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Detecting Luminous Gravitational Microlenses Using Spectroscopy

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Abstract. We propose a new method to detect the gravitational lenses in the ongoing microlensing experiments using medium and high resolution spectroscopy ($\lambda/\Delta\lambda >$ 6000). Since the radial velocity of the lens and lensed source typically differs by $\sim$ $100\,\mathrm{km\,s^{-1}}$, the spectral lines from the lens and source will be shifted relative to each other by $(1-2)$Å in the optical. We simulate realistic composite spectra assuming different spectral types for the lens and source and study the lens detectability as a function of the signal-to-noise ratio, spectral resolution and lens-to-source light ratio. We show that it is possible to measure the difference in radial velocity from an unequivocal signature in the difference of cross- and auto-correlation functions calculated from two spectra obtained at different magnifications. If the lens is brighter than 10% ($\Delta \mathrm{m_v} \sim 2.5$) of the unmagnified source we find that a spectral resolution of $\lambda/\Delta\lambda \sim 6000$ and a signal-to-noise of 50 (at magnification maximum) are sufficient to determine the relative radial velocity of the lens. At $\lambda/\Delta\lambda = 40000$, the spectral resolution of high resolution spectrographs of 8-10m class telescopes, the lens could even be detected at a brightness of $\sim 3\%$ ($\Delta \mathrm{m_v} \sim 4.0$) of the source. Radial velocities higher than $50\,\mathrm{km\,s^{-1}}$ can be measured with an accuracy of a few $\mathrm{km\,s^{-1}}$. Practical difficulties and observation strategies are also discussed.

Key words: Gravitational Lensing – Stars: kinematics – Techniques: spectroscopic – Methods: data analysis

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1. Introduction

Gravitational microlensing has been rapidly maturing in the last few years (see Paczyński 1996 for a review). Up to now, about two hundred microlensing events have been detected, about 15 of these are toward the Large and Small Magellanic Clouds (LMC, SMC, Alcock et al. 1993, 1997b; Aubourg et al. 1993) while the rest are toward the Galactic bulge (Alcock et al. 1995, 1997a; Udalski et al. 1994a, 1994b; Alard & Guibert 1997). Thanks to the early warning/alert systems (Udalski et al. 1994c; Alcock et al. 1996), microlensing events are now routinely identified in real-time. This allows simultaneous photometric (Alcock et al. 1997c; Albrow et al. in preparation) and spectroscopic observations (Lennon et al. 1996, 1997). To date, for all the microlensing events, the intervening lens has never been convincingly detected toward either the Galactic bulge or the LMC. Since the lens and source are aligned to about 10^{-3} arcsecond, if the lens is luminous, the observed light curve should include the light from the lens as well as the source. In fact towards the Galactic bulge the lenses are expected to be normal stars. The situation is less clear toward the LMC, however if some of the lenses are within the LMC itself (Sahu 1994; Wu 1994) or in tidal debris or streams (Zhao 1998), then these should be luminous as well. As it is most likely that the lens is less massive and considerably fainter than the source, the problem then is how to detect its presence. Photometric methods rely on the fact that the lens contribution will distort the light curve and potentially this can be used to detect the lens (Di Stefano & Esin 1995; Kamionkowski 1995; Buchalter et al. 1996). So far this photometric method has not yielded a reliable detection of the lens due to the source blending problem in the crowded fields (see discussion). In this paper, we suggest a spectroscopic method to infer the presence of the lens. This method is based on the fact that the lens and the source have radial velocities that differ by $\sim 100\,\mathrm{km\,s^{-1}}$, and hence the observed spectra should include stellar lines from both components shifted relative to each other by $(1-2)$Å in the optical range; the required resolution to detect such a line shift is therefore not exceedingly high. The detectability of the lens component in the composite is obviously a function of the ratio of the brightnesses of the source and the lens, and their intrinsic spectral distributions. The situation is analogous to the detection of spectroscopic binaries, except that there are two essential differences: the lens is normally expected to be much fainter than the source and the light ratio changes during the microlensing event. We make use of this latter effect in the method presented here, and, using simulated composite spectra, we have experimented with different methods to detect the lens. In brief we find that the differential cross-correlation of two spectra obtained at different epochs offers an efficient way of detecting the lens; this method is explained in Sect. 2 and the simulation results are presented in Sect. 3. We outline practical observing strategies and discuss our results in Sect. 4.

2. Method

A common method to measure radial velocities is the cross-correlation technique. The cross-correlation function for two functions $Y(x)$ and $h(x)$ is defined as

$$\langle Y, h\rangle(\xi) = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} Y(x)h(x+\xi)\,dx, \qquad (1)$$

where x is a function of wavelength. This method works well if the spectra Y and h focus their spectral power in similar features. Let h be a single component radial velocity standard. If Y is a single component spectrum, the radial velocity simply corresponds to the position of the correlation maximum. For a two-component spectrum, such as in our case, one might expect that the relative radial velocity can be measured from the distance of the correlation maxima, provided these are well separated and distinguishable from sidelobes. However, most lenses are expected to be much fainter than the source, and moreover the source itself is faint (with visual magnitudes typically between 19 and 21 for the Galactic bulge). In this case the use of a direct cross correlation technique is inappropriate, especially when the spectral resolution is low, since it becomes difficult to detect the correlation maximum due to the lens (see Fig. 1). We therefore experimented with other estimators. We found that a differential cross-correlation of composite spectra observed at two different magnifications (Eq. 4) provides a more sensitive signature to determine the relative radial velocity between the lens and source.

Suppose we have a series of spectra obtained during a microlensing event. Each spectrum is a composite of the lens and (amplified) source:

$$Y_i(x) = \mu_i \cdot S(x) + L(x) + N_i(x), \quad x \equiv \ln\lambda, \qquad (2)$$

where i is a sequence number, $S(x), L(x)$ are the intrinsic source and lens spectrum respectively, $N_i(x)$ is the noise term, and μ_i is the (intrinsic) amplification of the source. The observed spectra are sampled logarithmically, so a velocity shift is a uniform linear shift in x. Radial velocity measurements are usually performed using rectified spectra, i.e., spectra which are normalized to the continuum, where the continuum is determined by an interpolation of the observed spectrum by low-order polynomials. From here on, we will assume that Y_i has been rectified using standard procedures. Since we determine the radial velocity by comparing the relative shift in the positions of spectral lines, we are only interested in the alternating part of $Y_i(x)$ coming from the lines. Therefore we subtract the mean of $Y_i(x)$ and normalize the spectrum by its *rms*:

$$y_i(x) = \frac{Y_i(x) - \overline{Y_i}}{\sigma_i}, \qquad (3)$$

where $\overline{Y_i}$ and σ_i are the mean and rms of the rectified spectrum within a certain spectral range $x_1 < x < x_2$. Note that this normalization, which brings each composite spectrum onto the same scale, requires neither an accurate knowledge of the (intrinsic) magnification nor that of the absolute flux distribution. This property is one of the benefits compared to a method which makes direct use of Eq. (2) to disentangle S and L algebraically from at least two different observations Y_1 and Y_2.

Spectral regions with many well separated intrinsic atomic and molecular lines are well suited for correlation studies. Non-intrinsic features such as interstellar Na D lines, telluric or night sky lines should be avoided if the residues of these lines have significant spectral power. In practice, we choose the spectral window between 5100 Å and 5700 Å which includes mostly narrow metal lines. At low resolution, the spectral power is dominated by strong well separated features such as Mg b triplet, and few strong Fe I lines. We avoid the Balmer lines (e.g., Hβ) for the correlation because the significance of the radial velocity indicator varies with the spectral types if these temperature sensitive lines are included.

The differential correlation function of two spectra, y_1 and y_2, is defined as

$$\langle y_1, \Delta y\rangle = \langle y_1, y_2\rangle - \langle y_1, y_1\rangle, \tag{4}$$

where y_1 should be taken as the spectrum with the highest S/N, e.g., a spectrum observed near the maximum of magnification. The second term (auto-correlation of y_1) in Eq. (4) is symmetric, but the first term (cross-correlation term) is in general asymmetric, so the differential correlation function is asymmetric. It is easy to show that when the amplification is very high for y_1, the differential correlation function is essentially reduced to the cross-correlation of the source and the lens spectrum. The maximum of the differential correlation function simply corresponds to the difference in radial velocity between the lens and the source. We evaluate the errors in the relative radial velocity by comparing the derived radial velocity in simulations with different noise patterns.

3. Simulations

The composite spectra were created using rectified synthetic lens spectra, $l(x)$, and source spectra, $s(x)$,

$$Y_i(x) = \frac{\mu_i \cdot s(x) + \gamma_0 \cdot l(x)}{\mu_i + \gamma_0}, \tag{5}$$

where γ_0 is the lens-to-source light ratio when the source is at the baseline, i.e., when it is unamplified. We investigate three combinations of the lens and source spectra: a K0 star lensed by a K5 star, an F5 star lensed by a K5 star and an F5 source by a solar-type (G2) lens. The choice of source spectral types is guided by the fact that most sources identified in the bulge have magnitudes and colours implying that they are main sequence or turn-off stars of spectral types F to K. This is supported by recent spectroscopic observations (Lennon et al. 1996, 1997). The choice of the lens spectral types is more problematic since we cannot at present generate convincing M-dwarf spectra. We therefore restrict ourselves to the cases of K and G dwarfs, thereby limiting the lens masses (m) which we sample to $m > 0.5\mathrm{M}_\odot$. We return to this very important point in the discussion. Theoretical spectra are calculated using an extended grid of homogeneous, plane-parallel model atmospheres described by Fuhrmann et al. (1997). LTE-line formation was performed with molecular and atomic lines from Kurucz (1992). The f-values for most lines within $\lambda\lambda = 4800 - 5500$Å have been adjusted to the solar flux atlas (Kurucz et al. 1984). We find that the significance of the cross-correlation signatures depends on the assumed combination of spectral types (and spectral correlation range). However the physical approximations of the models and the accuracy of the line data have little impact on the results. For each spectrum, the spectral resolution has been reduced to the desired value by a convolution with Gaussian profiles; then normally distributed noise pattern are added according to the spectral S/N. The S/N of the composite when amplified by μ_i is given by $(S/N)_{(i)} = (S/N)_0(\frac{\mu_i+\gamma_0}{1+\gamma_0})^{1/2}$, where we have assumed that the S/N is dominated by photon noise. The baseline signal-to-noise ratio, $(S/N)_0$, has been scaled from our previous real-time spectroscopic observations of microlensing events (Lennon et al. 1996, 1997) or from technical specifications of typical high-resolution spectrographs for 8-10m class telescopes. The difference in radial velocity of the lens and source is taken to be $50-100\,\mathrm{km\,s^{-1}}$. This range is chosen because of the following reasons: Toward the LMC, the random radial motion of halo lenses is expected to be $V_c/\sqrt{2} = 160\,\mathrm{km\,s^{-1}}$, where $V_c \approx 220\,\mathrm{km\,s^{-1}}$ is the circular velocity of the halo. If the LMC self-lensing contributes significantly to the optical depth, then the LMC lenses are expected to be kinematically hot, with velocity dispersion $\sim 60\,\mathrm{km\,s^{-1}}$ (Gould 1995). The lenses and sources in the Galactic bulge have velocity dispersions of about $100\,\mathrm{km\,s^{-1}}$. Therefore the difference in radial velocity between the lens and source is about $100\,\mathrm{km\,s^{-1}}$. Since the lens is expected to be much fainter than the source, we have studied cases where the lens-to-source light ratio at the baseline is between 0.1 to 0.01, corresponding to differences in apparent magnitude ($\Delta \mathrm{m_v}$) of 2.5 and 5.0.

We first illustrate the difficulty in detecting the lenses using the standard cross-correlation technique. In Fig. 1, we show the auto-correlation functions for $\gamma_0 = 1/25, 1/75$ for two spectral resolutions, $\lambda/\Delta\lambda = 6000, 40000$ with $\Delta v = 100\,\mathrm{km\,s^{-1}}$ and $50\,\mathrm{km\,s^{-1}}$, respectively. One clearly sees that there is no secondary correlation maximum associated with the lens: It is simply lost in side lobes.

Since the minimum spectral resolution to detect the line shift is given by $\lambda/\Delta\lambda = c/\Delta V = 3000$, we first study simulations with medium resolution $\lambda/\Delta\lambda = 6000$. The S/N is chosen to be between 10 and 16 at the baseline and the S/N at the peak amplification is taken to be 50, implying magnifications of 25 and 10 respectively; such peak magnifications are typical for the observations conducted by Lennon et al. (1996, 1997).

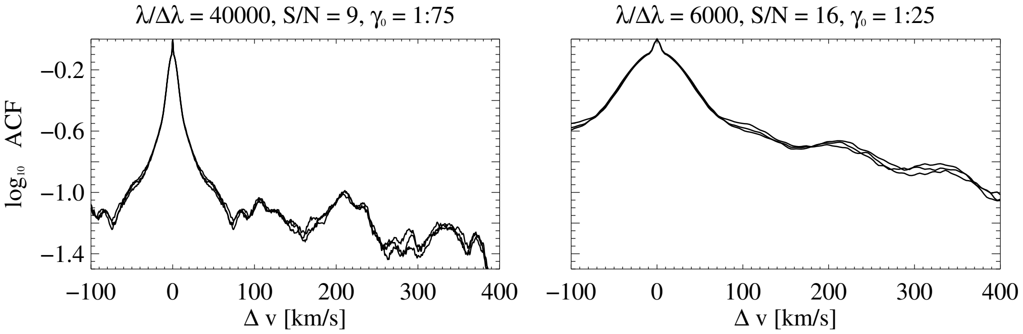

Fig. 1. Auto-correlation functions in logarithm are shown for two composite spectra where the baseline lens-to-source light ratio, γ_0, is $1/75$, $1/25$ respectively. The spectral resolution is taken to be 40000 and 6000 respectively. The lens and source have a difference in radial velocity of $\Delta v = 50\,\mathrm{km\,s^{-1}}, 100\,\mathrm{km\,s^{-1}}$ for these two resolutions. The adopted *S/N* is expected for a $V \sim 20$ star with one hour exposure for an 8-10m class telescope. For each case, three curves with different noise patterns are shown. Notice there is *no* secondary peak at $\Delta v = 50\,\mathrm{km\,s^{-1}}$, $100\,\mathrm{km\,s^{-1}}$.

Fig. 2 shows the results for $\gamma_0 = 0.1$ and 0.04, respectively. It appears that when the lens-to-source light ratio is 0.1, the radial velocity can be inferred with an accuracy of $\lesssim 10\,\mathrm{km\,s^{-1}}$. This determination is least reliable when the lens is a G2 star and the source F5, because the density of spectral lines from molecules and neutral metals is lower at higher effective temperatures. When the lens-to-source light ratio is reduced to 0.04, the reliability is still acceptable when the lens is a K5 star, but it becomes worse when the source is an F5 star and the lens a G2 star: two of the three simulations show large departures from the input radial velocity, indicating for such low values of γ_0, the differential correlation method is not sensitive enough. It appears that with spectral resolution of about 6000, the lens can be detected reliably when the intrinsic (unamplified) lens-to-source light ratio is about $\sim 10\%$. Note that the significance of the correlation maximum is better for the case where the lens and source are both cool stars. This is mainly caused by an increase in the number of metal lines as the effective temperature decreases.

We next consider the situation for high-resolution spectrographs available on 8-10m class telescopes. We will take the UVES instrument to be installed on the VLT (Pilachowski et al. 1995) as an example. The $(S/N)_0$ is taken to be 6 or 9 when the source is unmagnified; this corresponds to a *S/N* achieved for a $V \sim 20$ star with a one-hour exposure. Fig. 3 shows numerical results for $\Delta v = 50\,\mathrm{km\,s^{-1}}$ for a lens-to-source light ratios of 1.3% and 3.3%. The *S/N* at the maximum is taken to be 30, implying magnifications of 30 and 10 respectively. For the case of $\gamma_0 = 1.3\%$, some inferred radial velocity show large deviations from the input value. For $\gamma_0 = 3.3\%$, the situation is much improved. The radial velocity is recovered reliably, with an accuracy of $\lesssim 2\,\mathrm{km\,s^{-1}}$, for all combinations

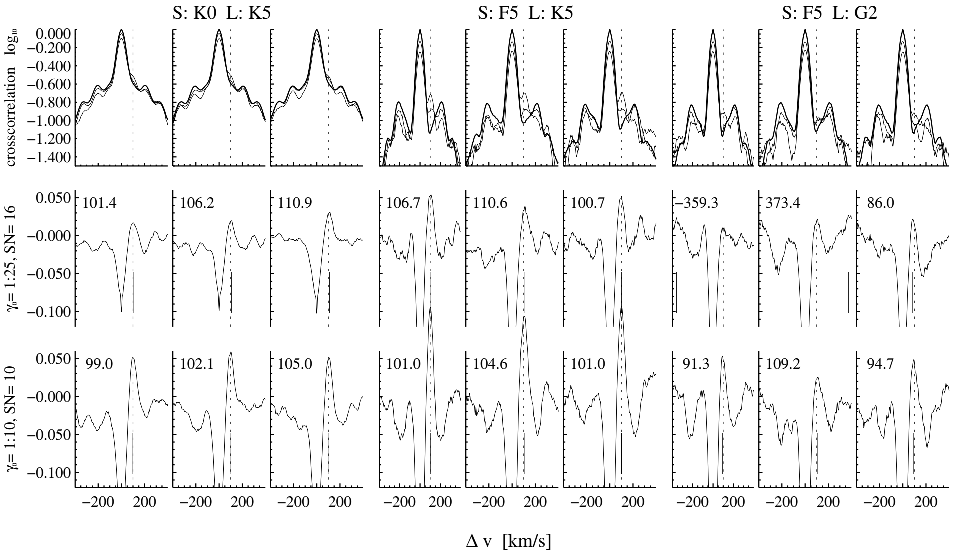

Fig. 2. Differential correlation functions (Eq. 4) are shown for three lens (L) and source (S) spectral combinations (indicated at the top). The spectral resolution is $\lambda/\Delta\lambda = 6000$, and the difference in radial velocity between the lens and source is $100\,\mathrm{km\,s^{-1}}$. The baseline *S/N* is 10 and 16, and the lens-to-source light ratio is 0.1 and 0.04, respectively. The peak *S/N* is taken to be 50, implying magnifications of 25 and 10 respectively. For each combination of the lens and source spectral types simulation results are shown for three noise patterns, along with the estimated Δv indicated in each sub-panel. The corresponding auto-correlation ($\langle y_1, y_1\rangle$) and two cross-correlation ($\langle y_1, y_2\rangle$) functions are shown in the first row, here y_1 is the peak spectrum, and y_2 is the two baseline spectra with $S/N = 10$ and 16. Notice that their differences are very small. The dotted line marks the input Δv whereas the solid vertical line indicates the detected correlation maximum.

of lens and source spectral distributions. We have ran simulations with radial velocity differences as low as $20\,\mathrm{km\,s^{-1}}$ for $\gamma_0 = 3.3\%$, and the radial velocity difference can still be inferred quite reliably. It is clear that with such high resolutions, the stellar lines are resolved, although contaminated by noise; the differential cross-correlation yields very reliable radial velocities for a lens-to-source light ratio of $\gtrsim 3\%$. Therefore, the detection of microlenses with such high-resolutions is clearly feasible.

So far we have mainly concentrated on the high-magnification microlensing events that allow us to obtain high S/N ratio spectrum at the peak, however, events with low magnifications are more common (the lensing frequency roughly scales as A^{-1}), we have therefore also ran simulations for a case with a peak magnification of 2.5. We found that in such cases, we can still detect the lenses spectroscopically when $\gamma_0 \gtrsim 10\%$ with baseline S/N $\gtrsim$ 10. It appears that our method works rather well for even modestly magnified microlensing events. However, in reality, highly magnified microlensing events are still preferred since the high S/N spectrum at the peak allows the intrinsic source properties be more realiably derived; such properties are valuable for not only lensing

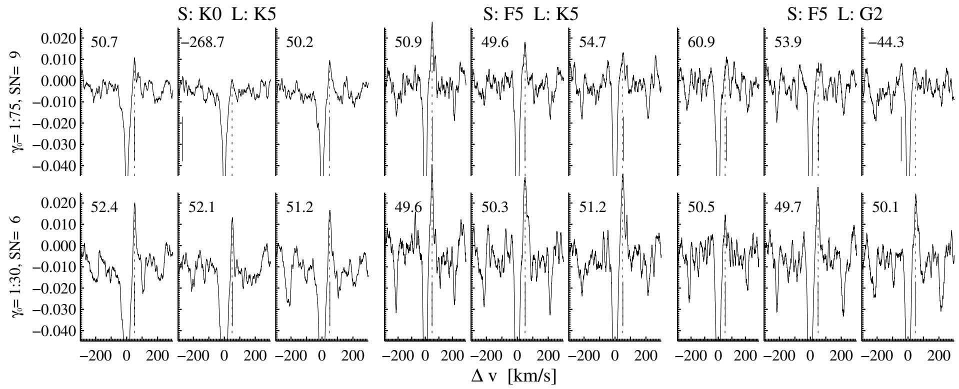

Fig. 3. Differential correlation functions (Eq. 4) are shown for three lens and source spectral combinations (labelled at the top). The input Δv is $50\,\mathrm{km\,s^{-1}}$ and the spectral resolution is $\lambda/\Delta\lambda = 40000$, appropriate for the UVES instrument on VLT. The symbols are the same as in Fig. 2. The baseline *S/N* is 6 and 9, and the lens-to-source light ratio is 3.3% and 1.3% respectively. The peak *S/N* is 30, implying magnifications of 25 and 10, respectively.

studies but also for the kinematical and chemical evolution of the Galactic bulge (Lennon et al. 1997).

4. Summary and Discussion

As we have implied above, the choice of our spectral types does not sample lens masses below about 0.5 solar masses. If we assume that the lensing in the bulge is primarily self-lensing, such that lens and source both reside there, then this implies a mean lens mass of around 0.3-0.5 solar masses (depending on the mass function). If the most likely lens is an M dwarf ($\sim 0.3 M_\odot$) with an absolute visual magnitude of around $\mathrm{M}_V \sim +10$ (compared with $\mathrm{M}_V \sim +7$ for a K5 dwarf), while a typical turn-off star in the bulge would have $\mathrm{M}_V \sim +3$ which implies that the light ratio would be of order 10^3. Detecting such a lens is clearly much more difficult and therefore it is necessary to investigate the fraction of lens with masses above about 0.5 solar masses. The luminosity function of the bulge stars implies a mass function of $\phi(m)dm \propto m^{-2.2}dm$ for $0.7 M_\odot < m < 1 M_\odot$ and $\phi(m)dm \propto m^{-1}dm$ for $0.3 M_\odot < m < 0.7 M_\odot$ (Holtzman et al. 1998), since the event rate scales as $m^{1/2}$, one can estimate that roughly 45% of the lenses have mass above $0.5 M_\odot$; in the above estimate, we have ignored the detection efficiency as a function of event duration since each lens mass produces very broad event duration due to the convolution of kinematics and lens distances (e.g., Mao & Paczyński 1996). This estimate is still uncertain, since the mass function of the bulge implied by the microlensing experiments is still under debate and of course is an important objective of microlensing surveys (see, e.g., Han & Lee 1997; Zhao & de Zeeuw 1998; see Gould 1996 for a review). In this respect the detection of even only the most luminous lenses is obviously very important.

We have shown through realistic simulations that it is possible to detect the presence of the lens using high-resolution spectrographs available on 8-10m class telescopes (Pilachowski et al. 1995), even when the lens to source light ratio is as small as $\sim 3\%$. This method complements the photometric detection of blending in microlensing. The spectroscopic observations will yield further kinematical information on the lens and source, which will provide more constraints on the modelling of microlensing events. The observations will require flexible scheduling of telescope time. Such real-time spectroscopic observations have already been carried out successfully by Lennon et al. (1996, 1997) using the NTT at ESO. Unfortunately, the spectral resolution used, $\lambda/\Delta\lambda \approx 1200$, was too low to detect the relative radial velocity as our numerical simulations suggest. The proposed spectroscopic observations should first be performed with the bulge microlensing events for two reasons. First, the number of events is a factor of ten larger toward the bulge, therefore we can select highly amplified events to perform high S/N observations. Second, the bulge sources are brighter than those in LMC. Notice that the lens-to-source light ratio obviously increases when the source becomes fainter. The best cases to study the lenses are therefore highly amplified faint stars. If the proposed method works for bulge microlensing events, then it is clearly very interesting to extend such high resolution observations toward the LMC.

Detailed photometric follow-up observations make the selection of spectroscopic observations simpler since the photometric effect detected in real-time can already tell us whether some additional light from the lens or a nearby source is present by chance alignment. The second possibility arises because the bulge and LMC are both crowded; many of the current observed microlensing events are influenced by such blending, since they exhibit astrometric centroid shifts of a few tenths of arcseconds during microlensing (Goldberg & Wozniak 1997). Photometric methods to detect the lenses (e.g., Kamionkowski 1995) are unable to tell whether the additional light is from the lens or from a blended source. Our method is subject to the same difficulty, although here the derived kinematical information will be helpful since the transverse motions (and hence indirectly the radial velocities) is subject to the duration constraint while that of a random blending star is not. The proposed method can of course be used to confirm such blending. However if one is more interested in detecting the lens, events with astrometric shifts should be eliminated. The seeing expected on the sites of 8-10m class telescopes will be substantially better than the typical seeing at the current microlensing survey sites ($\gtrsim 1.5''$). Many of the blended events will be spatially resolved. Furthermore, with the superior resolution of HST, one can largely tell whether the light is from the lens or a random star along the line of sight. If the additional light is not from a random star, then it is either from the lens or from a close binary. The latter possibility can be detected either photometrically from the light curve (Han & Gould 1996) or spectroscopically from the velocity shift in different epochs. The combination of HST and spectroscopic observations on 8-10m class telescopes therefore provides a powerful way of probing the lenses.

In this work, we have tried to address the rather modest goal of detecting the lens using spectrocopic techniques. The presence of the lens is inferred from the peak position of differential correlation function. It is clear that the peak height is correlated (in some way) with the lens-to-source flux ratio (see Figs. 2 and 3). However, it remains to be seen whether this quantity can be reliably deteremined when the lens spectral type is unknown and with realistic S/N. Clearly it will be very exciting if the lens-to-source flux ratio can be inferred, since this will provide additional constraints on the lensing parameters (Gould & Loeb 1992; Gaudi & Gould 1997). Although the proposed differential correlation technique seems to work reasonably well, it will be very interesting to explore other statistical techniques such as the TODCOR method developed by Zucker & Mazeh (1994) in the context of spectroscopic binaries. We plan to address these important issues in a further work.

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