THE INTERSTELLAR EXTINCTION LAW TOWARD THE GALACTIC CENTER. II.
$V$, $J$, $H$, AND $K_s$ BANDS

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ABSTRACT

We have determined the ratios of total to selective extinction directly from observations in the optical $V$ band and near-infrared $J$ band toward the Galactic center. The OGLE (Optical Gravitational Lensing Experiment) Galactic bulge fields have been observed with the SIRIUS camera on the Infrared Survey Facility telescope, and we obtain $A_V/E_{V-J} = 1.251 \pm 0.014$ and $A_J/E_{J-V} = 0.225 \pm 0.007$. From these ratios, we derive $A_J/A_V = 0.188 \pm 0.005$; combining this with the near-infrared extinction ratios obtained in Paper I for more reddened fields near the Galactic center, we obtain $A_V/E_{V-H} A_J/E_{J-H} A_K/E_{K-H} = 1:0.188:0.108:0.062$, which implies steeply declining extinction toward longer wavelengths. In particular, it is striking that the $K_s$-band extinction is $\approx 1/16$ the visual extinction $A_V$, much smaller than the $1/10$ usually employed.

Subject headings: dust, extinction — Galaxy: center — stars: horizontal-branch

1. INTRODUCTION

The wavelength dependence of interstellar extinction provides important diagnostic information about the properties of dust grains. The interstellar extinction law shows a large range of variability from one line of sight to another, especially at ultraviolet and optical wavelengths. In comparing the wavelength dependence among different lines of sight, normalization of the extinction curves by the total extinction $A_V$, instead of the usual color excess $E_{B-V}$, is vitally important, as Cardelli et al. (1989, hereafter CCM) have shown. According to CCM, the variation in Galactic extinction curves from the ultraviolet to the optical is described by a single parameter, which itself is the ratio of total to selective extinction $R_V = A_V/E_{B-V}$. Thus, the ratio $R_V$, or more generally $R_{\lambda} = A_{\lambda}/E_{\lambda-V}$, is very important, although very difficult to obtain. The usual way of determining $R_V$ is to extrapolate the ratio of color excesses $E_{\lambda-V}/E_{B-V}$ to $\lambda = \infty$ with reference to some model, but this can be compromised by emission or scattering by dust grains near the stars.

The past decade has seen a new method to determine the ratio of total to selective extinction $R_{\lambda}$. The method was first proposed by Woźniak & Stanek (1996); in essence, one simply measures the regression of the mean color of red clump (RC) stars in the Galactic bulge on their mean magnitude (the “RC method”). An increase in the amount of dust along a line of sight will make the clump fainter and redder. The slope of these changes in a color-magnitude diagram (CMD) is equivalent to $R_{\lambda}$. The method has been developed by Stanek (1996), Udalski (2003), and Sumi (2004) in the $V$ and $I$ bands and recently applied to the near-infrared wave bands in Nishiyama et al. (2006a, hereafter Paper I).

Early results from the RC method prompted Popowski (2000) to make the somewhat surprising suggestion for the interstellar extinction toward the Galactic bulge that the ratio of total to selective extinction $R_{VT} = A_V/E_{V-J}$ is approximately 2.0, much smaller than the value of 2.5 for the standard ($R_V = 3.1$) CCM extinction curve (Udalski 2003). This was confirmed by Sumi (2004) in a larger number of fields. Thus, the part of the extinction curve from $V$ (0.55 $\mu$m) to $I$ (0.80 $\mu$m) toward the Galactic bulge seems to be characterized by a smaller $R_{VT}$. In the near-infrared, the extinction law is frequently referred to as “universal,” and in fact CCM give an $R_{\lambda}$-independent curve. However, Paper I shows that the near-infrared extinction curve toward the Galactic center (GC) is different from those in the literature, also having a smaller $A_I/A_V$ at $J$, $H$, and $K_s$ wavelengths.

This paper, we apply the RC method and extend the $R_{\lambda}$ determination to the $J$ band (1.25 $\mu$m) by measuring the $J$ magnitudes of the stars whose $V$ photometry was obtained in Udalski (2003). Furthermore, assuming that the extinction curve can be extended to the more heavily reddened regions observed in Paper I, we estimate $A_J/A_V$ at $J$, $H$, and $K_s$ wavelengths.

2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

2.1. Near-Infrared Observations

All observations in the near-infrared wavelengths were made with the SIRIUS camera (Simultaneous Infrared Imager for Unbiased Survey; Nagashima et al. 1999; Nagayama et al. 2003) attached to the 1.4 m IRSF (Infrared Survey Facility) telescope, on the nights of 2004 May 18 and 19. The SIRIUS camera provides photometric images of a 7.7' $\times$ 7.7' area of sky in the three near-infrared wave bands $J$(1.25 $\mu$m), $H$(1.63 $\mu$m), and $K_s$(2.14 $\mu$m) simultaneously. The detectors are three 1024 $\times$ 1024 HgCdTe arrays, with a scale of 0".45 pixel$^{-1}$. The IRSF-SIRIUS system is similar to the MKO system (Tokunaga et al. 2002).

Over the range $17^h52^m \leq R.A. \leq 17^h56^m$ and $-30.2^\circ \leq decl. \leq -29.5^\circ$ (J2000), 32 images in each band were obtained (Fig. 1). These fields correspond to region “A” ($l \approx 0^\circ$, $b \approx -2^\circ$) of Udalski (2003) in the Optical Gravitational Lensing Experiment II (OGLE) maps of the Galactic bulge in the $V$ and $I$ bands, with
an absolute photometric accuracy of 0.01−0.02 mag (Udalski et al. 2002). The data files containing the photometry were downloaded from the OGLE Web site.7 Udalski’s (2003) region A consists of the five fields SC3, SC4, SC5, SC37, and SC39 (Fig. 1), but the SC5 data were excluded from the following analysis because the field suffers from the heaviest extinction and its $V$ magnitudes become unreliable, as Udalski (2003) also pointed out.

The observing weather was photometric, with seeing of ~1.1′′ in the $J$ band. Flat fields were obtained during each clear evening and morning twilight. Dark frames were taken at the end of each observing night. A single image comprises 10 dithered 5 s exposures.

The SIRIUS camera provides three ($J$, $H$, and $K_s$) images simultaneously, and thus we have the data sets for each region in three bands. However, the uncertainties in the $H$ and $K_s$ photometry are larger and the range of extinction is smaller, about one-half ($H$) and one-third ($K_s$) that in the $J$ band.8 Therefore, we obtained reliable results only for the $J$ band.

The IRAF9 software package was used to perform dark and flat-field corrections, followed by sky background estimation and subtraction. Photometry, including point-spread function (PSF) fitting, was carried out with the DAOPHOT package (Stetson 1987). We used the DAOFIND task to identify point sources, which were then input to the ALLSTAR task for PSF-fitting photometry. About 20 sources were used to construct the PSF for each image.

Each image was calibrated with standard star No. 9172 from Persson et al. (1998), which was observed every half-hour. We assumed that this star has $J = 12.48$ in the IRSF-SIRIUS system. The average of the zero-point uncertainties and the 10 $\sigma$ limiting magnitude in the $J$ band were ~0.02 and 16.8 mag, respectively.

Astrometric calibration was performed, field by field, with reference to the positions of stars in the Two Micron All Sky Survey (2MASS) Point Source Catalog (Skrutskie et al. 2006). Only stars with a photometric error of less than 0.05 mag in the 2MASS catalog and ours were used for the calibration. The positional difference was finally calculated by using the stars with ±0.1 mag photometric error, and we obtained a standard deviation of the positional differences of better than 0.1′′.

2.2. Cross Identification of the SIRIUS and OGLE Sources

The stars found with IRSF-SIRIUS and OGLE were cross-identified, field by field, using a simple positional correlation. The procedure consists of two steps. First, identification was performed with a large radius (1.5′′) to evaluate the astrometric offset between IRSF and OGLE coordinates. We found that the offsets in right ascension and declination range from ~0.7′′ to +0.1′′ and from +0.1′′ to +0.4′′, respectively. The offsets seem to depend on the position in the OGLE field. Second, the OGLE coordinates were corrected for these offsets, and a search radius of 0.7′′ was used for the identification.

We show histograms of the positional differences of the finally identified stars in Figure 2. We found ~25,000 matches in each field, with an rms error in the difference between SIRIUS and OGLE coordinates of 0.13′′ in right ascension and declination. The values of $\sigma$ obtained by fitting with a Gaussian function are 0.088′′ in right ascension and 0.081′′ in declination.

2.3. Data Analysis

To measure the ratios of total to selective extinction $A_V/E_{V-J}$ and $A_J/E_{V-J}$, we selected the bulge RC stars, which constitute a compact and well-defined clump in a CMD and are thus good tracers of extinction and reddening. The $V$ versus $V-J$ CMD constructed with the IRSF and OGLE data is shown in Figure 3. In this analysis we follow the procedure described in Udalski (2003), Sumi (2004), and Paper I.

First, we divide each SIRIUS field into nine subfields of ~2.8′×2.8′ on the sky. Then we construct $V$ versus $V-J$ and $J$ versus $V-J$ CMDs for each subfield. Second, in the CMDs we extract stars in the region dominated by RC stars, and these stars are used to create magnitude histograms (the luminosity function; see also Fig. 2 of Paper I). The peaks of the RC stars are fitted with a Gaussian function. Third, the stars in the range fitted above are employed to see the distribution of RC stars in $V-J$ color, and the color peaks of the RC stars are also fitted with a Gaussian function. Since the mean $V$ magnitudes of RC stars become too faint in highly reddened fields, estimates of their peak magnitudes and colors can be unreliable in such cases. To avoid this problem, we do not use the subfields in which we could not find a clear peak of RC stars. Note that this exclusion was made in the second and third steps, so a field employed in the $J$ versus $V-J$ CMD can be excluded in the $V$ versus $V-J$ CMD if its $V$ distribution does not have a clear Gaussian peak, and vice versa. As a result, 48 ($V$ vs. $V-J$) and eight ($J$ vs. $V-J$)}
out of 288 (32 × 9) subfields were excluded from our analysis. Therefore, the data points of the two CMDs are not identical, and the resultant slopes do not necessarily satisfy the relation

\[
\frac{AV}{EV} / C_0 J = \frac{AJ}{EV} / C_0 J + 1.
\]

3. RESULTS

Combining the IRSF J-band and the OGLE V-band data sets, we have made V versus V−J (Fig. 4, top) and J versus V−J (bottom) CMDs, in which the location of the RC magnitude and color peaks are shown. The error bars include uncertainties in the RC peak and photometric calibration. Least-squares fits to the data points provide us with the slope of the CMDs, \( \frac{AV}{EV} / C_0 J = 1.255 \pm 0.004 \) and \( \frac{AJ}{EV} / C_0 J = 0.225 \pm 0.005 \).

The errors in the slopes obtained using a least-squares fit seem to be underestimated, because the dispersion of the data points is large compared with the error bars, which is particularly noticeable in the J versus V−J CMD. Hence we estimated the errors of the slopes by fixing the \( \chi^2 / \text{dof} = 1 \) under the assumption that the errors are all equal. Application of this procedure to the data in both CMDs results in \( \frac{AV}{EV} / C_0 J = 1.251 \pm 0.014 \) and \( \frac{AJ}{EV} / C_0 J = 0.225 \pm 0.007 \).

These ratios of total to selective extinction provide the ratio of total extinction \( \frac{AJ}{AV} \) by simple algebra, \( [(\frac{AV}{EV} / C_0 J) - 1](\frac{AJ}{EV} / C_0 J) \) and \( (\frac{AJ}{EV} / C_0 J)[(\frac{AJ}{EV} / C_0 J) + 1] \), yielding \( \frac{AJ}{AV} = 0.201 \pm 0.011 \).

We made a J versus V−J CMD excluding 48 subfields, which are not used in the V versus V−J diagram, and confirmed that their exclusion changes the slope in the CMD by only 0.002.
The peak magnitude of the RC stars could be altered by the falling completeness. Therefore, we checked the completeness and the change in the peak magnitudes. First, we performed experiments in which we added artificial stars of various known magnitudes to our original images and subjected them to the same procedure described in § 2.1. The detection rates drop as the magnitude becomes fainter: ≈95% at \(J = 14\), ≈85% at \(J = 15\), and ≈70% at \(J = 16\). Second, we reconstructed luminosity functions, compensating for the detection rates, and fitted the RC peaks again. Comparing the RC peak magnitudes with the reconstructed ones, we find that the mean difference between them is 0.017 mag with an rms of 0.006. This rms is very small compared with the error on each of the data points in the CMDs, typically 0.02–0.03 mag. We cannot find a clear dependence of the difference on the peak magnitude or on the number of stars. Hence, we conclude that the effect of completeness does not change the slopes in the CMDs.

The zero-point uncertainty should be checked to derive the slope in the CMDs reliably. We examined the internal consistency of the duplicate sources in overlapping regions of adjacent fields. Histograms of the mean magnitude difference for the sources with photometric error less than 0.05 mag in each field set are shown in the left panel of Figure 5. The differences for adjacent fields in the directions of right ascension and declination are shown by open and hatched histograms, respectively. We determined the rms magnitude difference to be less than 0.02 mag. For another check, we made comparisons with the 2MASS catalog in the \(J\) band. The histogram of the mean difference between the 2MASS and IRSF \(J\) magnitudes for each field is shown in the right panel of Figure 5. The mean and rms variance of this histogram are 0.009 and 0.015 mag, respectively. The rms variance is similar to the zero-point uncertainty we derived from the observation of the standard star. We therefore conclude that the systematic error in our data sets is about 0.02 mag. Note that, in this study, the systematic error does not come from the absolute zero-point uncertainty, but from the relative one. Even if the absolute magnitudes of the RC stars have a systematic offset, the resultant plots shown in Figure 4 move as a whole, with the slope unchanged. Also, Figure 5 (right) shows that the absolute magnitude offset in the \(J\) band is small.

4.2. Error Estimates for \(R_J\)

The differing distances to RC stars in the observed area could be a factor in the systematic error, which could become large in the situation that distance is correlated with interstellar extinction. However, the distance changes with Galactic longitude because of the barred structure (see, e.g., Nakada et al. 1991), and the extinction seems to change with Galactic latitude in our observed area (Sumi 2004), suggesting no correlation between them. The extent of the observed area in Galactic longitude is only 1.7°, which leads to only a ~0.03 mag difference in the brightness of RC stars (Nishiyama et al. 2005), also suggesting a small systematic error due to the differences in distance.

Although the population effect for the RC stars is a source of systematic error, the dependence of the RC brightness on metallicity is very weak, and the metallicity gradient is expected to be very small in our small observed area (Udalski et al. 2002; Nishiyama et al. 2005). In addition, the metallicity should again be correlated with the interstellar extinction, and this situation seems unlikely.

4. DISCUSSION

4.1. Reliability of Our Data Sets

The faintest data points in the CMDs (Fig. 4) are \(V = 20.2\) and \(J = 14.7\). Udalski (2003) set a safety margin and regarded his points as complete to a limit of \(V = 20.7\), which is still fainter than our faintest data point by 0.5 mag. As described in § 2, the limiting magnitude in the \(J\) band is 16.8, also much fainter than \(J = 14.7\). Therefore, these margins seem to be large enough to have the mean magnitude of RC stars reliably measured.

(From \(A_J/E_{V-J}\) and \(A_J/A_V = 0.184 \pm 0.006\) (from \(A_J/E_{V-J}\)). Thus we obtain their weighted mean and error, \(A_J/A_V = 0.188 \pm 0.005\). However, the difference between the two values is 0.017, and the combined \(\sigma = (0.011^2 + 0.006^2)^{1/2} = 0.013\). Hence, this \(A_J/A_V\) could have an error of order 0.01.

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To examine the systematic errors due to the population effect and the different distances of RC stars, we performed linear fits to the data points in the $J$ versus $V−J$ CMD for four OGLE fields separately, keeping the same slope (0.225) but changing the intercept. The intercepts obtained are 13.37, 13.37, 13.35, and 13.38 for SC37, SC3, SC4, and SC39, respectively. Next, to check the dependence of the intercept’s deviation on the value of the slope, we also made linear fits for the four fields, changing the slopes separately, keeping the same slope (0.225) but changing the intercept. The intercepts obtained are 13.37, 13.37, 13.35, and 13.38 for SC37, SC3, SC4, and SC39, respectively.

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The change of effective wavelength in the $J$ band is very small. As shown in the bottom panel of Figure 4, the peak magnitudes of the RC stars are distributed between 0.211 (0.255 + 2 $\sigma$) and 0.239 (0.255 + 2 $\sigma$). We could not find any systematic trend, and the results are within the error of the intercept, 13.37 ± 0.03, for all subfields. We thus conclude that the differences in distance and the population effect do not affect our results.

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4.3. Extinction $A_J/A_V$ toward the Galactic Bulge

In the 0.5−0.9 $\mu$m wavelength range, extinction toward the Galactic bulge has been characterized by a “steep” curve whose ratio of total to selective extinction is small. The steep extinction curve was introduced to explain the anomalous ($V−I)_0$ color of RC stars in Baade’s window (e.g., Popowski 2000; Gould et al. 2001). A lower ratio was also reported from the MACHO $V$ and $R$ photometry ($A_V/E(V−R) = 3.5$; Popowski et al. 2003) and OGLE $V$ and $I$ photometry ($R_{VT} = A_V/E_{V−I} \sim 2.0$; Udalski 2003; Sumi 2004) toward the Galactic bulge. The empirical analytic formulae of CCM and Fitzpatrick (1999) corresponding to the extinction toward the Galactic bulge have the single parameter $R_V \approx 2$, which is much lower than the average value of 3.1 for diffuse regions in the local interstellar medium.

The CCM formula uses a simple $\lambda^{-1.61}$ power law in the wavelength region longward of 0.9 $\mu$m and seems to be independent of $R_V$. However, since $A_V$ depends on $R_V$, the ratios $A_V/E_{V−I}$ and $A_V/E_{V−R}$ are dependent on $R_V$, and these ratios derived in our work correspond to $R_V \sim 1.8$, which is also very small. The reddening vectors in the $V$ versus $V−J$ CMD for the case of $R_V = 3.1$ and our results are plotted in Figure 3, which shows a clear difference in the reddening direction.

Small values of $R_V$ are generally considered to indicate the prevalence of small dust grains, which will affect the extinction curve in the ultraviolet to optical wavelengths. Although a substantial number of lines of sight with low $R_V$-values have been found, especially at high Galactic latitude (e.g., Larson et al. 1996; Larson & Whittet 2005), only a few lines of sight exist with $R_V < 2.0$ (Szomoru & Guhathakurta 1999; Larson & Whittet 2005).

Next, we try to extend the extinction curve to 2 $\mu$m. Paper I determined the dependence of the interstellar extinction in the $J$, $H$, and $K$ bands toward the GC, and thus we can combine it with the result obtained in this paper to determine $A_J/A_V$ in the $H$ and $K$ bands. Here we need to take into account the variation in the extinction law along different lines of sight, because the area observed in Paper I ($|l| \leq 20'$ and $0.5' \leq |b| \leq 1.0'$) does not overlap with this study. The variation in $A_K/E_{H−K}$ was estimated to be

\begin{footnote}{$R_V \sim 1.8$ was found to reproduce our result $A_J/A_V = 0.193$ using the CCM formula.}
as large as \( \approx 7\% \) in a \( 4^\circ \times 2^\circ \) in the GC (Paper I), and hence we adopt this value as the variation in \( A_J/A_V \), resulting in \( A_J/A_V = 0.188 \pm 0.014 \), where the 0.014 = \([0.005^2 + (0.188 \times 0.07)^2]^{1/2} \). By using the ratios \( A_J/A_H: A_K/A_V = 1:0.573 \pm 0.009:0.331 \pm 0.004 \) (Paper I), we obtain \( A_J/A_H: A_K/A_V = 0.188 \pm 0.014:0.108 \pm 0.008:0.062 \pm 0.005 \).

The resultant \( A_J/A_V \) in the \( JHK_s \) wavelength range is a steeply decreasing function. As shown in Table 1, the CCM curve (for \( R_V = 3.1 \)), which is based on the work of Rieke & Lebofsky (1985), decreases much more slowly toward longer wavelengths. In particular, the \( K_s \)-band extinction is slightly greater than 1/10 the visual extinction \( A_V \) in the CCM curve, which contrasts with the van de Hulst (1946) curve, in which \( A_{K_s} \) is slightly less than 1/10 of \( A_V \). The derived extinction toward the Galactic bulge decreases more steeply as the wavelength increases. The steep decrease is rather striking but was already evident from Messineo et al. (2005) and Paper I, where a steep extinction power-law index \( \alpha \approx 2.0 \), consistent with the polarization law up to \( \approx 2.5 \mu m \) (Nagata et al. 1994), was proposed for the GC extinction. To confirm this, deep optical and infrared observations in the \( I \) to \( K_s \) bands for the same fields with appropriate extinction would be important.

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### TABLE I

| Ratio | IRSF | vdf\(^T\) | CCM\(^T\) |
|-------|------|----------|----------|
| \( A_J/A_V \) | 1.251 ± 0.014 | 1.325 | 1.393 |
| \( A_J/A_H \) | 0.225 ± 0.007 | 0.325 | 0.393 |
| \( A_J/A_K \) | 0.188 ± 0.014\(^e\) | 0.245 | 0.282 |
| \( A_H/A_K \) | 0.108 ± 0.008\(^e\) | 0.142 | 0.190 |
| \( A_K/A_V \) | 0.062 ± 0.005\(^e\) | 0.088 | 0.118 |

\(^a\) Van de Hulst 1946.

\(^b\) Cardelli et al. 1989, for the case of \( R_V = 3.1 \).

\(^c\) The error due to variations of the extinction law along different lines of sight is included.

\(^d\) The work of Rieke & Lebofsky (1985), decreases much more slowly toward longer wavelengths.

\(^e\) The derived extinction toward the Galactic bulge decreases more steeply as the wavelength increases. The steep decrease is rather striking but was already evident from Messineo et al. (2005) and Paper I, where a steep extinction power-law index \( \alpha \approx 2.0 \), consistent with the polarization law up to \( \approx 2.5 \mu m \) (Nagata et al. 1994), was proposed for the GC extinction. To confirm this, deep optical and infrared observations in the \( I \) to \( K_s \) bands for the same fields with appropriate extinction would be important.