NEW OPPORTUNITIES IN MICROLENSING AND MESOLENSING

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ABSTRACT

During the coming decade hundreds of thousands of lensing events will occur in fields that are targets of regular photometric monitoring. Although lensing events occur with low probability, the large numbers expected will allow us to detect signals from significant numbers of even exotic objects, and to conduct unique population studies of distant stellar systems and of dark and dim masses in the Solar neighborhood.

Much of the monitoring is designed to pursue goals not directly related to lensing. For example Pan-STARRS and LSST, both designed primarily with other science goals in mind, are well-suited to the discovery of lensing events. A large subset of the events can be well-studied by whichever team discovers them. Others, predicted to contain short-lived signals, can be the subjects of alerts that spark worldwide cooperative follow-up. Whatever the light-curve characteristics, the sites of many events will be observed at a variety of wavelengths, for example to identify the lens and measure its motion.

The ability to identify and correctly interpret lensing events requires a strong theoretical and technical framework, and can advance several important areas of astrophysics. These include establishing more definitive limits on the fraction of galactic dark matter comprised of *MAssive Compact Halo Objects (MACHOs)*, studying populations of binaries in galaxies out to 2-3 Mpc, and revolutionizing the study of the Solar neighborhood.

Lensing is the only avenue to the systematic study of the large but largely undiscovered population of local isolated neutron stars and black holes. Lensing can also provide gravitational measurements of the masses of nearby dwarf stars, brown dwarfs and planets. Lensing studies of nearby planetary systems can complement radial velocity, transit and imaging studies. In some cases, all of these approaches can be applied to the same system, for detailed studies of planetary system architecture.

Until now, the discovery of lensing events has proceeded entirely through photometric monitoring programs. During the next decade we expect astrometric effects to be detected when nearby masses serve as lenses. We also expect to predict and subsequently study lensing events, pioneering “targeted” studies. In short, improved monitoring and analysis techniques, supplemented by innovative approaches to the detection of lensing events can usher in a new era in lensing studies.

1. INTRODUCTION

We begin below by providing background on lensing and on observing programs designed to discover lensing events. We review their significant successes as well the challenges that lie ahead. In §2 we point out that all-sky surveys, specifically Pan-STARRS and LSST, will be capable of discovering large numbers of lensing events across the sky. This could yield rich science returns, for example exploring the content of the Galactic Halo in all directions. In addition, the variety of background fields containing both source stars and potential lenses will provide unique insights into the characteristics of stellar populations as a function of galaxy type and local environment. In §3 we focus on the rich science returns associated with the study of mesolensing, i.e., lensing by nearby masses. We discuss not only the science goals that can be achieved through mesolensing studies, but also the likely successes, within the next decade, of the search for astrometric events and of targeted lensing studies. We end in §4 with a brief discussion of the resources needed in order to achieve the goals possible within the next decade.

1.1. *Lensing*

A lensing event occurs when light from a background source is deflected by an intervening mass. Einstein (1936) published the formula for the brightening expected when the source and lens are point-like. The magnification is 34% when the angular separation between source and lens is equal to θ_E, an angle now referred to as the Einstein angle.

$$\theta_E = \left[\frac{4GM(1-x)}{c^2 D_L}\right]^{\frac{1}{2}}$$

$$= 0.01'' \left[(1-x)\left(\frac{M}{1.4\,M_\odot}\right)\left(\frac{100\,\mathrm{pc}}{D_L}\right)\right]^{\frac{1}{2}} \qquad (1)$$

In this equation, M is the lens mass, D_L is the distance to the lens, D_S is the distance to the source, and $x = D_L/D_S$. The time required for the source-lens separation to change by an Einstein diameter is

$$\tau_E = \frac{2\,\theta_E}{\omega}$$
$$= 70\text{days}\left[\frac{50\,\text{km/s}}{v_T}\right]\left[\frac{M}{1.4\,M_\odot}\,\frac{D_L}{100\,\text{pc}}\,(1-x)\right]^{\frac{1}{2}} \quad (2)$$

Although τ_E is directly related to the lens mass M, solutions are highly degenerate because of its dependence on the relative speed v_T, and on the distances to both lens and source.

Einstein did not consider the effect to be observable because of the low probability of such close passages and also because the observer would be too "dazzled" by the nearby star to detect changes in the background star. In 1986, Bohdan Paczyński answered both of these objections by noting that low-probability events could be detected because monitoring of large numbers of stars in dense source fields had become possible, and by suggesting lensing as a way to test for the presence of compact *dark* objects.

1.2. *Observing Programs*

The linking of the important dark-matter problem to lensing, at just the time when nightly monitoring of millions of stars had become possible, sparked ambitious new observing programs designed to discover lensing events. Given the fact that episodic stellar variability of many types is $100-1000$ times more common than microlensing, success was not assured. To be certain that events they discovered had actually been caused by lensing, the monitoring teams adopted strict selection criteria.

In fact, these early teams and their descendants have been wildly successful. They have convincingly demonstrated that they can identify lensing events. More than 4000 candidate events are now known[1], among them several "gold standard" events which exhibit effects such as parallax and lens binarity.

Perhaps the greatest influence these programs have had is in demonstrating the power afforded by frequent monitoring of large fields. In addition to discovering rare events, the "needles" in a "haystack" of other variability, they have also yielded high returns for a number of other astrophysical investigations, including stellar structure, variability, and supernova searches. One may argue that the feasibility of the wide-field programs discussed in §2 was established by the lensing monitoring programs.

1.3. *Challenges*

1.3.1. *Perturbed Light Curves*

Whether or not the lensing programs have successfully established the presence or absence of MACHOs in the Halo is more controversial. Although the maximum fractional component of MACHOs computed by the MACHO team is approximately 20% (Alcock et al. 2000), the fraction of Galactic dark matter in the form of MACHOs could be smaller.

Conversely, one may argue that the first generation teams, and even ongoing observations may be *underestimating* lensing event rates by overestimating their detection efficiencies. This would make the true rate, and perhaps the number of MACHOs, larger than presently thought. There is in fact some evidence that past and ongoing observations are either missing or misidentifying some lens events that deviate from the point-lens/point-source form. We can infer this from the fact that both binary lens and binary source events appear to be under-represented among published events (See e.g., Night et al. 2008).

It is important to develop the ability to reliably identify and correctly interpret all events that deviate from the standard point-lens/point-source form. These events provide diagnostics that allow the true detection efficiencies to be measured. They also provide a wealth of information about the lensing events themselves. They can break the degeneracy associated with the simplest light curves.[2] **Ensembles of such events can establish key population characteristics such as the frequency, mass-ratio distributions, and orbital distributions of binaries in external galaxies.**

1.3.2. *Planets*

The search for planets is an important ongoing enterprise. Lensing can contribute to this search in several important ways. For example, in contrast to transit and radial velocity methods, lensing is sensitive to planets in face on orbits. In addition, lensing is effective at discovering both low-mass planets and planets in wide orbits. Finally, it is ideally suited to discovering planets at large distances and therefore over vast volumes.

In addition, we have recently begun to explore the opportunities of using lensing to study planets orbiting nearby (<1 kpc) stars (Di Stefano 2007, Di Stefano & Night 2008). **Fortuitously, the Einstein ring associated with a nearby M dwarf is comparable in size to the semimajor axes of orbits in the M dwarf's zone of habitability (Figure 1). Events caused by nearby planets can be discovered by monitoring surveys, or through targeted lensing observation. A targeted observation is one in which the lens can be detected prior to the event, and its path predicted, so that the timing of a future event can be estimated and resources to monitor the event can be planned in advance.**

During the years just after planets began to be regularly discovered via radial velocity techniques, it was

[1]Most of the events discovered so far were generated by low-flux stellar masses along the direction to the Bulge.

[2]The additional features found in perturbed light curves can often allow physical dimensions, such as the radius of the source star, to be related to the Einstein radius.

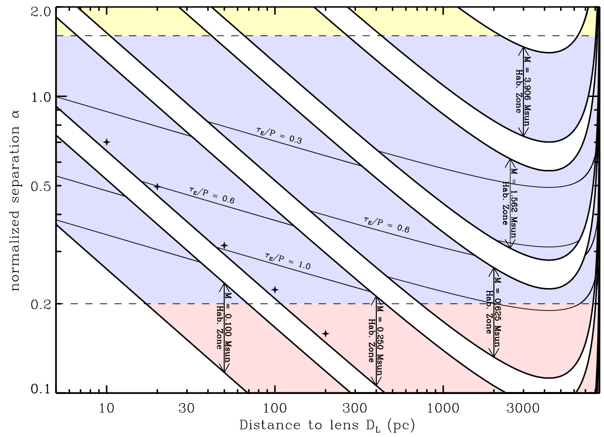

FIG. 1.— α vs D_L for the habitable zones (HZs) of low-mass stars. Each colored bar represents a star with a given mass: $M = 0.1\,M_\odot$ on the lower left, increasing by a factor of 2.5 for each subsequent bar. The lower (upper) part of each bar corresponds to the inner (outer) edge of the HZ for a star of that mass. The upper horizontal dashed line at $\alpha = 1.6$ marks the approximate boundary between "wide" systems, in which the planet and star act as independent lenses (Di Stefano & Scalzo 1999a, 1999b), and "close" systems in which distinctive non-linear effects, such as caustic crossings provide evidence of the planet (Mao & Paczyński 1991; Gould & Loeb 1992). All of the planets detected so far have model fits with α lying between 0.7 and 1.6. In this range, the effects of caustics are the most pronounced. As α decreases, the effect of the planet on the lensing light curve becomes more difficult to discern; the horizontal dashed line at $\alpha = 0.2$ is an estimate of a lower limit. Contours with constant values of the ratio τ_E/P, where P is the orbital period, are also shown. This is because the probability of detecting the planet in close systems ($\alpha \leq 0.5$) is increased by the orbital motion. For $\alpha > 0.2$, systems with large orbital motion are potentially detectable by current observations.

hoped that lensing would soon take its place as an important and high-throughput planet-discovery method. Microlensing planet searches have focused on discovering short-lived signatures in ongoing lensing events (Mao & Paczyński 1991; Gould & Loeb 1991; Bolatto & Falco 1992). Such signatures are produced when there is a near coincidence between the size of the Einstein ring associated with the star and the projected orbital separation of a planet orbiting it. Although only a relative handful have been discovered so far, the rate of discovery is increasing (Bond et al. 2004; Udalski et al. 2005; Beaulieu et al. 2006; Gould et al. 2006; Gaudi et al. 2008a; Bennett et al. 2008; Dong et al. 2008).

An alternative method was suggested soon after lensing planet searches began. The method identifies planets in wider orbits, in which the star and planet can serve, almost independently, as lenses. The signature can be a short-lived event (from several hours to several days), when the planet alone serves as a lens (Di Stefano & Scalzo 1999a), or a "repeating" event, consisting of both a short- and long-duration event that signals sequential lensing by the planet and star (Di Stefano & Scalzo 1999b). It is even possible to detect a succession of events involving different planets orbiting the same star. If stars tend to harbor multiple planets, the wide-orbit channel is likely to be important for planet discovery (Han 2007, Di Stefano & Scalzo 1999b)

Ongoing observations already can discover short-duration events. The OGLE team (Udalski 2003) and the MOA team Bond et al. 2001) now monitor some directions of the sky several times per day. The results have been dramatic. Events with estimated values of $\tau_E \sim 2$ days have been identified, and are well-sampled enough to allow meaningful fits. While not all of the candidate events are likely to be lensing events, many of the light curves appear to be well fit by lensing models. The OGLE team is moving forward with plans for further improvements. In addition, the Korean government has recently approved a project that will be a significant step forward: the combined efforts of three Southern Hemisphere sites will provide 10-minute cadence monitoring of approximately 16 square degrees. Sampling this frequent will discover short-duration events caused by Earth-mass planets, and will also allow the monitoring team to serve as its own "follow-up" team.

The frontiers in using lensing to discover planets lie in broadening the criteria presently used in planet searches. By identifying short-duration events we will discover planets in wide orbits. We may be able to subsequently image some of these. Lensing can discover free-floating planets as well. Using lensing to discover nearby (<1 kpc) planets is an intriguing new direction of research. When nearby stars pass in front of background stars, we will either see evidence of lensing by a planet or else will be able to assess the probability that the star is orbited by a planet.[3] Finally, lensing is ideally suited to the discovery of planets in the habitable zones of nearby low-mass stars. Such planets may be the most common places in the Universe to host life. Although the short-duration events that can signal their presence have characteristics that have not yet been observed, detecting them should be within reach during the next decade. (This assumes that sufficient

[3] While the requirement of passing a background star may seem restrictive, we note that transits, e.g., can also only be detected in a small subset of all possible stars.

telescopic resources and theoretical and analysis support is available.) Photometry precise to $\sim 1\%$ provides good sensitivity to the effects of planets, and extends the duration over which subtle effects can be detected.

2. LENSING EVENTS IN WIDE-FIELD SURVEYS

During the next few months, Pan-STARRS, which will monitor the sky from Hawaii, is slated to begin taking data. Within a decade it is likely to be joined by a second all-sky monitoring program, LSST, which will be based in Chile. **Although the design of these surveys was primarily motivated by other science goals, they can nevertheless discover more lensing events per year than most programs designed specifically for lensing studies (Table 1).** Some directions of the sky will be monitored every night, and others will be visited at intervals of $3-6$ days.

Although the monitoring cadence may not seem ideal for the study of lensing events, calculations show that excellent photometry can compensate. In fact, most lensing events discovered so far are long enough in duration that a dozen or more points above baseline will be sampled for typical events. Consider that $\sim 2/3$ of the > 600 candidate events identified by the OGLE team in 2008 had values of $\tau_E > 20$ days. The majority of these relatively long duration events had values of τ_E larger than 30 days, many much longer. In addition, with the photometric sensitivity of the all-sky programs, many events can be detected for intervals ~ 3 times longer than τ_E. By pinning the light curve down at the $\sim 1\%$ level for a dozen or more points, even many perturbations from the point-lens form can be correctly identified (Di Stefano 2007). This means that **the all-sky surveys can themselves provide satisfactory sampling of a wide range of light curves. To accomplish this, identification and analysis tools must be designed and employed. In addition, identification and alert strategies must be developed if short-duration events or short-lived deviations of longer events are to be studied.**

The science goals that can be achieved by the all-sky programs are diverse, and each is important. Table 1 shows only results for nearby lenses, or *mesolenses*. These are discussed in §3. Because wide-field surveys will be successful in finding dark compact objects that serve as lenses, we note that **one of the most important type of nearby lens that can be found by the all-sky surveys are isolated neutron stars and black holes. Lensing can discover them and measure the masses of a subset. Events caused by nearby dark compact objects are good candidates for observations with *HST* because the astrometric shifts caused by lensing, never before detected for a stellar lens, can be measured.**

For more distant lenses, all-sky monitoring confers several advantages. Whereas the only directions out of the Galactic plane consistently monitored by microlensing programs so far have been toward the Magellanic Clouds and M31, **Pan-STARRs and LSST will monitor many directions through the Halo and will thereby provide definitive results on the MACHO and stellar content of the Halo (and Local Group dwarf galaxies as well), if they look for evidence of lensing.** In addition, **searches for both simple and perturbed light curves will allow these all-sky surveys to measure the mass function and binary frequency for galaxies within $2-3$ Mpc.**

3. MESOLENSING

The portion of the Universe we know best is our local "neighborhood", the region within a few hundred parsecs. Yet, in addition to many well-studied stars and nebulae, this region hosts numerous dim objects that we still know little or nothing about. For example, within 450 pc there are roughly 10^7 low-mass dwarfs (M-, L-, and T-dwarfs), 10^6 white dwarfs (WDs), 10^5 neutron stars (NSs), and 10^4 black holes (BHs). However, the only BH candidates, and all confirmed BH binaries are more distant (Mao et al. 2002; Bennett et al. 2002; Poindexter et al. 2005; McClintock & Remillard 2003). Moreover, only about 20 radio pulsars and isolated NSs have been detected within 450 pc (see, e.g., Posselt et al. 2007). While perhaps 1% of the local WDs are now known (see, e.g., Kleinman et al. 2004; Luyten 1999; McCook & Sion 1999), and many low-mass dwarfs as well (Kirkpatrick 2005; Cruz et al. 2003; Reid et al. 2002; Burgasser 2001), key characteristics of the population, such as the mass distribution, have not yet been well measured. Fortunately, because these objects deflect light from background sources, they can be studied through their actions as gravitational lenses. Gravitational lensing can measure mass, and can discover and study dim companions, including planets.

Nearby lenses form a particularly interesting class (Di Stefano 2008a, 2008b). They tend to have larger Einstein rings (Equation 1). Consequently it can be easier to detect the astrometric effects they induce when they serve as lenses (see, e.g., Dominik & Sahu 2000; Honma & Kurayama 2002). In addition, their angular speeds tend to be higher. The combination of high angular speed and large Einstein ring produces high event rates, and can also yield photometric effects, such as apparent "jitter" in the baseline of an otherwise "normal" microlensing light curve. The chance to successfully measure the lens mass is greatest for nearby lenses (§3.1). Perhaps most exciting, the lensing regions of nearby lenses can cover so much area so quickly, that future events can be predicted. Nearby lenses have been referred to as *mesolenses*.

The advantages of lensing studies of M dwarfs and brown dwarfs are to obtain direct mass measurements and to probe for the presence of dim companions, including planets. Lensing is sensitive to planets in the zone of habitability of nearby M dwarfs (Di Stefano & Night 2008). There are many reasons to identify NSs and BHs within roughly a kpc. Fundamental science can be advanced by determining the relative numbers

TABLE 1
Nearby-Lens Event Rates

Lens type	**Past** per decade per square deg.	**Present** per decade per square deg.	**Future** per decade per square deg.	**Future** per decade **over 150** square deg.
M dwarfs	2.2	46	920	1.4e5
L dwarfs	5.1e-2	1.1	22	3200
T dwarfs	0.36	7.6	150	2.3e4
WDs	0.4	8.6	170	2.6e4
NSs	0.3	6.1	122	1.8e4
BHs	1.8e-2	0.38	7.7	1200

Each predicted rate is valid for the direction toward the Bulge. (See Di Stefano 2008a, 2008b for details.) **Past:** the observing parameters apply to the first generation of monitoring programs, including MACHO. **Present:** applies to the present generation, including OGLE III and MOA. **Future:** applies to upcoming projects such as Pan-STARRS and LSST. The effective area containing high-density source fields is ~ 150 sq. deg.; this is used in the last column. In fact, near-field source stars spread across the sky will also be lensed, adding to the rate of lensing by nearby masses; the above estimates for lensing by nearby masses are fairly conservative. **The high rate of mesolensing is demonstrated by the serendipitous lensing of an A0 star at 1 kpc by an unknown nearby mass (Fukui et al. 2007; Gaudi et al. 2008b). The rate of nearby-lens events is high. Even if the efficiency of event selection is only $\sim 1/3$, the number of events that can be studied is large. Each provides a test for multiplicity. In addition, even if masses can be extracted for only $1/10-1/3$ of selected events, the consequences will be important. Note that the total rate of lensing, including by lenses located beyond 1 kpc, is higher.**

of NSs and BHs, measuring the distributions of NS and BH masses and velocities, and determining the fraction of them with low-mass companions. In addition, if lensing is to discover or place meaningful constraints on the fraction of the halo comprised of MACHOs, it is crucial to identify and eliminate the contribution of nearby stellar lenses.

3.1. *Measurements of Gravitational Mass*

Understanding the fundamental properties of stars is of crucial importance in astrophysics and cosmology. Stars and stellar populations have rich and interesting physics of their own, but also serve as distance indicators, tracers of gravitational potential, and probes of the intervening diffuse matter. In order to provide a necessary foundation for theoretical models, quantities such as stellar masses, radii, and luminosities must be measured without making any assumptions about the internal physics of stars. Despite their prime significance, such absolute measurements are extremely hard to obtain.

The key parameter of a stellar-evolutionary model is the total mass. There are only two methods that have provided direct mass estimates of stars, i.e. estimates based solely on the gravitational effect of a star on other objects. The first method is to apply a generalized Kepler's Third Law to the motion of binary stars and planetary systems. The second approach is to observe the deflection of light from a distant source in the gravitational field of the star, as described by General Relativity. The fundamental problem with the former technique is that the presence of a binary companion can significantly alter the star's evolution. The latter effect, on the other hand, is very small for normal stars and occurs with low probability. However, with the advent of wide-area time domain surveys the prospect of applying the light deflection technique improves dramatically.

In principle, the duration of a microlensing event carries information about the mass of the lens. Unfortunately, while the microlensing light curve provides the key discovery signature, it is insufficient to solve uniquely for the mass, the distance and the transverse velocity of the lens. The parameter degeneracy can be broken completely if both the relative lens-source parallax $\pi_{rel} = D_L^{-1} - D_S^{-1}$ and θ_E are known, yielding a purely geometric mass measurement: $M = \theta_E^2/(\kappa\,\pi_{rel})$, where $\kappa = 4G/c^2$.

This is the only method that has been successfully applied to weigh a star–other than the Sun–without making assumptions about its interior structure or the effects of binary evolution. (See the papers on the event "LMC-5": Alcock et al. 2001a; Alcock et al. 2001b; Gould 2004; Gould, Bennett, & Alves 2004; Drake, Cook, & Keller 2004; Nguyen et al. 2004.)

A few percent of microlensing light curves constrain the dimensionless parallax $\pi_E = \pi_{rel}/\theta_E$. In the ideal case of a resolved lens, the relative lens-source proper motion μ_{rel} can be measured, providing the remaining piece of the puzzle: $\theta_E = \mu_{rel}\,\tau_E$. However, it is difficult to obtain both pieces of information required for a complete microlensing solution, primarily because in all but two cases so far the lens is only detected indirectly by its influence on the source. Out of a few thousand events discovered to date, only a handful allowed any estimate of the lens mass. The only existing mass measurement for a single microlens comes from the LMC-5 event caused by a nearby M dwarf.

The main difficulty with estimating lens masses using currently available samples is that the lens-source separation remains below the HST resolution for many years after the maximum light (closest approach). A deep all-sky survey has a much better potential for finding events that can be directly resolved. Event rates in searches that tend to look away from the Galactic plane are dominated by disk-disk lensing in the near field where the apparent relative motion of the lens to source tends to be large.

3.2. *Targeted Programs*

In 1966, Walter Feibelman identified a system that appeared to be a good lens candidate. He computed that in 1988, 40 Eridani A, a 5th magnitude star in a triple system which includes a white dwarf, would pass very close to a 15th magnitude star, "X", producing a photometric event that would last for 3.5 days. This appears to be the first specific suggestion of a targeted study to determine the mass of a specific lens. Unfortunately, subsequent observations that better established the relative positions and motions of 40 Eridani and star X, found that the closest approach would be $3''$, too large to allow lensing effects to be observed at that time.

Bohdan Paczyński suggested that the number of nearby dwarf stars is large enough that, if all-sky catalogues of high-proper-motion stars could be compiled, individual dwarf stars could be targeted for lensing studies (1995). With both the lens and source star known, the dates and durations of events could be predicted. He later generalized this suggestion to include astrometric events (Paczyński 1996).

The most ambitious attempt to predict specific events was made by Salim & Gould (2000). They used three catalogs (Hipparcos, ACT, and NLLT) to identify nearby high-proper-motion stars that could act as lenses. They then searched for potential sources in the USNO-A2.0 catalog. Through this process they identified candidate events predicted to take place during the interval from 2005 to 2015. For most of these events, the distance of closest approach was comparable to an arcsec, much larger than θ_E. This means that the expected image deflection is small, on the order of 100μ arcsec, yet potentially detectable with the *Space Interferometry Mission* (SIM; http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm), which could have measured the masses of the high-proper-motion stars.

Today, the chances of successfully predicting an event that can subsequently be monitored either from the ground or with *HST* are significantly improved. The improvements come through high-precision photometry over large regions of the sky. The SDSS, for example, provides a rich background of foreground stars, and even high-surface-density fluctuations in external galaxies can provide bright sources whose lensing is potentially observable. High-proper motion studies conducted from the ground provide large numbers of potential lenses (see, e.g., Alcock et al. 2001, Lepine 2008). In addition, multiple HST images of many fields can be used to predict future events. Within the next decade we expect that intensive monitoring of predicted events will yield mass and multiplicity measurements.

To assess the likely rate, consider for example a population of L or T dwarfs, with a local spatial density of $\eta \times 10^{-2}$ pc^{-3}. Per square degree, there are roughly $8\,\eta$ of these potential lenses within 200 pc. When the combination of Pan-STARRS and LSST are operating, we will have a census that includes the proper motion as well as magnitudes and colors of a large fraction of these low-mass dwarfs. Therefore, if even $\sim 0.5\%$ of the sky provides a suitable background for the detection of mesolensing, then there are approximately $1600\,\eta$ potential nearby lenses. If a few percent of these objects produce events that can be well studied, we will be able to determine the masses of dozens of individual brown dwarfs and low-mass stars. Note that an even larger number of potential nearby dim lenses are M dwarfs; for M dwarfs, $\eta \sim 10$.

4. THE NEXT DECADE

Twenty years ago, the identification of lensing events was a unproven concept. Today we are approaching a time in which thousands of events can be discovered every year, even by programs not specifically designed for lensing studies. What is important about these events, however, is not their sheer numbers, but is instead the remarkable breadth of astrophysical problems they can address.

Even with the data in hand, however, it is not assured that the majority of lensing events will be discovered or correctly interpreted. This will happen only if lensing studies are considered to be of high-priority, and if funds for surveys are supplemented by funds for developing a complete theoretical background, a comprehensive set of analysis techniques, and collaborations between theorists and observers working across wavebands.

4.1. *What is needed*

- **Support for Observing Programs** Wide-area surveys, including Pan-STARRS and LSST, can play an important role in advancing science through the study of lensing. We recommend that they be supported. In addition, US participation in high-cadence observations is highly desirable, and would represent a significant step forward in the study of planets and other dim low-mass objects.

- **Support for Theory and Analysis:** The data now available can yield much more fundamental science than has emerged so far, in spite of the best efforts of the community. While this may be disappointing, the primary problem is that the theoretical work and the framework for comprehensive analysis of the data has not moved forward quickly enough to allow new programs with even higher data collection rates to do better.

- Support for observing programs must be accompanied by **parallel and significant support for research programs that focus on extracting the maximum science value from the data.** It must be a priority to set aside a small but significant fraction of the funds needed by the observing programs for research to support the science goals of the observations. **It would be desirable for NSF to target microlensing and mesolensing for funding,** since the research would make significant progress in advancing the Foundation's science goals, and could be linked to a good deal of the other research it supports. In addition,**NASA support is appropriate, because key elements of the required research use data from NASA missions.**

- Overall, this is an area where **cooperative research by theorists, experts in data management, and observers using a variety of ground-based and space-based facilities is essential.** Cooperative efforts can ensure that we do the fundamental science that can be addressed by lensing, and do it at a time when it will have the most impact. Efforts like these are not naturally supported as high priorities by any single group or project.
- Members of the Decadal Survey can make a difference by emphasizing the great scientific value that can emerge from studies of lensing events and by specifically recommending support.

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