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MICROLENSING BY STARS

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ABSTRACT

If faint dwarfs are responsible for the microlensing events observed in the Galactic bulge, then light from the lensing star contributes to the observed brightness. The background and lensing stars generally have different colors, and the relative brightness changes during the microlensing event. Therefore, microlensing light curves are not perfectly achromatic if hydrogen-burning stars are the lenses. In most cases, the color shift will be too small to be observable, but we argue that given the current microlensing rates, it is plausible that a few color-shifted microlensing events could be observed in the near future, especially if strategies are optimized to search for them. Although rare, such events would be very interesting: Light curves in two (or more) bands could provide information about the masses of and distances to both stars as well as the transverse speed of the lensing star.

Subject headings: Galaxy: general — Galaxy: structure — gravitational lensing

1. INTRODUCTION

Microlensing (ML) was first proposed as a means of probing the Galactic halo for massive compact halo objects (MACHOs), for example, black holes, neutron stars, or brown dwarfs (Paczyński 1986; Griest 1991). If the halo is composed of MACHOs, then observation of several million stars in the LMC should produce a significant number of ML events. Although such events have been observed (Aubourg et al. 1993; Alcock et al. 1993), the rates appear to be too low to account for the dark matter needed to support rotational velocities at large radii.

It was similarly proposed that observation of the Galactic center could be used to study disk dark matter and to probe the mass function of stars too faint to be observed optically. Both the OGLE (Udalski et al. 1994a) and MACHO (Alcock et al. 1995) collaborations have recently reported observation of numerous candidate ML events toward the Galactic center. They find an optical depth toward Baade's window of $\sim(3.3 \pm 1.2) \times 10^{-6}$, significantly higher than the optical depth expected from ML by faint stars in the disk or bulge, or from MACHOs which account for the disk dark matter; these theoretical estimates generally fall in the range $(0.5\text{–}1.0) \times 10^{-6}$ (Paczyński 1991; Griest et al. 1991; Kiraga & Paczyński 1994; Giudice, Mollerach & Roulet 1994; Han & Gould 1994).

Using a self-consistent model for a bar (Zhao 1994) which matches kinematic observations of the bulge (Zhao, Spergel, & Rich 1994, hereafter ZSRa) as well as the *COBE* image of the Galaxy, the optical depth to ML was calculated (Zhao, Spergel, & Rich 1995, hereafter ZSRb). The optical depth from lensing by dwarfs with a mass function $dn/d\mathscr{M} \propto \mathscr{M}^{-2}$ in this model matches the OGLE and MACHO results. Furthermore, the best fit to the OGLE time-duration distribution is obtained with a mass-function cutoff at $0.1\ \mathscr{M}_\odot$, and the mean lens mass is found to be $0.4\ \mathscr{M}_\odot$, i.e., *above*, the hydrogen-burning threshold. Most of the lenses are found to be in the bulge with a line-of-sight distance 6.25 kpc, distances comparable to—but slightly smaller than—the stars being lensed.

If the lenses are faint dwarfs, then the observed light comes from the lens as well as from the source star. The two stars will generally have different colors, so the ML light curves should not be perfectly achromatic. In fact, since the majority of lenses are much fainter than the source stars being monitored, most of the light curves are effectively achromatic. However, in some fraction of the events, the brightness of the lens should be comparable to or greater than the brightness of the background star being lensed, in which case there could be an observable color shift. In this *Letter*, I argue that measurement of light curves in two (or more) wavebands in a color-shifted (CS) microlensing event can provide information about the masses and distances to the background and lensing star, as well as the transverse speed of the lens through the ML tube. Thus, observation of a few of these events could potentially provide as much information on the lensing objects as numerous achromatic events. Conversely, the achromaticity in observed events could be used to constrain masses, distances, and speeds of faint dwarfs that act as lenses.

In the following section, I describe CS events, and in § 3, I estimate the rates. Although small, the fraction of events which are detectably color-shifted may be large enough that such events could be observed in the near future, especially given the unexpectedly large rate of achromatic events observed so far. In § 4, I explain how masses, distances, and transverse velocities can be obtained from CS light curves in two (or more) bands, and some concluding remarks are made in the final section.

2. COLOR-SHIFTED MICROLENSING EVENTS

First, let us review standard ML by a nonluminous (or faint) lensing star. Assume that the lensing and lensed stars are both on the main sequence. The brightness of a star of luminosity L at a distance d is $l = L/d^2$. In most ML events, a background star with mass $\mathscr{M}_b$ at a distance d_b is lensed by a foreground star of mass $\mathscr{M}_f \ll \mathscr{M}_b$ and at a distance $d_f < d_b$ such that the brightness of the lens is smaller than that of the background

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star, $l_f \lesssim l_b$. So, the foreground star is too faint to be distinguished. If the distance of the lensing star from the lensed-star line of sight is $R_e u$, where (Griest 1991)

$$R_e = \left[\frac{4G\mathscr{M}_f d_f(d_b - d_f)}{c^2 d_b}\right]^{1/2}$$
$$= 3.2 \text{ a.u.} \left(\frac{\mathscr{M}_f}{\mathscr{M}_\odot} \frac{d_b}{8 \text{ kpc}} \frac{x'}{0.8} \frac{1-x'}{0.2}\right)^{1/2} \quad (1)$$

is the Einstein radius of the lens and $x' = d_f/d_b$, then the amplification of the background star as a function of time t is $A[u(t)] = (u^2 + 2)/[u(u^2 + 4)^{1/2}]$ and $u(t) = [\omega^2(t - t_0)^2 + u_{\rm min}^2]^{1/2}$, where $u_{\rm min}$ is the impact parameter in units of the Einstein radius, $\omega = v_\perp R_e^{-1}$ and $v_\perp$ is the transverse speed of the lens through the ML tube, and t_0 is the time at which peak amplification, $A_{\rm max} = A(u_{\rm min})$, occurs.

A ML event is registered when the amplification exceeds a threshold A_T which corresponds to a dimensionless lens–line-of-sight distance of u_T (e.g., $A_T = 1.35$ for $u_T = 1$). An achromatic event is described by three parameters: $u_{\rm min}$ (or equivalently, $A_{\rm max}$), the timescale ω^{-1}, and the time t_0. The event duration t_e is the time that the amplification is above threshold, and it is also the time the lens remains within a distance $u_T R_e$ from the line of sight; it is related to the timescale ω^{-1}. The system parameters (the distances to and masses of both stars and the transverse speed) cannot be determined uniquely in any given event. These quantities can in principle be disentangled in a statistical manner if a number of events are observed, and only with some assumptions about the mass, spatial, and speed distributions of the lenses. ML is a gravitational effect, so the amplification is the same in all wavelengths. Therefore, if the lens is too faint to be observed, the event will be achromatic.

Now consider the more general case where the brightness of the lens is comparable to or greater than that of the background star, $l_f \gtrsim l_b$. If the lenses responsible for the observed events are faint dwarfs, then there should be similar (although rarer) events where more massive dwarfs act as lenses. The light observed is a combination of the light from both stars, and the colors of the two stars will generally be different.[2] When the foreground star passes within the lensing tube, the background star will be amplified, and the relative brightnesses will change. Consequently, the color will change, and achromaticity is lost. To properly describe the event, we must consider the brightness in each waveband separately. If the amplification of the background star is A, then the brightness in waveband λ is $l_\lambda = l_{f\lambda} + A l_{b\lambda}$, where $l_{f\lambda} = L_{f\lambda}/d_f^2$ is the brightness of the foreground star in λ, $L_{f\lambda}$ is the luminosity of the star in λ, and similarly for the background star. The baseline brightnesses are obtained by setting $A = 1$.

Although A is the amplification of the background star, the observed light in this case comes from both stars, so the *observed* amplification, which I will denote by $\mathscr{A}$, is different from the ML amplification A. Although the amplification of the background star is indeed achromatic, the observed amplification will depend on wavelength, and in waveband λ it is

$$\mathscr{A}_\lambda(t) = \frac{l_{f\lambda} + A(t) l_{b\lambda}}{l_{f\lambda} + l_{b\lambda}} = (1 - r_\lambda) + A(t) r_\lambda , \quad (2)$$

where $r_\lambda = l_{b\lambda}/(l_{b\lambda} + l_{f\lambda})$ (Griest & Hu 1992). Suppose, for example, light curves are measured in two bands, α and β. If $l_f \gtrsim l_b$ (in both bands), then the baseline color observed will be $l_{f\alpha}/l_{f\beta}$ (the color of the lens), but in a lensing event with amplification $A \gg 1$, the observed color will be $l_{b\alpha}/l_{b\beta}$ (the color of the background star).

Such a CS event (CSE) will be registered when the *observed* amplification is greater than threshold, $\mathscr{A} > A_T$. This depends on the band, so strictly speaking, the exact time at which an event is registered (or whether it is registered at all) may depend on the waveband. If events are triggered by the light curve in λ, they will be registered when the ML amplification is $A \geq A_{\rm thresh} = [A_T - (1 - r_\lambda)]/r_\lambda$, or only when the dimensionless lens–line-of-sight distance is $u \leq u_{\rm thresh} = u(A_{\rm thresh})$.

The duration of a CSE is $t_e = 2(u_{\rm thresh}^2 - u_{\rm min}^2)^{1/2}\omega^{-1}$. The duration of any given event depends on the transverse speed, the mass of the lens, and the distances to both stars through ω, and it depends on the impact parameter and the luminosities and distances to both stars through the r dependence of $u_{\rm thresh}$. In general, however, the duration of the CSEs should be shorter than the duration of achromatic events. First note that $R_e \propto \mathscr{M}_f^{1/2}$, and that $u_{\rm thresh} \propto (l_b/l_f) \propto (\mathscr{M}_b/\mathscr{M}_f)^3$ for $\mathscr{M}_b \ll \mathscr{M}_f$ (and a mass-luminosity relation $L \propto \mathscr{M}^3$). Assume both stars to be roughly at the same distance, and fix the impact parameter and the transverse speed. Then consider the duration of an achromatic event ($l_f \ll l_b$ and $\mathscr{M}_f \ll \mathscr{M}_b$) relative to the duration of a CSE ($l_f \gg l_b$). Although the Einstein radius is larger in the latter case (which would make the duration longer), the fraction of the Einstein radius that gives rise to an observed amplification above threshold is smaller, and the latter effect dominates.

3. RATE OF COLOR-SHIFTED EVENTS

It is easy to see that CSEs will be rare compared to achromatic events for two reasons. First, CSEs require lenses with masses which are generally larger than those in achromatic events, and the mass function decreases with increasing mass, at least by assumption (ZSRa, b). Second, although the Einstein radius is larger for a lens of larger mass, the cross section for a CSE is generally smaller due to the fact that the fraction of the Einstein radius that gives rise to an observed amplification above threshold is reduced. Even so, it is still plausible that a handful of CSEs can be observed in the near future given the large achromatic-event rates reported so far and the estimate for the fraction of CSEs provided in this section.

To estimate the rate of CSEs, assume that the observed ML events are all due to lensing by faint dwarfs in the bulge, and consider only events where the source star is a dwarf. Strictly speaking, all events are then color shifted. However, if the bacground star is brighter (which implies $\mathscr{M}_f > \mathscr{M}_b$ assuming both stars are in the bulge), then the observed light at baseline comes primarily from the lensing star and the light at peak amplification comes primarily from the background star, so it is plausible that there will be an observable color shift. Take the mass function to be $dn/d\mathscr{M} \propto \mathscr{M}^{-2}$; then the rate for achromatic events is

$$R_{\rm achrom} \propto \int_{\mathscr{M}_{\rm min}} d\mathscr{M}_b \int_{\mathscr{M}_{\rm cut}}^{\mathscr{M}_b} d\mathscr{M}_f \frac{dn}{d\mathscr{M}_b} \frac{dn}{d\mathscr{M}_f} R_e^2(\mathscr{M}_f) , \quad (3)$$

[2] The analysis here is similar to that for lensing of binary stars by MACHOs as discussed by Griest & Hu (1992). Light from an additional unresolved star was also considered by Gould & Loeb (1992) and Gould (1995), and was included in the analysis of the possible binary microlens detected by the OGLE collaboration (Udalski et al. 1994b).

while the rate for CSEs is

$$R_{cs} \propto \int_{\mathscr{M}_{\min}} d\mathscr{M}_f \int_{0.1\mathscr{M}_\odot}^{\mathscr{M}_f} d\mathscr{M}_b \frac{dn}{d\mathscr{M}_b} \frac{dn}{d\mathscr{M}_f} R_e^2(\mathscr{M}_f) u_{\mathrm{thresh}}^2(\mathscr{M}_b, \mathscr{M}_f), \quad (4)$$

where $\mathscr{M}_{\min}$ is the mass of the faintest star (in the bulge) observable in the experiment, $\mathscr{M}_{\mathrm{cut}}$ is the smallest mass (i.e., where the mass function drops to zero), and $R_e(\mathscr{M}_f) \propto \mathscr{M}_f^{1/2}$. The upper limit to the first integral in equation (3) is of no consequence. The lower limit, $0.1\mathscr{M}_\odot$, in equation (4) is the smallest mass at which a star undergoes hydrogen burning and is therefore luminous. The function $u_{\mathrm{thresh}}(\mathscr{M}_b, \mathscr{M}_f)$ can be obtained from the formulas in the previous section and taking $L \propto \mathscr{M}^3$ and $d_f \simeq d_b$. The maximum amplification due to the finite size of the source is roughly $2R_e/r_b$, where r_b is the radius of the lensed star, and this leads to a lower limit to u_{thresh}.[3] The ratio of CSEs to achromatic events is then estimated to be roughly $(R_{cs}/R_{\mathrm{achrom}}) \sim 0.4/[\ln(\mathscr{M}_{\min}/\mathscr{M}_{\mathrm{cut}})]$. For example, if the faintest stars monitored in current experiments are $\mathscr{O}(10\ \mathscr{M}_\odot)$ and we take the smallest stellar mass to be the cutoff ($0.1\ \mathscr{M}_\odot$) suggested by ZSRb, then there should be roughly one CSE for every $\mathscr{O}(10)$ achromatic events in which a dwarf is lensed.

The fraction depends logarithmically on the mass of the faintest observable star, $\mathscr{M}_{\min}$ and increases as this mass is decreased, as it should. Unlike the case of microlensing by MACHOs, the probability for color-shifted ML is *not* independent of the star's spectral class. The probability for a CSE increases if fainter objects are monitored, as the number of objects that could give rise to a signal above threshold increases. Therefore an observing program that goes deeper in magnitude could potentially increase the fraction of CSEs as well as the total number of lenses observed.

Of course, to provide a more precise estimate of the fraction of events in which there is an observable color shift, the bands in which light curves are measured as well as a minimum color shift must be specified, and a color-magnitude relation for dwarfs must be employed. Although I have not yet done such a calculation carefully, we can adapt the results of the calculation for a related type of event. Griest & Hu (1992) considered ML of binary sources by MACHOs. As in the case considered here, lensing of a dwarf by another dwarf, the observed light from a binary source is a combination of the light from the two sources, and if the fainter object is lensed, there may be an observable color shift. If the mass function of stars in binaries is the same as that for single stars, then the fraction of events which are color shifted that they find should be similar to the fraction of CSEs which occur when dwarfs are lensed by dwarfs. They estimated the fraction of events in which there would be a color shift greater than 0.1 mag to be about 2%–5%, a rate consistent in order of magnitude with the estimate above. As they point out, the fraction is small because it is rare to find two stars in a binary with comparable brightness and different colors. If lensing occurs by dwarfs, then the distances will generally be different. Furthermore, some (or most) of the lenses are in the Galactic disk so the distance between the two stars is generally greater. Therefore, the chance of finding two stars with comparable brightness but different colors is greater, so the fraction of events which are color shifted should generally be higher than the estimate of Griest & Hu (1992).

[3] I thank D. Bennett for pointing this out.

4. MASSES, DISTANCES, AND TRANSVERSE VELOCITIES

So far, we have seen that if dwarfs are responsible for the observed ML events, then there should be events in which the lens is not too faint which give rise to CS light curves. The rate for such events should be small, and it may require some effort to actually observe these. Although rare and perhaps elusive, observation of a CSE would be more than just a curiosity. Sufficiently accurate measurement of CS light curves in two (or more) bands can potentially break the degeneracy between the undetermined system parameters that occurs in achromatic ML events. In particular, the masses and distances of the two stars, and the transverse speed of the lensing object (relative to the ML tube) can be determined, at least in principle. In addition, one might be able to discriminate between such events and lensing of binary sources by MACHOs.

Consider first a distance determination for dwarfs: If the brightness is measured in two bands, α and β, say, then the color, l_α/l_β, determines the spectral class, and therefore the mass and luminosity (in any band) of the star. The distance is then obtained by comparing the luminosity with the measured brightness in either (or both) bands. In other words, the two unknowns (mass and distance) are determined by the two observations (brightness in α and β). Measurements in other bands as well as additional spectral information can be used to break the possible degeneracy between dwarfs and giants, and to account for the effects of interstellar absorption, etc.

If CSEs are observed, similar arguments can yield masses and distances to the lensing and background stars. An achromatic light curve is fitted by three parameters: ω, t_0, and $A_{\max}$. On the other hand, the more general CS light curve is determined by four parameters, the additional parameter being the brightness ratio r_λ. If measured precisely enough, a fit to the light curve yields r_λ, which together with the observed baseline brightness, l_λ, determines the brightnesses, $l_{f\lambda}$ and $l_{b\lambda}$, of both stars. The masses and distances to both stars are then determined from the brightnesses in two bands. Moreover, by demanding that the lensing amplification $A(t)$ be the same in both bands, the statistical significance of the fit can be improved. Additional observations may be needed, for example, to break the possible degeneracy between giants and dwarfs (although it is unlikely that a giant will act as a lens).

Once the mass of the lens and distances to both stars are determined, the Einstein radius is known. The transverse speed of the lensing star through the ML tube can then be determined from the Einstein radius and the value of ω obtained from the fits to the light curves. Furthermore, if it is found that $d_f \neq d_b$, then the event cannot be lensing of a binary source by a MACHO. Additional spectral information can also potentially make the determination more precise. In fact, measurement of the baseline brightness alone in four or more bands provides, in principle, enough information to determine the masses and distances to both stars. In addition, shifts in the relative strengths of spectral lines characteristic of the two stars could be similarly used (Spergel 1994).

5. DISCUSSION

It is quite plausible (if not likely) that the ML events observed toward the Galactic bulge can be explained by low-mass dwarfs in the bulge and disk. In the vast majority of events, the lensing star is much fainter than the background star, so it is effectively achromatic. On the other hand, in a small fraction of the events, the brightness of the lensing star may be comparable to or greater than the brightness of the background star being lensed, in which case there should be an observable color shift. Although rare, it is quite plausible that such events could be observed in the near future given the unexpectedly large rate of ML events observed so far. Measurements of light curves in two (or more) bands can be used to provide information about the masses of and distances to both stars, and thus the transverse speed of the lensing star.

It is still not clear whether such CSEs are observable by MACHO, the only current experiment monitoring the bulge with light curves in two bands. It is likely that the two bands monitored by MACHO are not ideal for detecting CSEs. Color shifts may be more pronounced in other bands (Kamionkowski et al. 1995). If so, the current experiments may need to be augmented to increase the sensitivity to CSEs. Another possibility is that quick responses by other telescopes to "early-warning" systems which notify of a ML event in progress could provide the required spectral information during the event.[4] Measurement of the strength of spectral lines during the ML event could also provide data which could make the mass and distance determinations more precise (Spergel 1994). There may be additional background events, e.g., from variable stars, that may mimic CSEs. If so, ML events can be distinguished by the symmetry of the light curves about t_0 and by demanding that the fits for $A(t)$ obtained in both (or all) bands agree with the standard ML light curves and with each other.

[4] There have already been measurements of spectral lines by other telescopes after detection of a ML event on the rise (C. Alcock & K. Griest 1994, private communication).

The exact rate of events will depend not only on a detailed model of the bulge, but also on the catalog of stars monitored by any given experiment. Some or all of the lenses may be low-mass disk stars. If so, the fraction of events that are color shifted should be greater than that if all the lenses are in the bulge. Calculation of the time-duration distribution of CSEs is needed to evaluate the event rate in any given experiment. Such a calculation can be performed reliably only with a detailed model of the bulge and disk that reproduces the ML events observed so far (Kamionkowski et al. 1995).

Spectroscopic-parallax distances to ordinary stars are often inaccurate. Therefore, it is unlikely that the techniques discussed here will be precise. Even so, multiple-band imaging of CS events can plausibly provide information on the system parameters that is inaccessible in achromatic events. Finally, it should be possible to place an upper limit to the color shifts in the MACHO events observed so far. These could be used to constrain the brightness (and with some assumptions about the distance, the mass) of the lens, and thus the transverse speed.

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