Microlensing as a Tool of Astronomy *

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As a result of the technical development of methods allowing *massive photometric survey* of microlensing events, microlensing has become a very unique tool of astronomy to investigate the dark matter problem, the shape of our Galaxy, and to search for extra-solar planets, especially, Earth-like planets. 1∼ 2 m class Space Telescope such as the Hands-On Universe Telescope (SHOUT); which is planning to build on the Japanese Experiment Module(JEM)/International Space Station (ISS), will open a new stage of microlensing observations not only follow-up observations of microlensing events, but also survey observations of new targets, i.e. the Galactic center, globular clusters, and nearby galaxies. The follow-up and survey observations of microlensing events using the Space Telescope will answer these questions; *What is dark matter?* , *What kind of object is MACHO?* , *Is our solar system unique?* and, *Are we alone?* .

keywords: microlensing,dark matter,MACHO,extra-solar planets, Earth-like planets,Space Telescope, Space Hands-On Universe Telescope(SHOUT)

1. Introduction

Microlensing is one of the effects of gravitational lens, where a star acts as a lens. When the lens star and the background source are well aligned at the milli-arcsecond level, due to the proper relative motion of each star, a time-dependent light amplification of the source is detectable(Paczynski 1986). This is called microlensing. But such alignment is very rare, *once in a million* .

Through the development of improved observation technology, this low probability of lensing has been overcome, *massive photometric survey* of microlensing events has become possible, and microlensing has become a very unique astronomical tool for investigating the dark matter problem, the shape of our Galaxy, and for searching for extra-Solar planets, especially, low mass planets like the Earth.

There are two main strategies applied in microlensing observations. One is microlensing *survey observations* performed with the primary goal of investigating the dark matter problem. To accomplish this, survey observations of huge numbers ($>10^7$) of stars must be made every night, using wide field ($>$ 1 square deg) detectors.

The other approach is *follow up observations* of microlensing events, the occurrence of which is announced through real-time alerts provided by microlensing survey teams, to detect anomalies of the light curve of microlensing event. These anomalies provide much information, for example, information indicative of the existence of planetary companions. However, the signals from these anomalies are often weak and of short duration (e.g. a few hours in the case of Earth mass planets). Thus, such observation requires high photometric precision and dense temporal sampling.

The Space Hands On Universe Telescope (SHOUT) has the potential to search for mi-

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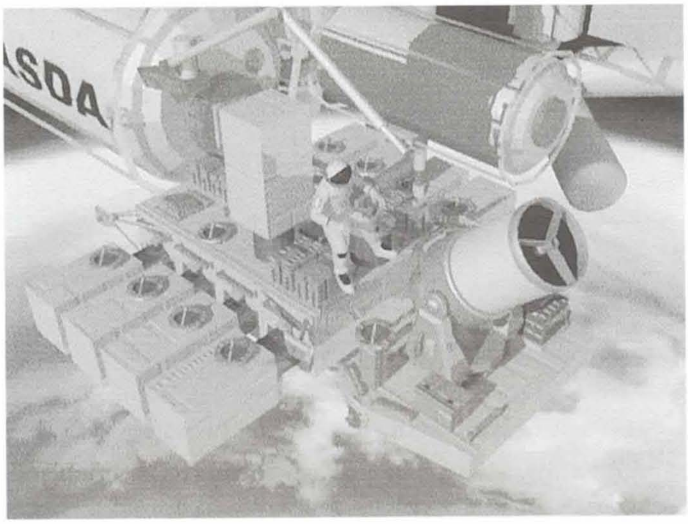

Fig.1 Artistic view of Space Hands-On Universe Telescope (SHOUT) attached to Japanese Experiment Module (JEM)/ Exposure Facility on International Space Station (ISS)

crolensing events using wide field detectors, and moreover, by means of SHOUT, it is possible to monitor anomalies of the light curve of a microlensing event without a break.

Thus SHOUT will open a new stage on microlensing observations allowing researchers to investigate the dark matter problem and to search for extra-solar planetary systems.

2. Space Hands-On-Universe Telescope

At presence, we start the discussion of the concept of *Space Factory* on Japanese Experiment Module(JEM)/International Space Station (ISS) and its application for building large astronomical facilities, such as a 10-20 m optical space telescope, *SPACE SUBARU*. At the same time, we will consider the astronomical mission as engineering prototypes for the building on JEM/ISS by EVA of astronauts and robotic arms; *Space Hands-On Universe Telescope (SHOUT)* for scientific education and research.

SHOUT is a 1~2m optical telescope. A space telescope is free from extinction and disturbance of light due to terrestrial atmosphere. Diffraction limited images of astronomical objects in a large field of view of a telescope is profitable to search for microlensing and to follow up anomalous light curve of microlensing events.

3. Microlensing

If the lens, the observer, and the source are perfectly aligned, then the lens images the source into a ring, called the Einstein ring, which has an angular radius of

$$\begin{aligned}\theta_E &\equiv \sqrt{\frac{4GM}{c^2}\frac{D_s - D_d}{D_d D_s}} \\ &= 0.9\mathrm{mas}\left(\frac{M}{M_\odot}\right)^{1/2} \\ &\quad \times \left[10\mathrm{kpc}\left(\frac{1}{D_d} - \frac{1}{D_s}\right)\right]^{1/2}, \qquad (1)\end{aligned}$$

where M is the mass of lens, and D_s and D_d are the observer-source and the observer-lens distances, respectively. This corresponds to a physical distance at the lens plane, Einstein ring radius r_E,

$$r_E = \theta_E D_d = 2 \sim 7\mathrm{AU}\sqrt{M/M_\odot} \qquad (2)$$

when the source is in the galactic bulge. If the lens is not perfectly aligned with the line of sight, then the lens creates multiple images of the source. The separation of these images is $\Delta\theta = \sqrt{\theta_s^2 + 4\theta_E^2}$, where θ_s the angular distance between the lens and the observer-source sight line. θ_s corresponds to a physical distance at the lens plane of the impact parameter $b = \theta_s D_d$. Note that the order of the separation angle is ~ 1 milli-arcsecond for a star in our galaxy, so it is impossible to see such images separately by traditional imaging methods. However, we can observe the amplification of the source light A due to the combination of magnified multiple images,

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \qquad (3)$$

where $u = \theta_s/\theta_E = b/r_E$ is the instantaneous source-lens separation in the units of the Einstein angle(Paczynski 1986). This phenomenon is called microlensing (Paczynski 1996; Gould 1996; Roulet and Mollerach 1997; Moa 1999 for a review).

The typical duration of the microlensing event is the Einstein ring radius r_E crossing time, $t_e =$

Fig.2 Galactic Bulge, photo by K.Ohnishi, Microlensing Observations in Astrophysics (MOA) Project at Mt John University Observatory, New Zealand.

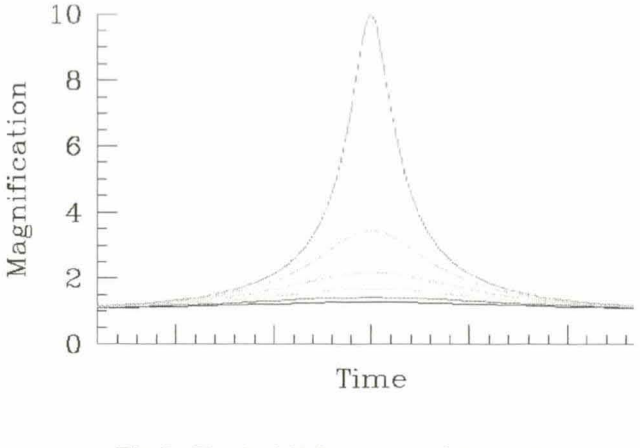

Fig.3 Typical light curve of microlensing, This show the each light curve with the minimum impact parameter $u_{min} = 0.1, 0.3.0.5, 0.7, 0.9, 1.1$ $r_E/v_\perp \sim 78\text{day}\sqrt{M/M_\odot}$,where $v_\perp$ is the transverse velocity of the lens relative to the observer-source line.

The *standard* light curves of microlensing event are *symmetric, achromatic*, and *non-repeating*. These signatures can be used to distinguish microlensing events from images of other variable stars.

From eq.3, $A - 1 \sim u^{-4}$ when $u > 1$. Thus such amplification phenomena due to a gravitational lens occur only when the sources exist within the Einstein angle of the lens. Therefore the optical depth is given by

$$\begin{aligned} \tau &= \int_0^{D_s} \mathrm{d}D_d \mathrm{d}M n(M) \pi (D_d \theta_E)^2 \\ &= \int_0^{D_s} \mathrm{d}D_d \left(\frac{4\pi G\rho}{c^2}\right) D_d \left(1 - \frac{D_d}{D_s}\right) \quad (4) \end{aligned}$$

where $n(M)$ is the mass number density of the lens and $\rho = \int \mathrm{d}M M n(M)$ is the mass density of the lens. The order of optical depth τ is 10^{-6} for Massive Compact Halo Objects (MACHO), and 10^{-7} for disk stars. The optical depth is so small that we must observe many source stars ($\sim 10^7$) to detect this effect. That is, the survey region at present is limited to dense star regions, i.e. LMC, SMC, and the Galactic bulge.

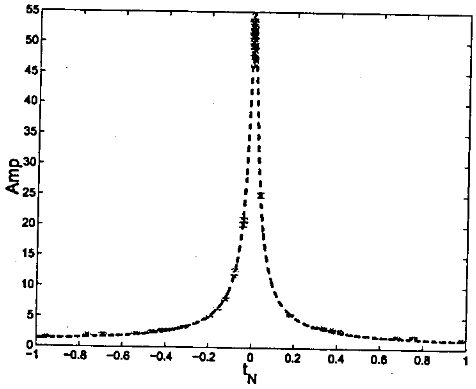

Fig.4 High magnification event OGLE-2000-BUL-12 by MOA Project (Yock et al. 2000)

4. Dark Matter

While we know the light distribution in our Galaxy reasonably well, the matter content of the Galaxy is not well understood. From the rotational curve of the Galaxy, it appears that there is a large amount of dark matter in the halo of the Galaxy. Paczynski (1986) proposed that microlensing can be used to detect or rule out astrophysical dark matter candidates, MACHOs. Three teams (MACHO collaboration, EROS, OGRE) began to search for microlensing events with the primary objective being to investigate dark matter. In 1993, these teams independently announced the first discovery of microlensing event (Alcock, et al. 1993; Aubourg, et al. 1993; Udalski et al. 1993).

At present, several survey groups (OGREII, EROSII, MOA, AGAPE) and follow-up groups (GMAN, MOA, MPS, PLANET) are searching for microlensing events.

In the survey observations, $\sim$ 500 events have been detected in the direction towards the Galactic bulge, 26 events towards LMC and 3 events towards SMC. The result obtained by these groups (Alcock et al. 2000; Lasserre et al. 2000) include the following: (1) the mass contribution of MACHO to dark matter in the Galaxy is less than 20%, (2) the mass of MACHO is $\sim 0.5 M_\odot$, (3) the optical depth towards the Galactic bulge is larger than expected. The latter finding strongly suggests that the bulge does not have simple spherical symmetry but instead has a barred structure. The former two findings are puzzling to us: we know that a white dwarf and a red dwarf are not MACHO candidate objects from the star counts with HST (Gould, et al. 1996). Thus, it is still highly controversial just what kind of object the MACHO is.

5. Breaking the Mass Degeneracy

Here we see how to determine the mass of MACHO from the observations. The microlensing light curve is characterized in terms of 4 parameters, $M, D_d, v_\perp$ and b. However, from the observations, we can obtain only two items of information, A_{max}, t_e. Thus, the MACHO mass cannot be determined for each microlensing event. Instead, the MACHO mass is evaluated statistically by assuming a halo model that describes the distribution of lens distance D_d and velocity $v_\perp$. A previous estimate of the MACHO mass ($\sim 0.5 M_\odot$) by Alcock et al. (2000) was obtained by assuming the *standard halo model* of the Galaxy. However, if we adopt the *non-standard halo model* proposed by Honma and Kan-ya (1998), it is possible to decrease the MACHO mass to a level below the brown dwarf mass. Is there any possibility to break the mass degeneracy in each microlensing event? The answer is *yes*, but only when we can get two additional items of information from the observations.

5–1 Finite source size effect and the case of a binary lens

The finite source size effect is important to obtain the proper motion of the lens, $v_\perp/D_d$. Assume that the source angular size θ_* is comparable to the Einstein ring angle θ_E. When the lens is on the surface of the source in the lens plane, each part of the finite source surface is amplified in a manner dependent on each impact parameter. Therefore, the maximum amplification of light A_{max} is smaller than that in the case of a point source. This *anomaly* of the light curve happens only when the lens passes over the surface of the source, and it depends on the ratio of θ_* to θ_E. If the radius of source can be estimated from its spectrum, we can obtain the proper motion of the lens.

A more important case in which it is possible to obtain other information concerning microlensing events is the binary lens case which occurs in about 10% of all microlensing events. When the source is outside of the caustic region, the two lens stars act as a single lens. However, when the source is within the caustic region, each lens star acts as a lens, that is, the source images are splint into 4. Note that the boundary of the caustic region is a singularity, i.e., the amplification is infinity if the source is a point source. In fact, when the source is on the caustic boundary, the amplification is much larger than that in the case of a single lens. This amplification depends on the size of the source. From this, we can obtain the size of the source. Moreover, the duration of such *spike* amplification is just the same as the caustic crossing time of the source. Therefore, we can obtain the transverse proper motion from this observation.

5–2 Parallax effect

Once the proper motion is measured, the only quantity necessary for determination of the lens mass is the lens distance. If more than three well separated telescopes monitor a caustic crossing event simultaneously, the time delay in the light curve caused by the parallax effect is detectable (Hardy & Walker 1995). From this, we can break the mass degeneracy completely. However, this method is limited by a requirement for optimum positioning of the telescopes.

Recently, Honma (1999) pointed out that a space telescope (e.g., HST or SHOUT) is a good instrument to observe the parallax effect of a caustic crossing event. A space telescope in orbital motion automatically causes the parallax effect. Through good photometric observations, we can detect the variation of the light curve at the caustic crossing event without a break. If we monitor the caustic crossing event using a SHOUT, we can break the MACHO mass degeneracy and we can unmask the nature of MACHO.

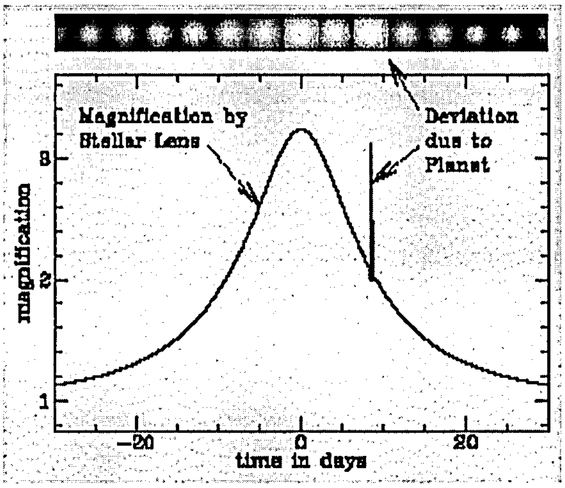

Fig.5 Extra spike peaks in microlensing light curve due to the planets (This figure is taken from web page of Microlensing Planet Search(MPS) Project).

6. Planet search

6–1 Planetary microlensing

If the lensing star has a planetary system, the signature of the planet can be seen, in most cases, as extra *spike* peaks in the microlensing light curve. Here the ratio of the mass of the planet to that of the main star is denoted by q. The area within the Einstein ring of the planet is q times smaller than that of the main star. Then, the ratio of the probability that the trajectories of the sources pass through the region of the Einstein ring of the main star is $\sim \sqrt{q}$. This rate is approximately 3% for Jupiter and the Sun. Thus, the probability of planetary detection seems to be small. However, the source passes through the caustic of the planetary system, which exits near the Einstein ring of the main star in the case where $q \ll 1$, and the light is amplified at infinity in the case of a point source. Then, the probability of detection of planets is much higher near the Einstein ring, in the region called the *lensing zone*. The typical length of the *lensing zone* for a lens towards the Galactic bulge is a few AU (see eq.2). This is a good match to many planets in the solar system. The typical duration in the case of a planet is $\sqrt{q}$ times that of the main star, i.e. a few hours for Earth mass planets. Table 1 shows the efficiency of planet detection and the typical time scale of a microlensing event (Gaudi et al. 1998; Nishi et al. 1999; Gaudi and Sakett 2000). Here we can say that in searching for planets, the microlensing technique is sensitive to planets as small as Neptune's mass, with orbital radii of a few AU.

There are many methods available to search for extra-solar planetary systems. An orbiting planet can make its presence known by altering the speed (radial velocity technique) or position (astrometry) of its main star. Up to now, more than 20 extra-solar planets have been detected by the radial velocity technique. However, these planetary systems are far from our own solar system: i.e., these systems have Jupiter-like mass planets whose orbit is a considerably smaller distance than that in the case of our solar system. This is due to a strong selection effect using this technique.

On the other hand, in the search for planets, microlensing is a sensitive technique for detection of Jupiter-like planets and the only technique available for detection of Earth-like planets. In the future, this technique may also be capable of detecting Earth-like planets using a special-purpose telescope in the case of high amplification microlensing events. From statistical studies of microlensing events, we can recognize how many planets exist around a typical star in the disk of the Galaxy, including planets similar to those in our own solar system.

Recently, the MPS and MOA collaboration reported the first discovery of an Earth-like mass planet through microlensing observations (Rhie et al.(MPS & MOA Collaboration) 2000). A slight variation in the brightness of the MACHO-98-BLG-35 event has been seen, and this may be caused by planets with a mass between that of the Earth and that of Neptune. This event is a high magnification event with a maximum magnitude magnification of ~ 80 in which slight variation in the light curve is caused by the small caustic at the center of the Einstein ring of the main star. Note that such a high magnification event has some advantages as a planetary survey target (Grist& Safizadeh 1998,Gaudi et al.1998). The advantages are that (1) the efficiency of detection of planets is high for this subset of events, (2) accurate photometry can be performed, (3) real-time electronic alerts for dense sampling can be issued easily, and (4) the time of a high magnification peak can be predicated well in advance. Of course microlensing events occur really, i.e. the probability of an event with peak magnification greater than A decreases with a tendency of $\sim 1/A$. However, since the efficiency of detection of planets is high in the case of such events, the probability of detection of planets of near Earth mass using for this strategy is of the same order as that for observations made by the ordinary strategy (see Table 1).

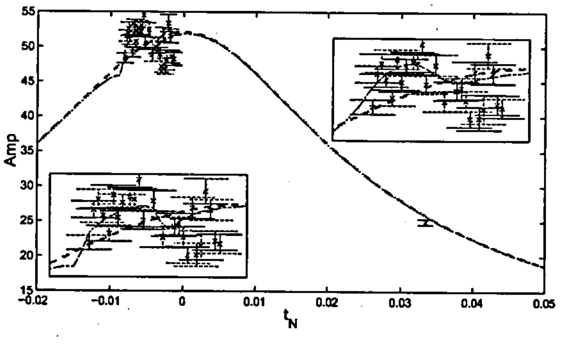

Fig.6 Light curve anomaly due to the plants (Yock et al. 2000).

6–2 Planet search by SHOUT

The main strength of the microlensing planet search technique is that it is sensitive to lower mass planets. If we use SHOUT, signals from planets down to the mass of Mars may be detectable. However, such an event is much more rare and of short duration. In order to detect low mass planets, a large number of stars must be monitored with a high sampling frequency. In the central Galactic bulge fields where the optical depth is highest, Ground-based images obtained using a 1 m-class telescope are seriously incomplete at or above the bulge main sequence turn-

Table 1 Planet detection efficiency and time scale of a microlensing *event.*

	Jupiter-like mass planets	Earth-like mass planets
well-monitored case	$10 \sim 30\%$	$\sim 3\%$
high amplification case	$\sim 100\%$	$\sim 10\%$
time scale	a few days	a few hours

off. On the other hand, in space images obtained using SHOUT, many of the main sequence stars are separately resolved. Thus, for the microlensing planet search, we require a large field view (> 1 square degree) and a high angular resolution (< 0.1") , i.e., a very large number of CCD pixels, $> (3.6 \times 10^4)^2$. Using such CCD, more than $\sim 2 \times 10^8$ stars are monitored once every 30 minutes or so with a photometric accuracy of $\sim 1\%$. Bennett & Rhie (2000) simulated the number of microlensing events detectable using a space telescope ($\sim$ 1.5 m aperture) and showed that it is possible to detect more than 4000 microlensing events and $\sim$ 2000 planets per bulge season. Using SHOUT, we can ascertain whether our solar system is quite a unique system or whether it is common kind of system in the Universe.

7. Probing the structure of Galaxy

The shape of the galactic halo is not well known due to lack of knowledge about the content of dark matter and its actual spatial distribution. Thus the optical depth and event rate of microlensing have a information of galactic structure, we can obtain the galactic structure to do the microlensing observation for every direction. But the direction of the present microlensing survey is limited to the LMC, SMC and Galactic bulge, because the number density of star to other direction is low or too high that it is impossible to separate the each star due to seeing limit due to terrestrial atmosphere. To obtain the knowledge of the structure of our galaxy, we need more large or different direction survey than the present survey. SHOUT has its potential to survey the region that is difficult on the ground based telescope, i.e., near Galactic center, globular cluster, and M31, and using SHOUT, it may be possible to make a map of the MACHO halo distribution through microlensing towards the galactic bulge, the spiral arm and globular clusters.

7–1 Galactic Center using K-band

Microlensing survey toward the galactic center($|\ell|, |b| < 1°$) is a good target. At presence, due to the high extinction($A_v \sim 20 - 30$) to Galactic center region, the survey is limited to the direction of Baade's window, which apart the $\sim 4°$ from Galactic center. Only this region, it is difficult to separate the contribution on the optical depth due to the bulge-bulge lensing and the bulge-disk lensing. Then we cannot determine the detail bulge structure. If we observe the galactic center using K-band, main contribution of microlensing is bulge-bulge lensing, and its time scale is very short $\sim$ 2 day, and its event rate is large $\Gamma \sim 3 \times 10^{-7}$/day (Gould 1995). Then using SHOUT during a fee week(or month), we could obtain the "new" information of inner bulge structure.

7–2 M31

It may be possible to make a MACHO halo map of M31 and other extragalaxies. M31 is considered to be a good target. Recently, a new technique for microlensing survey in the very dense region has been proposed (Alard and Lupton 1998), and the AGAPE group has started a survey of M31. M31 is well observed and the rotation curve has been measured out to 30 kpc, thus systematic uncertainties due to galactic model degeneracy are lower for M31 than that for the Galaxy. The inclination (77°) of M31 is advantageous for probing the M31 halo by the microlensing technique. The lines of sight to the far disk pass through a larger part of the M31 halo than the line of sight to the near side of the disk. Thus, the detection of near-far asymmetry in the spatial position of a candidate event would suggest the existence of M31 MACHO halo (Gyuk and Crotts 2000).

8. Conclusion

Microlensing is a new tool for astronomy, being applied to investigate dark matter, to study the structure of our galaxy, and to search for extra-solar planets. SHOUT has the potential to search for microlensing events and to monitor anomalies of the light curve of a microlensing event without a break. Thus SHOUT will open a new stage of microlensing observations to investigate the dark matter problem and to search for extra-solar planetary systems.

And more, from the byproduct of this observation, more than million's variable stars can be detected without any bias. This is good sample not only for science, but also for education!

In the new century, SHOUT will answer the primitive questions, *Is our solar system unique?* , *Are we alone?* .

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