solar mass for the mass of binary lenses. The result is the maximum magnification of the planet’s signal, \( \mu_{\text{max}} = 75 \), during the caustic crossing. Using Equation (8) for a minimum amount of magnification for the detection, we obtain the limiting distance of \( D_L < 10 \) kpc for observability, which is well within the observable distance of sources in bulge microlensing events. Hence, the wave optics formalism does not change the results of what is calculated based on gravitational lensing in the geometric optics.

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