STUDYING THE GALACTIC BULGE THROUGH SPECTROSCOPY OF MICROLENSED SOURCES. II. OBSERVATIONS

STEPHEN R. KANE and KAILASH C. SAHU
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; srk1@st-andrews.ac.uk, ksahu@stsci.edu

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ABSTRACT

The spectroscopy of microlensed sources toward the Galactic bulge provides a unique opportunity to study (1) the kinematics of the Galactic bulge, particularly its far side, (2) the effects of extinction on the microlensed sources, and (3) the contributions of the bulge and the disk lenses to the microlensing optical depth. We present the results from such a spectroscopic study of 17 microlensed sources carried out using the ESO Faint Object Spectrograph (EFOSC) at the 3.6 m ESO Telescope. The spectra of the unlensed sources and Kurucz model spectra were used as templates to derive the radial velocities and the extinctions of the microlensed sources with respect to the unlensed sources. There is an extinction shift between the microlensed population and the nonmicrolensed population, but there is no apparent correlation between the extinction and the radial velocity. This extinction offset, in our best model, would imply that 65% of the events are caused by self-lensing within the bulge. The sample needs to be increased to about 100 sources to get a clear picture of the kinematics of the bulge.

Subject headings: Galaxy: stellar content — Galaxy: structure — gravitational lensing — stars: kinematics

1. INTRODUCTION

By now, several authors (Kiraga & Paczyński 1994; Paczyński et al. 1994b; Mollerach & Roulet 1996; Zhao et al. 1995) have pointed out that the stars within the Galactic bulge may play a dominant role as gravitational lenses, and a significant fraction of the detected events may be due to lensing by stars within the bulge. If a significant fraction of these events are indeed due to lenses within the bulge, then the microlensing characteristics can provide a powerful technique for deriving the stellar mass density and mass function within the Galactic bulge (Zhao et al. 1995). However, the contributions of different populations to the microlensing optical depth remain uncertain, and their determination is important in using the microlensing characteristics to derive other quantities such as the stellar mass density and the stellar mass function.

If the lensing is caused predominantly by bulge stars, then a major fraction of the lensed stars will be at the far side of the bulge so that there are enough stars in front to cause the lensing. Thus the lensed sources would be fainter in general, and it was shown by Stanek (1995) that the magnitude offset between the lensed sources and nonlensed sources can be a good measure of the fraction of the events caused by bulge lenses. A similar test was suggested by Kane & Sahu (2000, hereafter Paper I) through the measurement of extinction, and it was shown that an extinction offset may be measurable from the spectra of lensed and nonlensed sources. This test used the principle that the lensed stars should have larger extinction since they would predominantly be on the far side.

If the sources are predominantly in the far side of the bulge, then the spectra of these sources give a unique opportunity to derive the radial velocities of the objects in the far side of the Galactic bulge. The radial velocities derived from the observed spectra can be combined with the proper motion derived from the microlensing timescales to determine the three-dimensional velocity structure of the far side of the Galactic bulge.

This paper presents the results of a spectroscopic study of microlensed sources conducted using data obtained with the 3.6 m telescope of the European Southern Observatory (ESO) at La Silla, Chile. Kurucz model spectra were used to create theoretical extinction effects for various spectral classes of stars toward the Galactic bulge. These extinction effects are used to interpret spectroscopic data consisting of a sample of microlensed stars toward the Galactic bulge. The extinction offsets of the lensed sources with respect to the average population is derived, and a measurement of the fraction of bulge-bulge lensing is made. Measurements of the radial velocities of these sources are used as an attempt to determine the kinematic properties of the far side of the Galactic bulge.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Details of the Observations

The observations were taken with the ESO 3.6 m telescope using the ESO Faint Object Spectrograph and Camera (EFOSC). The data were obtained in two observing runs: the first run was from 1995 June 28 to July 1, during which a major part of the observations were taken, and the second run was on the night of 1996 June 14, during which only one source was observed. The sky condition was clear during the whole 1995 observing run; the 1996 observations, however, were affected by passing cirrus and clouds. Table 1 shows the grisms that were used for the observations. The CCD detector used has 512 × 512 pixels and a pixel scale of 0.61 pixel$^{-1}$ in both the dispersion and the cross-dispersion directions. The seeing during the observations was about 1", and a slit-width of 1.5" was used for all the observations. The spectral resolution depends on the chosen slit width, and for our observations, the true spectral resolution is approximately 2.46 times the dispersion (Å pixel$^{-1}$), shown in
Table 1. At the time of observations, the camera was set to have a gain of 3.8 electrons count\(^{-1}\) for which the readout noise is 8.5 electrons pixel\(^{-1}\).

As the name implies, the EFOSC is both an imaging and a spectrographic camera. The imaging capability of this spectrograph greatly facilitates the spectroscopic observations of stars in crowded fields such as the Galactic bulge by examining the field first, before placing the slit on the object of interest. This facility was particularly useful for our purpose of simultaneously obtaining the spectra of a few non-microlensed sources along with the microlensed source, by placing them all along the same slit. In order to achieve this, an image was obtained first, with a typical integration time of about 2 minutes. This image was taken using a clear (unfiltered) aperture to avoid any shift while placing the slit. Then the slit was centered on the microlensed source, and its orientation was set such that (1) it was close to the east-west direction (so that the differential atmospheric dispersion was minimum along the slit) and (2) there were a sufficient number of nonlensed sources on the slit (which would be later used as the control sample in the analysis). Since the size of the detector is rather small (512 × 512 pixels), the spectral coverage in each setting is accordingly small. So it was generally necessary to take two separate spectra using two grisms in the blue and the red in order to cover the wavelength range of our interest. This limited spectral coverage in a single grism setting had the advantage that the effect of the differential atmospheric dispersion at various wavelengths in a spectrum is minimal. Nevertheless, attempts were made to do the observations in low air masses to further minimize any differential atmospheric dispersion at different wavelengths in a given setting.

To correct for the electronic noise associated with the detector readout, five bias exposures were taken every evening, the median of which was used for subtracting the bias level. To correct for pixel-to-pixel sensitivity variations of the detector, flat-field exposures were taken by observing a part of the dome illuminated with a tungsten lamp. Typically, three flat-field exposures were taken for each grism in the beginning of each night, the average of which was used during the data reduction.

For wavelength calibration, spectra were taken by illuminating the slit with a He lamp, followed by an Ar lamp in the same exposure. The combination of He and Ar was necessary to get enough lines both in the blue and the red region of the spectrum simultaneously. The rms deviation of the residuals from the dispersion relations for each grism are shown in Table 1. The lamp spectra were taken for each grism at the beginning and end of every night. The typical wavelength shift during a night was less than 0.1 pixels, which is not more than the rms deviation of the residuals from the dispersion relations.

In this study, since we are mostly interested in the relative fluxes and line strengths rather than their absolute values, observing a single standard star per night was deemed sufficient. The standard star LTT 9239 was used for the 1995 observations, and the standard star LTT 8702 was used for the 1996 observations. The uncertainty in absolute flux calibration would normally be in the range of 10%–20% in clear sky conditions and worse if the sky is not photometric; however, the relative fluxes will be more accurate.

The spectra of 17 different microlensed sources were obtained during these observing runs. Since the purpose of this study is to compare the spectra of microlensed sources with a control sample of other stars, five nonlensed stars were chosen from each field whose spectra were also reduced. The microlensing events observed are summarized in Table 2, where \( t_\text{E} \) is the time taken by the lens to cross the Einstein ring radius. This information has been extracted from the MACHO alerts\(^3\) and from the OGLE and DUO publications (Alard et al. 1995; Woźniak & Szymański 1998). The binary events have an undetermined characteristic timescale \( t_\text{E} \). The Galactic longitude and latitude of the sources lie in the range 0°55 < \( l \) < 3°98 and \(-4°92 < b < -2°68\), respectively. A summary of the observations of these events is shown in Table 3. DUO 95-BLG-2 and OGLE 95-BLG-3 were also observed, but the sky was scattered with clouds during these observations. As a result, the signal-to-noise ratio (S/N) in these spectra are considerably lower. Hence these two sources and their associated non-microlensed stars are not included in the following analysis.

2.2. Data Reduction

After the usual bias subtraction, the wavelength calibration for the entire two-dimensional image was carried out through the lamp spectra obtained with the appropriate

See http://darkstar.astro.washington.edu.

| Event                  | R.A. (J2000.0) | Decl. (J2000.0) | \( V \) | \( R \) | \( t_\text{E} \) (days) |
|-----------------------|---------------|----------------|-------|-------|-------------------|
| DUO-1995-BLG-2-65     | 18 10 17.2    | -27 28.49      | ...   | 18.6  | Binary            |
| MACHO 95-BLG-2-2      | 18 08 25.2    | -27 58.38      | 19.0  | 17.9  | 61.0              |
| MACHO 95-BLG-3-3      | 18 02 37.5    | -29 39.36      | 18.7  | 17.6  | 1.0               |
| MACHO 95-BLG-4-4      | 18 00 30.4    | -29 11.04      | 18.1  | 17.1  | 3.5               |
| MACHO 95-BLG-8-8      | 18 16 46.0    | -26 11.43      | 17.1  | 16.3  | 15.5              |
| MACHO 95-BLG-9-9      | 18 06 32.3    | -30 55.55      | 17.2  | 16.2  | 12.0              |
| MACHO 95-BLG-10-10    | 17 58 16.0    | -29 32.11      | 18.9  | 18.0  | 47.5              |
| MACHO 95-BLG-12-12    | 18 06 04.8    | -29 52.38      | 18.6  | 17.7  | Binary            |
| MACHO 95-BLG-13-13    | 18 08 47.0    | -27 40.47      | 16.6  | 15.6  | 73.5              |
| MACHO 95-BLG-14-14    | 18 01 26.3    | -28 31.14      | 17.4  | 16.5  | 9.0               |
| MACHO 95-BLG-17-17    | 18 03 01.1    | -28 21.09      | 18.8  | 18.0  | 18.5              |
| MACHO 95-BLG-18-18    | 18 07 20.6    | -28 36.51      | 18.7  | 17.8  | 39.5              |
| MACHO 95-BLG-19-19    | 18 11 32.5    | -27 45.27      | 18.6  | 17.9  | 31.5              |
| MACHO 95-BLG-30-30    | 18 07 04.3    | -27 22.06      | 16.1  | 14.7  | 13.5              |
| OGLE 95-BLG-3-3       | 18 04 43.5    | -30 14.11      | 17.7  | ...   | 11.5              |
| OGLE 95-BLG-7-7       | 18 03 35.8    | -29 47.06      | 19.3  | ...   | Binary            |
| OGLE 95-BLG-16-16     | 18 02 07.6    | -30 01.12      | 20.0  | ...   | 26.2              |

Note.—Information includes the coordinates of the sources, the base-line \( V \) and \( R \) magnitudes, and the characteristic timescales of the events. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
grism during that particular night. The one-dimensional spectra were extracted for the microlensed source and five nonmicrolensed sources in the image using an extraction height of 5–7 pixels for each source. The images being crowded, sky subtraction was tricky, so care was taken in choosing an appropriate region for the sky subtraction. The flat-field images obtained with the illuminated dome were found to be relatively smooth, and the pixel-to-pixel response variation was found to be small, so the flat-field images were not used in the reduction.

### 3. ESTIMATING SPECTRAL TYPE, EXTINCTION, AND RADIAL VELOCITY

In order to process the large number of spectra that were obtained, a MIDAS script was written which estimates both the spectral type and the extinction for each individual spectrum. This script uses a large library of model spectra that was constructed from the Kurucz database and a cross-correlation technique to achieve this, as explained in more detail later. An additional script was written using a high S/N template spectrum and a cross-correlation technique to determine the radial velocities of the microlensed and nonmicrolensed sources. More details of the method used in these scripts are given in § 3.2. (The script itself, with ample comments describing the algorithms, is published by Kane 2000.)

#### 3.1. The Model Spectra

The 1993 Kurucz stellar atmospheres atlas (Kurucz 1993) covers a wide range of metallicities, effective temperatures, and gravities. The models were first developed by Kurucz in 1970 using the stellar atmosphere modeling program ATLAS (Kurucz 1970). The 1993 atlas contains about 7600 models that are convenient to access using the IRAF (Image Reduction Analysis Facility) task synphot, which is available in the STSDAS package developed at the Space Telescope Science Institute. The task synphot was used to extract a full grid of model spectra from the atlas by specifying the appropriate range of temperatures, metallicities, and the surface gravities, as explained below.

To extract the model spectra from the atlas, an exhaustive list of stellar parameters was needed for each of the stellar subtypes and luminosity classes. The values for the effective temperature $T_{\text{eff}}$, the surface gravity log $g$, and the absolute magnitude $M_V$ characterizing each star were obtained from Schmidt-Kaler’s compilation of physical parameters of stars (Schmidt-Kaler 1982). However, the values of log $g$ were found to be severely lacking in their coverage of the stellar subtypes, and so the remaining values were determined from the interpolation of the values given by Schmidt-Kaler. As shown in Figure 1, a fourth-order polynomial of the form $y = ax^4 + bx^3 + cx^2 + dx + e$ was fitted to the available data for each luminosity class. The coefficients for the polynomial fitted to each luminosity class are shown in Table 4. The estimates obtained for the required values of log $g$ by this method were sufficient to create the desired spectral models since spectral classification within a luminosity class has a weak dependence on surface gravity. It is worth noting that the errors in the values of log $g$ for luminosity classes III and V were larger due to the lack of data.

#### TABLE 4

| Coefficients for Polynomial Fits to log $g$ Values |
| --- |
| Class | $a$ | $b$ | $c$ | $d$ | $e$ |
| I | $1.71 \times 10^{-3}$ | $-0.05$ | $0.37$ | $-1.50$ | $4.05$ |
| III | $5.75 \times 10^{-3}$ | $-0.06$ | $0.04$ | $0.44$ | $2.91$ |
| V | $9.30 \times 10^{-3}$ | $-0.13$ | $0.56$ | $-0.80$ | $4.30$ |

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**Fig. 1.—Surface gravity log $g$ for luminosity classes I, III, and V**
mentioning that the grids of theoretical isochrones calculated by Bertelli et al. (1994) also provide a useful set of stellar parameters. Although there are slight differences in the model parameters between these two references, they are too small to affect the main results of this study. A total of 226 spectra were produced for this analysis. Galactic bulge stars tend to have a large range of metallicity. Although most stars are thought to be more metal poor than solar (Seeds 1999), recent work suggests that there is a large dispersion in the stellar metallicity in the Galactic bulge stars, ranging from 0.2 solar to more than solar (Feltzing & Gilmore 2000; Stanek et al. 2000). We used an extensive library of model spectra that included metallicity ranges from high metallicity of approximately solar to low metallicity of 0.1 times solar corresponding to Population II stars.

3.2. Fitting Routine for Determining Spectral Class and Extinction

Spectral classification is based on the strength of various spectral features in the spectra, which are compared with those of a set of standard stars defining the classification system. Although the classification of the observed spectra is not the primary goal of this analysis, it serves as a tool in deriving necessary information such as the extinction and the radial velocity.

The main purpose of this MIDAS fitting routine was to provide a reasonable estimate of the extinction present in each of the measured spectra. The fitting routine first combines spectra of a star observed through multiple grisms into a single spectrum in order to increase the reliability of the spectral classification. The fitting routine then sequentially compares the spectrum with each of the model spectra from the constructed model spectral library. The details of this routine will now be outlined.

The observed spectrum was divided by the model spectrum and then linear regression was used to calculate the slope of the resulting image. This step was then repeated, incrementing the interstellar extinction (Galactic extinction data from Seaton 1979) applied to the model spectrum with each repetition, until the slope was approximately equal to zero. The value of $E_{B-V}$ used to achieve a slope of zero was then adopted as the extinction value for that model spectrum.

Once the extinction was estimated for the model spectrum, the extincted model was fitted to the observed spectrum. The flux of the model was first approximated to the flux of the observed spectrum by normalizing the continuum. The flux of the model was then corrected for the extinction value derived from this method, which is used to cross-check the classifications.

We note that our fitting routine described here uses a combination of line ratios and the shape of the entire continuum. So our classification should be as reliable as the MK classification method. As an example, the method described here provides a classification of M2 III for MACHO 95-BLG-30, a close match (within the uncertainties) to the result of M4 III derived by the MACHO collaboration (Alcock et al. 1997; more on this comparison in §4).

Second, we have also used the luminosities as a safeguard against the “degenerate” models. The observed luminosities are expected to be different for different spectral types, and this information can be used to choose the correct model. As explained later, the observed luminosities are consistent with that expected from the model, which suggests that the derived models are reasonable.

The limitations in the model spectra also play some role in the spectral classification. The model spectra cover a wavelength range from ultraviolet (1000 Å) to the infrared (10 μm). However, the model spectra are particularly unreliable for wavelengths greater than 9000 Å, largely because of very strong atmospheric water band extinction, and indeed spectral information in this region has been obtained only in recent years (after the models were created). To account for this, wavelengths greater than 9200 Å were ignored for spectra obtained through the R300 grism. However, R300 observations are available only for one source (MACHO 95-BLG-13). Furthermore, this source has been observed both in B150 and O150 gratings with good S/N, making the spectral classification fairly secure.

There is a truncation error in the stellar parameters used for each model due to the limitations in the grid of models.
available from the Kurucz stellar atmospheres atlas. This resulted in a limitation in the number of models that could be produced and, consequently, in the resolution of the fitting procedure. The lower threshold in the grid of temperatures of 3500 K meant that stars cooler than spectral types of about M2 could not be created. This consideration led to an estimated uncertainty in the classification of about two spectral subtypes if it is M2 or later. However, we do not expect any of the observed stars to be later than M2 (because of the magnitude limit of the sample), and hence this limitation in unlikely to have a significant effect on our analysis.

It should be noted that for eight of the 17 observed events, spectra were obtained only through the O150 grism. The limited wavelength range in these spectra (5230–6970 Å) made the fitting of an adequate model a more challenging task. Further limitations were found when the fitting routine attempted to fit models for late K and early M-type stars, particularly for stars that were observed using only the O150 grism. The spectral bands (such as the TiO band that is characteristic of M-type stars) that tend to dominate these stellar types created problems that in some cases caused a misclassification of the spectra. In these cases, special care was taken to identify the spectra through the use of the previously mentioned libraries of stellar spectra and their luminosities.

It is important to remember, however, that the exact spectral classification is not important for our purpose as long as the extinction values are not severely affected. As explained above, we have taken several precautionary measures in estimating the spectral classes and extinction values. The error in the extinction of an individual star may be high, but we are interested in comparing the extinctions of a sample as a whole. Hence the derived extinction values should be adequate for the statistical investigation that we intend to undertake in this study.

3.3. Procedure for Radial Velocity Determination

In general, the radial velocity of a star may be measured from the Doppler shift of stellar spectral lines. The radial velocity is then given by \( v_r = (\Delta \lambda / \lambda_0) c \), where \( \Delta \lambda = \lambda - \lambda_0 \) is the Doppler shift of the line from its rest wavelength \( \lambda_0 \). However, there are factors intrinsic to stellar structure, such as surface convection and magnetic fields, which can affect the symmetry and wavelength of line profiles (Dravins 1999). An approximate value of the radial velocity may still be determined from one of the few lines, such as Hα (6563 Å), which are less sensitive to the velocity structure of the photosphere.

A more reliable and accurate method for measuring the radial velocity of a star is to cross-correlate the stellar spectrum with a template spectrum. The correlation between them may be analyzed using the cross-correlation function from which the location of the main peak is used to determine the wavelength shift. Cross-correlation techniques and the theory of correlation analysis have been described in detail by, for example, Tonry & Davis (1979).

![Fig. 2.—Observed spectrum of MACHO 95-BLG-10 fitted with four different Kurucz models. The fitted extinction values for the models G0 III, G2 III, G5 III, and G8 III are 1.1, 0.99, 0.86, and 0.71, respectively. The best-fitting model, G2 III, is shown in the top right-hand panel.](image-url)
To obtain absolute radial velocities (radial velocities relative to the barycenter of the solar system), it is often necessary to cross-correlate the stellar spectrum with that of a radial velocity standard star, such as those monitored by CORAVEL (Udry et al. 1999). No such standard stars were observed to carry out such an analysis since we are mostly interested in the relative radial velocities. As noticed earlier by Morse et al. (1991), when a large number of spectral lines are used for the radial velocity determination, the systematic errors caused by lines formed at different regions of the stellar atmosphere average out, and the resultant radial velocity determination is insensitive to the choice of template for late-type stars. So the radial velocities measured relative to a template bright star are adequate for this analysis. The template used for these measurements (see Fig. 3) was a bright star with high S/N selected from the MACHO 95-BLG-12 field. By fitting a Gaussian to the Hα line, the absolute radial velocity of the template star was found to be \(-98.5 \pm 18.0 \text{ km s}^{-1}\). Taking into account the wavelength calibration residuals, the absolute radial velocity is correctly stated as \(-98.5 \pm 37.3 \text{ km s}^{-1}\). Note that the random errors in the data, which are subsequently used for the cross-correlation, can significantly affect the results. So it is important to make sure that the S/N of the template spectrum is large enough to make sure that the S/N of the template spectrum is large enough.

The cross-correlation function that results from correlating the template with itself. The shift of the central peak is approximately zero, as expected.

Fig. 3.—*Top:* Normalized spectrum of the star to be used as the cross-correlation template. *Middle:* The result of subtracting the continuum, applying a bandpass filter, and extracting the region of the spectrum that excludes atmospheric lines. *Bottom:* The cross-correlation function that results from correlating the template with itself. The shift of the central peak is approximately zero, as expected.

4. RESULTS AND DISCUSSION

For each source an estimate of the spectral type, extinction, and relative radial velocity is made as discussed above. It is important to remember that the measurements of the microlensed sources apply only to the source and not the lens itself. The contribution of the lens is assumed to be small because the stellar mass function is biased toward lower masses and hence the lens is likely to be less massive.
and considerably fainter than the source (Mao et al. 1998). Low-luminosity stars do not contribute significantly as sources since these would not normally be detected by the magnitude limited microlensing surveys.

Table 3 gives the details of the observations, such as the grisms used, the date of observations, and the exposure times for all the observations. Table 5 shows the results of the analysis for all the observed microlensed sources. For the purpose of this table, the names of the microlensed sources have been abbreviated, the first letter indicating the name of the collaboration and the following two numbers indicating the identity of the source. The results include the estimated spectral class, the color excess, and radial velocity, along with the uncertainties for each source.

For illustration, more details of the analysis procedure are presented for MACHO 95-BLG-17, which was observed with B150 and O150 grisms. For this event, the observed spectra of the microlensed source and five other stars in the field, along with their associated model spectra, are shown in Figure 4. The results from fitting models to the spectra are given in Table 6. Shown in Figure 5 is the cross-correlation function for the spectrum when cross-correlated with the chosen radial velocity standard.

The spectra of the remainder of the microlensed sources are shown in Figures 6–9. Note that most stars were fitted better by the lower metallicity models. This is an expected result since the Galactic bulge tends to be dominated by Population II stars (Seeds 1999).

Unfortunately, our wavelength coverage is 3500–7000 Å, which is different from that of the MACHO collaboration.

![Fig. 4. — Spectra (solid line) and fitted models (dashed line) for MACHO 95-BLG-17 and five nonmicrolensed stars in the field.](image)

![Fig. 5. — Cross-correlation function for the spectrum of MACHO 95-BLG-17.](image)

### Table 3

| Spectrum | Class   | $E_{B-V}$ | $v_r$  |
|----------|---------|-----------|--------|
| D02...... | K2 III  | 0.22 ± 0.09 | −97.3 ± 16.6 |
| M02...... | G2 III  | 1.19 ± 0.01 | −210.7 ± 11.2 |
| M03...... | G0 III  | 1.31 ± 0.01 | −376.6 ± 19.0 |
| M04...... | K0 III  | 0.63 ± 0.03 | −467.6 ± 10.0 |
| M08...... | G0 III  | 0.61 ± 0.03 | −219.9 ± 11.2 |
| M09...... | K4 III  | 0.39 ± 0.21 | −342.7 ± 7.8  |
| M10...... | G2 III  | 0.99 ± 0.01 | −411.7 ± 7.9  |
| M12...... | K0 III  | 0.58 ± 0.16 | 9.5 ± 8.0     |
| M13...... | K1 I    | 0.48 ± 0.07 | −659.9 ± 9.1  |
| M14...... | K4 III  | 0.32 ± 0.06 | −1810.1 ± 11.4 |
| M17...... | G5 III  | 0.55 ± 0.04 | −213.3 ± 6.6  |
| M18...... | K0 III  | 0.66 ± 0.09 | −1026.6 ± 6.9 |
| M19...... | G2 III  | 0.47 ± 0.11 | −623.0 ± 8.8  |
| M30...... | M2 III  | 0.56 ± 0.02 | −1620.0 ± 22.7|
| O03...... | K2 I    | 0.08 ± 0.01 | −63.1 ± 11.3  |
| O07...... | G0 III  | 0.79 ± 0.02 | −137.9 ± 11.5 |

### Table 6

| Spectrum | Class   | $E_{B-V}$ | $v_r$  |
|----------|---------|-----------|--------|
| Source:................... | G5 III | 0.55 ± 0.04 | −213.3 ± 6.6 |
| Star 1:................. | K3 III | 0.42 ± 0.13 | −72.1 ± 10.4 |
| Star 2:................. | K5 III | 0.33 ± 0.03 | −150.1 ± 10.3|
| Star 3:................. | K2 III | 0.64 ± 0.09 | −72.1 ± 9.4  |
| Star 4:................. | G2 III | 0.29 ± 0.03 | −182.1 ± 17.4|
| Star 5:................. | K2 III | 0.46 ± 0.07 | −180.9 ± 12.5|

![Fig. 4.](image)

**Table 5**

Classification, Extinction, and Relative Radial Velocity Results for Each of the Observed Microlensed Sources

| Spectrum | Class   | $E_{B-V}$ | $v_r$ (km s$^{-1}$) |
|----------|---------|-----------|---------------------|
| D02...... | K2 III  | 0.22 ± 0.09 | −97.3 ± 16.6        |
| M02...... | G2 III  | 1.19 ± 0.01 | −210.7 ± 11.2       |
| M03...... | G0 III  | 1.31 ± 0.01 | −376.6 ± 19.0       |
| M04...... | K0 III  | 0.63 ± 0.03 | −467.6 ± 10.0       |
| M08...... | G0 III  | 0.61 ± 0.03 | −219.9 ± 11.2       |
| M09...... | K4 III  | 0.39 ± 0.21 | −342.7 ± 7.8        |
| M10...... | G2 III  | 0.99 ± 0.01 | −411.7 ± 7.9        |
| M12...... | K0 III  | 0.58 ± 0.16 | 9.5 ± 8.0           |
| M13...... | K1 I    | 0.48 ± 0.07 | −659.9 ± 9.1        |
| M14...... | K4 III  | 0.32 ± 0.06 | −1810.1 ± 11.4      |
| M17...... | G5 III  | 0.55 ± 0.04 | −213.3 ± 6.6        |
| M18...... | K0 III  | 0.66 ± 0.09 | −1026.6 ± 6.9       |
| M19...... | G2 III  | 0.47 ± 0.11 | −623.0 ± 8.8        |
| M30...... | M2 III  | 0.56 ± 0.02 | −1620.0 ± 22.7      |
| O03...... | K2 I    | 0.08 ± 0.01 | −63.1 ± 11.3        |
| O07...... | G0 III  | 0.79 ± 0.02 | −137.9 ± 11.5       |
| O16...... | G5 III  | 0.60 ± 0.01 | −1029.4 ± 10.0      |

![Fig. 5.](image)

**Table 6**

Classification, Extinction, and Relative Radial Velocity Results for the MACHO-1995-BLG-17 Field

| Spectrum | Class   | $E_{B-V}$ | $v_r$ (km s$^{-1}$) |
|----------|---------|-----------|---------------------|
| Source:................... | G5 III | 0.55 ± 0.04 | −213.3 ± 6.6        |
| Star 1:................. | K3 III | 0.42 ± 0.13 | −72.1 ± 10.4        |
| Star 2:................. | K5 III | 0.33 ± 0.03 | −150.1 ± 10.3       |
| Star 3:................. | K2 III | 0.64 ± 0.09 | −72.1 ± 9.4         |
| Star 4:................. | G2 III | 0.29 ± 0.03 | −182.1 ± 17.4       |
| Star 5:................. | K2 III | 0.46 ± 0.07 | −180.9 ± 12.5       |
Fig. 6.—Spectra of the microlensed sources DUO 95-BLG-2, MACHO 95-BLG-2, MACHO 95-BLG-3, and MACHO 95-BLG-4.

Fig. 7.—Spectra of the microlensed sources MACHO 95-BLG-8, MACHO 95-BLG-9, MACHO 95-BLG-10, and MACHO 95-BLG-12.

Fig. 8.—Spectra of the microlensed sources MACHO 95-BLG-13, MACHO 95-BLG-14, MACHO 95-BLG-18, and MACHO 95-BLG-19.

Fig. 9.—Spectra of the microlensed sources MACHO 95-BLG-30, OGLE 95-BLG-3, OGLE 95-BLG-7, and OGLE 95-BLG-16.
Furthermore, the spectrum by the MACHO group was obtained when the source was amplified. So the blending fraction (i.e., fraction of light from a possible blended object) may be different at the two epochs, which may affect the result. And, as explained earlier, the limitations in the theoretical models make our spectral classifications uncertain if the spectral type is about M2 or later.

It would be interesting to compare our spectral classification with other such estimates available in the literature. There is one such source, MACHO 95-BLG-30, which has been studied in detail by the MACHO collaboration (Alcock et al. 1997), who obtained spectra with a wavelength coverage of 6230–9340 Å. From this they estimated a spectral type of M4 III, which is close to and within uncertainties of our determination of M2 III.

As explained earlier, our velocity determinations are relative and the absolute velocity can have large uncertainties because of the uncertainty in the absolute velocity of the template star. However, we are interested only on relative velocities in this study, which are more accurate, as explained before.

4.1. Color-Magnitude Diagram Analysis

In carrying out a comparative study of the properties of the microlensed and nonmicrolensed sources, it is important to check the distributions of both samples of the sources in the color-magnitude diagram (CMD) since they can provide some insight into the sample being analyzed.

There have been several studies performed on Galactic bulge CMDs, such as Terndrup (1988), who was one of the first to use a CCD in this analysis. The OGLE collaboration has since presented CMDs of 14 fields surveyed in the direction of the Galactic bulge (Ulacski et al. 1993). Some of the features common to these CMDs have been further studied, such as the well-defined red clump branch (Stanek et al. 1994) and the distribution of the disk stars (Paczyński et al. 1994a).

During the 1995 observing season, photometric data from seven of the 17 fields studied in this paper were obtained by the PLANET collaboration (Albrow et al. 1998). The CMDs for the individual fields have been combined into a single CMD, as shown in Figure 10. The combined CMD contains about 11,000 stars from the MACHO bulge fields 10, 12, 13, 17, 18, 19, and 30. Since the distribution of stars in the individual CMDs was almost identical, the colors and magnitudes were calibrated by adopting the position for the bulge red-clump giants as estimated by Paczyński & Stanek (1998), who found an average $V-I$ for the red clump region of 1.22 and an average $I$ magnitude of 14.34. The microlensed sources are shown as triangles in the CMD, and the nonmicrolensed sources are shown as squares.

The combined CMD is in good agreement with the CMDs published by OGLE. As expected, the CMD is dominated by bulge stars contained in a wide main-sequence turnoff point and the red giant branch. Also visible in the diagram is a high concentration of stars in the blue part of the CMD, suggested to be dominated by disk stars (Paczyński et al. 1994a). The nonmicrolensed stars chosen for this study are of similar brightness to the microlensed sources. The combined CMD shows that these stars lie within the same sample as the microlensed sources and are generally located in the recognizable main sequence or red giant branch. Hence, the nonmicrolensed stars chosen for comparison in this study are fairly typical of the population toward the Galactic bulge and are suitable for use in this study.

It is of interest to compare the magnitudes and colors of the sources as derived from the CMD with the spectral classifications derived from the spectra. Shown in Table 7 are these results along with an estimate of the absolute magnitude $M_V$. The value of $M_V$ derived here assumes that the peak of the red clump is at $m_V = 14.34$ and $V-I = 1.22$, as found by Paczyński & Stanek (1998). This is equivalent to assuming that the star is approximately in the middle of the bulge corresponding to a distance modulus of 14.62. The error in $M_V$ is dominated by the intrinsic dispersion of the bulge stars, which is $\sigma_V \sim 1.5$ mag. These results show that the luminosities measured from the CMD are roughly consistent with the classifications derived from the spectra and that giant stars have been preferentially selected since they are most likely to be in the Galactic bulge. Note that the magnitudes and colors shown in Table 7 are not the calibrated values, but they are the expected dereddened magnitudes and colors if the sources were at the middle of the Galactic bulge. This also shows that the nonmicrolensed stars chosen here are also within the bulge, and hence they form a good sample for our comparative study.

4.2. Extinctions of Microlensed versus Nonmicrolensed Sources

Although the internal extinction within Baade’s window is thought to be small, there are large uncertainties. As discussed earlier, the microlensed sources will show an extinction offset relative to the unlensed stars if the extinction within the bulge is nonnegligible. We note that almost all the sources (the microlensed as well as the comparison stars) are expected to be within the bulge and that the sources lie
within a fairly restricted region of the bulge (0°55 < l < 3°98 and −4°92 < b < −2°68). Hence the foreground extinction caused by the Galactic disk (i.e., excluding the extinction within the bulge) is expected to be about the same for all the sources. Thus, any extinction offset between the nonmicrolensed and microlensed samples would indicate that extinction within the bulge is nonnegligible. As explained in Paper I, this extinction offset can be used to estimate the fraction of bulge-bulge lensing.

Shown in Figure 11 is a histogram of the extinction for microlensed and nonmicrolensed stars. There is a surprising number of stars with little or no extinction among the nonmicrolensed stars which is most likely due to disk stars of low mass. This could be explained in part by the findings of Paczynski et al. (1994a) that indicate that there is an excess of disk stars by a factor of ~2 between us and a distance of 2.5 kpc toward the Galactic bulge and a rapid drop by a factor of ~10 beyond that distance. The average extinction is \( E_{B-V} = 0.68 \) for the microlensed sources and \( E_{B-V} = 0.43 \) for the nonmicrolensed stars. As expected, the distributions peak at these average values. The offset between the two mean values of \( \Delta E_{B-V} = 0.25 \) is equivalent to a magnitude offset of \( \approx 0.80 \) in \( V \).

To investigate the significance of the offset between the two mean values, a \( t \)-test was performed on the histogram data. A value of \( t = 3.07 \) was obtained for 93 degrees of freedom (dof), which results in a probability of \( p = 0.01 \). In other words, the difference in the mean values of the two distributions is significant at the 99% confidence level. To test how much weight is held by the unlensed stars with zero extinction, the \( t \)-test was performed again after removing these stars from the sample. This reduced the values to \( t = 2.42 \) for 81 dof, which results in a probability of \( \approx 0.02 \), or significance at the 98% confidence level.

This test assumes a normal distribution for the data sets, which is difficult to determine given the relatively small number of microlensed sources included in this sample. These results appear to agree with the previous discussions regarding the extinction bias of microlensed sources, and a clear trend is seen in the presented histogram. As explained in Paper I, from the extinction distribution for microlensed sources it is possible to make an estimate of the fraction of bulge-bulge lensing. Using the formalism of Paper I, a simple estimate of the fraction of bulge-bulge lensing is found to be \( \approx 65\% \). This is consistent with earlier predictions based on the presence of the bar (Paczynski et al. 1994b; Zhao et al. 1995).

We now turn to another possible effect: the timescales of the microlensing events versus the extinction. For self-lensing within the bulge, the Einstein ring size increases if the distance between the lens and the source is larger. Since the microlensed sources are preferentially located at the far side of the bulge, the characteristic timescale should be longer for events exhibiting larger extinction if the internal extinction is important. However, the timescale of an event is also a function of the velocities of the lens and the source, and so the timescale may depend upon the Galactic kinematics. If

### TABLE 7

| Star       | Classification | \( m_V \) | \( V-I \) | \( M_V \) |
|------------|----------------|----------|----------|----------|
| MB 95010:  | G2 III         | 16.25    | 0.65     | 1.63     |
| Star 1     | G0 III         | 16.13    | 0.67     | 1.51     |
| Star 2     | K5 III         | 14.28    | 1.69     | −0.34    |
| Star 4     | K5 III         | 15.67    | 1.40     | 1.05     |
| Star 5     | K3 III         | 15.63    | 1.41     | 1.01     |
| MB 95012:  | K0 III         | 16.27    | 1.18     | 1.65     |
| Star 1     | G2 III         | 17.13    | 0.94     | 2.52     |
| Star 2     | G2 III         | 15.86    | 1.29     | 1.24     |
| Star 3     | K3 III         | 15.45    | 1.38     | 0.83     |
| Star 4     | G5 V           | 16.82    | 0.66     | 2.20     |
| Star 5     | G2 III         | 16.02    | 0.59     | 1.40     |
| MB 95013:  | K1 II          | 13.38    | 1.24     | −1.24    |
| Star 1     | K5 III         | 15.40    | 1.39     | 1.78     |
| Star 2     | G2 III         | 14.96    | 1.18     | 0.34     |
| Star 3     | K5 III         | 15.38    | 1.25     | 0.76     |
| Star 4     | K5 III         | 15.46    | 1.42     | 0.84     |
| Star 5     | K3 III         | 15.43    | 1.25     | 0.81     |
| MB 95017:  | G5 III         | 16.58    | 0.88     | 1.94     |
| Star 1     | G5 III         | 14.57    | 0.52     | −0.05    |
| Star 3     | G5 III         | 15.70    | 0.58     | 1.08     |
| MB 95018:  | K0 III         | 15.78    | 1.13     | 1.16     |
| Star 1     | K4 III         | 14.66    | 1.21     | 0.04     |
| Star 2     | K2 III         | 14.98    | 1.22     | 0.36     |
| Star 3     | K4 III         | 15.79    | 1.41     | 1.17     |
| Star 4     | G5 III         | 16.64    | 0.84     | 2.02     |
| Star 5     | K5 III         | 14.20    | 2.04     | −0.42    |
| MB 95019:  | G2 III         | 15.96    | 0.75     | 1.34     |
| Star 1     | G5 III         | 15.66    | 0.96     | 1.04     |
| Star 2     | G5 III         | 17.45    | 1.06     | 2.83     |
| Star 3     | G8 III         | 16.17    | 1.14     | 1.55     |
| Star 4     | K3 III         | 16.66    | 1.18     | 2.04     |
| Star 5     | G8 III         | 16.26    | 1.01     | 1.64     |
| MB 9503b:  | M2 III         | 14.28    | 2.55     | −0.34    |
| Star 1     | G8 III         | 14.89    | 0.54     | 0.28     |
| Star 2     | K3 I           | 12.73    | 1.00     | −1.89    |
| Star 3     | K I            | 14.20    | 1.21     | −0.42    |
| Star 4     | G5 III         | 14.55    | 0.57     | −0.07    |

FIG. 11.—Histogram of extinction values for microlensed and nonmicrolensed stars.
the velocity dispersion is the dominant component and is similar in different regions of the bulge, then the timescale should be larger for a higher value of extinction. On the other hand, if rotation is the dominant component, then the timescale may show a behavior that is only a small function of the extinction value. Shown in Figure 12 is a plot of the extinction of the microlensed sources as a function of their characteristic timescales. The top frame uses the abbreviated names of the events to show their positions on the plot, and the bottom frame shows the corresponding data points with error bars. We should note that MACHO 95-BLG-13 is a very bright source and has relatively low extinction. Therefore, it is almost certainly a disk star and hence should not be included in this analysis. MACHO 95-BLG-3 has an extremely short timescale, which could mean that the source and the lens are very close to each other (both at the far side of the bulge), rather than a very small mass of the lens or a very high relative velocity. As indicated in Paper I, this would make the event quite unusual and not typical of Galactic microlensing.

Rejecting these two anomalous points for the reasons expressed above, a line was fitted to the data using linear regression. This fit is shown in the bottom panel of Figure 12. The trend in these data shows that the velocity dispersion component of the Galactic kinematics is strong enough that there is a correlation between the extinction and the characteristic timescale of the event. Linear regression was used to obtain a linear fit, which produces the following equation for this trend

$$E_B - V = 0.018t_E + 0.13 \ .$$

Of course, contamination due to disk lensing will cause greater scatter in this result. This clear trend seems to further confirm the earlier result that the microlensed sources suffer from larger extinction and that they are predominantly at the far side of the bulge. We emphasize however, that the uncertainty in individual extinction measurements can be large. Furthermore, although there seems to be a clear linear trend, the trend is dominated by just two points, namely, MACHO 95-BLG-02 and MACHO 95-BLG-10. Further observations will help in confirming this result.

4.3. Kinematics of Microlensed Sources

The microlensed sources provide a unique opportunity to investigate the kinematic properties in this region. The kinematic properties of our Galaxy have been studied and used with microlensing to construct consistent models of the Galaxy (Méra et al. 1998). It was suggested by Walker (1997) that one could use the kinematic properties of microlensed sources to distinguish between a lens population in the disk and a lens population in the bulge. It was also found that the radial velocity distributions between the two populations should not be substantially different for an axisymmetric bulge model but may exhibit a relative shift if the bulge is nonaxisymmetric (barred), depending upon the kinematics of the bar. As we found in the previous section, the distribution of transverse velocities of these two populations should be substantially different.

Shown in Figure 13 is a histogram of the relative radial velocities for microlensed and nonmicrolensed stars. The average relative radial velocity is $v_r = -81.2$ for the microlensed sources and $v_r = -71.5$ for the nonmicrolensed stars. There appears to be a slight shift between the peak values of these two distributions, but this is well within the velocity dispersions of the sources, and given the small number of samples and the low-resolution of the spectra, this is not statistically significant.

To investigate the significance between the two mean values, a $t$-test was performed on the histogram data. A value of $t = 0.52$ was obtained for 92 dof, which results in a very
high probability that the difference in the mean values of the two distributions is not statistically significant.

This lack of correlation could be due to any of the following: (1) there is no intrinsic correlation, (2) the uncertainties in the velocity measurements is larger than estimated here, or (3) the resolution is insufficient to see any correlation. Clearly, more spectroscopic observations with better S/N at a higher resolution will help in finding the exact cause.

We note that there was a significant difference between the extinction distributions for the microlensed and nonmicrolensed sources. Since there is no such difference between the radial velocity distributions, it is not expected that there will be a correlation between the extinction and radial velocity of the observed sources.

Shown in Figure 14 is a plot of the extinction of the microlensed and nonmicrolensed stars as a function of their relative radial velocities. This figure excludes only one star, namely, star 3 from the MACHO 95-BLG-30 field, for which there were not enough spectral lines in the star’s B150 spectrum for an accurate estimate of the radial velocity. (For this source, the routine produced a relative radial velocity measurement of \( v_r = -399.8 \pm 14.1 \), but this may be because of a misidentification of some spectral lines.)

The microlensed sources are shown as circles, and the nonmicrolensed sources are shown as crosses. As expected, there is an extinction shift between the microlensed population and the nonmicrolensed population, but there is no apparent correlation between the extinction and the radial velocity. These results appear to agree with the postulates made by Walker (1997). These results are also expected since the total extinction varies depending upon the line of sight.

We have presented spectra of 17 microlensed sources taken with the EFOSC at the ESO 3.6 m telescope. These spectra were used to derive the spectral type, extinction, and the radial velocities of these stars. Spectra were also taken of many nonmicrolensed sources in the same fields. The same analysis was done for the nonmicrolensed sources, and their spectral types, extinctions, and radial velocities were determined. This was carried out by developing MIDAS scripts to provide estimates of the extinction, spectral type, and radial velocity for each individual spectrum. A large library of Kurucz model spectra was constructed to model the spectra, and the radial velocities were measured relative to a bright star using the cross-correlation technique. These results are used for a comparative study of the physical properties of the microlensed and nonmicrolensed stars.

A comparison of the extinction distributions for microlensed and nonmicrolensed stars have been carried out through a statistical analysis. The average extinction is \( E_{B-V} = 0.68 \) for the microlensed sources and \( E_{B-V} = 0.43 \) for the nonmicrolensed stars. The offset between the two mean values of \( \delta E_{B-V} = 0.25 \) corresponds to a magnitude offset of \( \delta A_V \approx 0.80 \). A t-test performed on these distributions showed that the difference in the mean values of the two distributions is significant at the 99% confidence level.

A plot of the extinction of the microlensed sources as a function of their characteristic timescales shows that the sources with larger extinction, in general, correspond to larger timescales. This is consistent with the expectation that the sources with larger extinction lie farther along the line of sight.

The histogram presenting the relative radial velocities for microlensed and nonmicrolensed stars shows that the difference between the two distributions is not statistically significant. The sample needs to be increased to about 100 sources to detect any possible offset. Thus, more spectra of microlensed sources will be very useful in modeling the kinematics of the Galactic bulge. It is expected, however, that the transverse velocities of these two populations would be different. Hence it would be of great interest to determine the transverse velocities of the microlensed sources as these would, when combined with the radial velocities, contribute significantly to the knowledge of the kinematics of the far side of the Galactic bulge. It should be possible to make such measurements with the Hubble Space Telescope or with future space telescopes, such as the James Webb Space Telescope.

An estimate of the fraction of bulge-bulge lensing was made from the extinction distribution for microlensed sources. This simple method provides a rough estimate of the fraction of bulge-bulge lensing and is found to be \( \sim 65\% \). This value is similar to the results obtained by previous investigations (Paczynski et al. 1994b; Zhao et al. 1995; Kiraga & Paczyński 1994).

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![Figure 14](https://example.com/figure14.png)
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