1. INTRODUCTION

Dark matter searches are hybrids of particle physics and astrophysics in many aspects, and naturally, one can find the infusion of techniques and research paradigms from one field into the other. One very important fallout of this hybridization is that the importance of single purpose dedicated telescopes is being widely recognized. Baryonic dark matter searches utilize gravitational microlensing phenomenon that occurs when a foreground dark object traverses the line of sight of a target star (in the LMC, SMC and M31). What is measured in the microlensing experiments is the time variation of the brightness of the target stars. Therefore the stars have to be monitored constantly and that is not unlike tending an accelerator beam line day and night. (A subtle difference must be that an observer does not have to stay up during the day.) This “new mode” of telescope usage is orthogonal (and complementary) to the conventional “time-sharing mode” where “photon-starved” astronomers build the largest possible telescopes the funding allows and share them by allocating each observer a few nights at a time so that many different astrophysical phenomena are pursued independently and thus incoherently.

This “new telescope mode” is expected to become a new tradition in astronomy due to the enormous success of the current microlensing experiments (See Pratt et al, Bennett et al and Lehner et al in this volume). It is not hard to imagine the importance of single purpose dedicated telescopes if one is interested in learning the dynamics of the celestial bodies directly by monitoring their changes in time. The impressive catalog of ~ 40,000 variable stars collected by the MACHO experiment should be only the beginning of what are to come in the near future. The bread-and-butter astrodynamics single purpose telescopes can bring is boundless. Here we advocate that one of the most immediate beneficiaries of the “new tradition” of dedicated telescopes in optical and infrared bands can be the search for low mass planets through microlensing.

The trademark of microlensing signature of baryonic dark matter has been advocated to be the light curves that are achromatic, symmetric and non-repetitive. The symmetric light curve is due to the spherically symmetric gravitational...
potential of a point mass. When the mass has a small companion, the distribution of the gravitational potential changes ever slightly, but the light curve can have a substantial deviation from the symmetric shape, even though briefly in time. That is because lensing is a catastrophic phenomenon. We can capitalize on this catastrophic behavior of lensing to detect planets as small as the earth. Microlensing is the only ground-based method capable of detecting earth-mass planets and providing planetary statistics much needed for the future space-based planet search programs envisioned by the ExNPS panel.

2. The First Planet found through Microlensing?

The first candidate Jupiter mass planet was “found” in the first microlensing candidate event (GPE: Gold Plated Event) of the MACHO experiment. The microlensing event toward the LMC is achromatic and fits the symmetric single lens light curve with peak amplification 7.2 fairly well and there is no doubt that that is a microlensing event (Alcock et al., 1993). However, there are a couple of “anomalous data points” near the peak that are systematically shifted to the left from the single lens fit curve. One of us found that the ‘misfit’ can be explained if the lensing object has a companion of the fractional mass $\epsilon = 0.01$ (Rhie, 1994). On the other hand, the assumption of a binary lens introduces three more fit parameters and that leaves room for other fit parameter values. Dominick and Hirshfeld (1994) found that the data can be fit with $\epsilon = 0.414$. A binary lens system is characterized by two parameters, namely, the mass ratio and the separation (transverse distance on the lens plane) between the two masses, and a binary lens behaves very closely to a single lens (of the total mass) when the mass ratio or the separation is small. In other words, when the GPE is considered as a binary lensing event, the parameter space is confined to two small regions of small mass ratio or small separation because of the close proximity to the single lens behavior. (The binary lenses in the parameter space of small mass and small separation are practically a single lens and can not explain the “deviation points”.) Our best fit values are $\epsilon = 0.01$ and $\epsilon = 0.463$ and the corresponding fit curves are shown in figure 1. One should note that the two fit curves are quite distinct: The highest amplification point lies on the rising side of the curve with $\epsilon = 0.01$ and on the falling side of the curve with $\epsilon = 0.463$. In retrospect, one more data point near the peak might have resolved the dilemma of whether the lensing star has a Jupiter mass planet or is a dwarf binary star. For this particular event, we wouldn’t ever know because the probability for the lensing object to lens another star is $\sim R_E^2 n \sim 10^{-6}$, where $R_E$ is the Einstein ring radius and $n$ is the

Figure 1. The binary lens fits to the GPE: The solid curve is the small mass fit for $\epsilon = 1 - \epsilon_1 = 0.01$, and the lens parameters are shown on the right. The dashed curve is the small separation fit for $\epsilon = \epsilon_1$, whose lens parameters are shown on the left. $\hat{t}$ is the transit time of the Einstein ring radius of the total mass, $|\text{sep}|$ is the separation, $\theta$ is the angle of the source trajectory with respect to the lens axis where $\epsilon_1$ is the fractional mass to the positive direction in our convention, and $|u_{\text{min}}|$ is the distance of the source trajectory to the lens axis.
surface number density of the LMC.

3. Microlensing Signature of Earth Mass Planets

If we summarize the lesson from the GPE event as a binary lens, (1) When the mass of the companion is small ($e << 1$), the microlensing light curve is largely that of a single lens. (2) However, the small mass companion can produce an unmistakable signal by modulating the single lens curve substantially. (3) The modulation signal lasts only briefly and the unambiguous detection can be made only through dense sampling of the light curve. In addition, (4) The separation (transverse distance between the star and planet on the lens plane) can not be too big because the planetary signal will be dissociated from the stellar signal. Therefore, the separation has to be within a certain interval, and the interval is called the ‘lensing zone’. Of course, the “lensing zone” scales with the total mass ($\approx 0.6 R_E - 1.6 R_E$ for low mass planets, where $R_E$ is the Einstein ring radius of the total mass ($\approx$ stellar mass). What should be noted here is that the “lensing zone” scales with the Einstein ring radius $\propto \sqrt{\text{stellar mass}}$. It is a practical “rule of thumb” that the “lensing zone” is given by $\approx a^{-1} R_E - a R_E$, where $a (> 1)$ is the fudge factor depending on the mass ratio of the planet, detection strategy, and etc.

The duration of a microlensing event depends on many parameters such as the mass, transverse velocity and reduced distance of the lens, and also the size of the source star. However, for the current microlensing experiments toward the Galactic Bulge and the Large Magellanic Cloud, one can estimate the duration as a function of the mass of the lens by considering the typical transverse velocity and reduced distance. The mass dependence goes as $\propto \sqrt{\text{mass}}$, and the duration for a solar mass object is typically a couple of months and a few days for a Jupiter mass brown dwarf, etc. When the Jupiter mass object is a planet around a star, we can estimate that the modulation duration is typically a few days. If we consider the exposure time of a few minutes as is the case in the current microlensing experiments toward the Bulge, one can sample a given modulation due to a Jupiter mass planet about 1400 times in principle. Of course, the currently active telescopes for microlensing experiments are survey telescopes and can not afford to follow one event with such a scrutiny, but it demonstrates that planet search via microlensing is not an idle idea at all.

What one immediately realizes is that earth mass planet search via microlensing is also a sure possibility. The modulation duration due to an earth mass planet is a few hours and hence the signal can be sampled as many as 45 times in principle. The modulation signal typically has the shape of a wavelet and one can resolve the peaks and troughs of the “modulation wavelet” without ambiguity. Actually, detecting Mars’s ($0.1 m_{\odot}$) doesn’t seem to be an impossibility when estimated along the same line. However, the size of the source stars begins to affect the signal seriously when the mass of the planet falls below 10 $m_{\oplus}$ or so. In other words, the size of the source star (precisely speaking, the size of the star projected onto the lens plane with the observer at the focus of the projection) becomes comparable to the variation in the modulation wavelet (of a point source), and the planetary signal gets smoothed over due to the integration effect. If the modulation wavelet has comparable troughs and peaks, the planetary signal can be completely washed out, whose case we would like to term “interference effect”. If the peak is dominant over the troughs – or, the trough is dominant over the peaks, the signal will not be averaged to zero, but it gets broadened and eventually buried below the measurement error, which we may term “broadening effect” (meaning smoothing without destructive interference).

Therefore, it is important to carry out realistic calculations to decide upon the feasibility of detecting $1 - 10 m_{\oplus}$ planets. According to our calculations (Bennett and Rhie, 1996), the probability to detect the planetary signal of an $10 m_{\oplus}$ planet in the lensing zone is $\sim 15\%$, and for an earth mass planet, the probability drops to $\sim 2\%$. We expect that the probability will decrease even more drastically for the mars mass planets, and a work is in progress for the sake of confirmation.
4. Planetary Binary Lenses

In order to discuss what we can learn from a given planetary binary lensing event, it is necessary to know about binary lenses. When a planetary system falls in the line of sight of a background star, the planetary system can be considered primarily as a binary lens because what matters is the planet falling in the lensing zone. (Of course, more than one planets can fall into the “lensing zone”, and the signature will be multiple “modulation wavelets”.) A binary lens simply means that the lens system consists of two bodies jointly governing the gravitational potential that determines the optical paths, and the resulting configurational behavior of the images and their sources are described by the binary lens equation. If $\omega$ and $z$ denote the source and image positions in the lens plane as a complex plane, the binary lens equation is

$$\omega = z - \frac{1 - \epsilon}{\bar{z} - \bar{x}_s} - \frac{\epsilon}{\bar{z} - \bar{x}_p},$$

(1)

where $\epsilon$ is the fractional mass of the planet, and $x_s$ and $x_p$ are the positions of the star and planet respectively. We work in units of the Einstein radius, $R_E$, of the total mass $M$. Eq. (1) has 3 or 5 solutions ($z$) for a given source location, $\omega$.

If $J_i$ is the Jacobian determinant of (the transformation given by) the lens equation at the position of the $i$-th image, the amplification of the image is given by the size of the image with respect to the size of the source. Therefore, the microlensing amplification (or total amplification) is given by

$$A = \sum_i |J_i|^{-1}.$$

(2)

The sign of $J$ describes the relative orientation of the area elements, and hence an image with $J < 0$ is a flipped image and an image with $J > 0$ is an unflipped image. $J = 0$ not only defines the boundary between flipped and unflipped images but also where the images enormously brightens because of the inverse relation with the amplification $A$. This singular (or catastrophic) behavior is at the heart of the microlensing as one of the most powerful tools in planet search. The source
positions that produce images falling on the critical curve \( (J = 0) \) are called \textit{caustic curve}, and the caustic curve of the binary lenses changes its shape, size, position, and topology by joining and splitting as the lens parameter (\( \epsilon \) and \( l \equiv |x_s - x_p| \)) changes. The caustic of a binary lens consists of one, two, or three \textit{closed cuspy loops}, and this geometric diversity needs to be understood somewhat rigorously because that is where the planetary signature lies.

For a planetary binary lens (\( \epsilon << 1 \)), one caustic (almost a point) is always near the star (just as in a single lens – so, we might as well call “stellar caustic”), and hence the planetary signature “modulation wavelets” are determined by the distribution of the “planetary caustics”. When the separation \( l > 1 \), there is one “planetary caustic” (of diamond shape) near the planet, and the “modulation wavelets” are “peak-dominated”. When the separation is \( l > 1 \), there are two triangular shape caustics (reflection symmetric), and the “modulation wavelets” tend to be “trough-dominated”. (See the plates in Bennett and Rhie, 1996.)

5. Conclusion

So, what can we learn about the planet once a planetary microlensing event is detected? As we have discussed before, the mass ratio of the planet with respect to the stellar mass can be determined without ambiguity. The projected distance between the star and the planet can be determined (in units of the Einstein ring radius) from the time difference between the peak of the stellar light curve and the appearance of the planetary signal. The possible two-fold ambiguity – the separation \( l \) or \( l^{-1} \) \( (l > 1) \) – can be resolved because of the distinctive nature of the modulation wavelets for \( l > 1 \) and \( l < 1 \).

More than one planet can fall into the “lensing zone”, and the lens system may have to be considered as an \( n \)-point lens system where \( n > 2 \). However, the gravitational interference between the planets can be ignored most of the time and hence the signature of two planets, for example, in the “lensing zone” will be simply two modulation wavelets on the symmetric stellar light curve. (The interference becomes significant when the separation of the planets is order of the Einstein ring radius of the total mass of the planets.)

The only feasible target site for microlensing planet search is the Galactic Bulge not only because the other galaxies have low microlensing probabilities (the detection rate by the MACHO experiment toward the LMC is \( 3 - 4 \) per year) but because one is looking for lensing events by normal stars (main sequence stars) that may host planets. With a 2m survey telescope, one can detect \( \approx 250 \) microlensing events, and a network of 1.5 – 2 m follow-up telescopes in Australia, Chile and the South Africa (and also the South Pole) will be able to monitor the events with sufficient precision. With photometric precision 1%, the detection probability of an earth mass planet in the lensing zone is \( \approx 2\% \) and hence one may be able to detect a couple of earth mass events per year. The frequency of planets and especially that of earth mass planets constitutes a totally unknown territory. It is an exciting possibility that one can detect planets \textit{unambiguously} through microlensing from earth mass to Jupiter mass.

The Galactic Bulge is not visible during the austral summer (Nov., Dec., Jan.), and the telescope network can be pointed toward the satellite galaxies for dark matter search or possible signatures of planets orbiting the stars in the satellite galaxies.

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