Structure of the Galactic Bulge:
Is the Milky Way a Double-barred Galaxy?

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Abstract. Using the data of the IRSF/SIRIUS infrared survey along the Galactic plane (|l| \leq 10.5 at b = +1\degree), we find a distinct structure, which is probably a secondary bar, inside the primary bar of our Galaxy. The apparent magnitude peak of Bulge red clump stars changes continuously from $K_S \sim 13.5$ (l = -10\degree) to $K_S \sim 12.3$ (l = +10\degree), and this can be explained by the bar structure of the Galactic Bulge. However, the apparent magnitude changes by only $\sim 0.1$ mag over the central 8\degree, and this indicates that there is a distinct structure inside the primary bar. In the process of the distance derivation, we have used the infrared extinction law in the $J, H,$ and $K_S$ bands toward the Galactic center newly determined from our survey.

1. IRSF/SIRIUS Galactic Center Survey
The IRSF/SIRIUS Galactic center (GC) survey project is a deep near-infrared ($J, H, K_S$) survey of the central region of our Galaxy. The survey has been carried out with the 1.4m telescope IRSF and the SIRIUS camera. IRSF/SIRIUS were constructed and have been operated by Nagoya University (Japan), National Astronomical Observatory of Japan, and the South African Astronomical Observatory. The SIRIUS camera [1, 2] can provide three ($J, H, K_S$) images simultaneously with a field of view of $7.7 \times 7.7$ and a pixel scale of 0.45. The limiting magnitudes of our survey are 17.0 ($J$), 16.6 ($H$), and 15.6 ($K_S$), which are $\sim 2$ to $3$ mag deeper than 2MASS at the GC. A more detailed description of our survey is given in the PhD thesis by Nishiyama [3]. A three color composite image of the GC, whose field size is 100' in R.A. and Dec, is shown in Fig. 1\textsuperscript{8707}.

2. Bulge Red Clump Stars As a Standard Candle
Red clump (RC) stars are the equivalent of the horizontal-branch stars for metal rich population. They can be used as a good standard candle due to their abundance, brightness ($M_{K_S} = -1.52$ for Bulge population [4, 5, 6]) and narrow distribution in luminosity and color. The Hipparcos catalogue allows us exact calibration of absolute magnitudes. Owing to their abundance, RC stars are the only type of standard candles that do not suffer from a large statistical error.

\textsuperscript{8707}You can find this image at the web site http://www.z.phys.nagoya-u.ac.jp/~sirius/press/ASJM04a/gc100min.jpg
3. New Extinction Law in $J, H, \text{ and } K_S$ bands toward the Galactic Center [7]

With an increasing number of observation of highly obscured objects by interstellar extinction in the GC, a precise determination of the extinction law is important. However, the large difference between the extinction law quite often used ([8] and [9]) and those obtained from new observations has been reported in the optical wavelengths [10, 11]. Hence we have determined the interstellar extinction law toward the GC in the near infrared ($J, H, K_S$) wavebands from the observation of the region $|l| \leq 2^\circ 0$ and $0^\circ 5 \leq |b| \leq 1^\circ 0$ [7]. Using the “RC method”, the ratios of total to selective extinction have been directly obtained (Table 1). The ratio of absolute extinction $A_J : A_H : A_{K_S} = 1 : (0.573 \pm 0.009) : (0.331 \pm 0.004)$ is also obtained. The power law
Table 1. Interstellar Extinction Laws obtained in our study and previous studies.

|                       | IRSF        | van de Hulst[12] | R&L[8]  | Cardelli[9] | Indevetouw[13] |
|-----------------------|-------------|------------------|---------|-------------|----------------|
| \(A_{K}/E_{H-K}\)    | 1.44 ± 0.01 | 1.58             | –       | 1.83        | 1.82           |
| \(A_{K}/E_{J-K}\)    | –           | 1.33             | 1.78    | 1.63        | –              |
| \(A_{K}/E_{J-K}\)    | 0.494 ± 0.006| 0.55             | –       | 0.73        | 0.67           |
| \(A_{K}/E_{J-H}\)    | –           | 0.49             | 0.66    | 0.68        | –              |
| \(A_{K}/A_{J}\)      | 0.57 ± 0.009| 0.58             | 0.62    | 0.65        | 0.62           |
| \(A_{K}/A_{J}\)      | 0.331 ± 0.004| 0.36             | –       | 0.42        | 0.40           |

approximation \(A_{\lambda} \propto \lambda^{-1.99±0.02}\) is shown to be good enough in the wavelength range 1.2–2.2\(\mu\)m.

The most widely used technique to obtain the interstellar extinction law is the color-difference (CD) method, where the extinction curves are determined in the form of the ratios of color excesses, e.g., \(E_{\lambda-V}/E_{B-V}\), as a function of \(\lambda^{-1}\). The absolute extinction \(A_{\lambda}\) can be derived from the ratios of color excesses, only if the ratio of total to selective extinction \(R_{V} = A_{V}/E_{B-V}\) is evaluated \([A_{\lambda}/E_{B-V} = E_{\lambda-V}/E_{B-V} + R_{V}]\). The value of \(R_{V}\) can only be deduced by the extrapolation of the extinction curve to \(\lambda^{-1} = 0\), but the extrapolation has uncertainty due to the contamination by dust emission and the neutral extinction by large grains.

In the RC method, we expect the difference between the observed and absolute magnitudes to be the same for every RC star in the Galactic bulge except for differences produced by variations in the amount of interstellar extinction along the line of sight to each star. They are thus located in a straight line in a color-magnitude diagram with the slope of \(R_{\lambda} = A_{\lambda}/E_{\lambda-V}\), in accordance to the variable extinction to each of them. We can obtain \(R_{\lambda}\) directly from the observed data, and therefore \(R_{\lambda}\) can be much more reliable than that obtained by the extrapolation of the extinction curve in the CD method. The reliable \(R_{\lambda}\) provides the precise absolute extinction value \(A_{\lambda}\).

Previous results in the literature are listed for comparison in Table 1 [8, 9, 12, 13]. Our results show a clear difference to those obtained in previous works. The ratios of total to selective extinction determined in our study are smaller. This corresponds to a faster decrease in the absolute extinction \(A_{\lambda}\) when the wavelength increases. Our results are the closest agreement to the van de Hulst No. 15 curve [12] which was based on the Mie scattering theory and has been used to estimate the wavelength dependence.

Rieke & Lebofsky[8] (R&L) determined the optical-infrared extinction law applying the CD method to their observations of stars near the GC. Their results and that derived by the analytic formula of the average extinction law by fitting the data of R&L [9] have quite often been referred to as the standard extinction law, especially toward the GC. Since their determination requires the ratio of total to selective extinction, R&L set \(E_{V-K}/E_{B-V} = 2.744\) and assumed \(R_{V} = A_{V}/E_{B-V} = 3.09\) for the GC sources to evaluate \(A_{\lambda}/E_{B-V}\) and \(A_{\lambda}/A_{V}\). Although the lower limit of \(R_{V}\) in R&L was determined by the extinction at \(L, M, 8, \) and \(13\mu\)m, the observations at these wavelengths have relatively large uncertainties, and a small change in \(R_{V}\) results in a large difference in \(A_{\lambda}/E_{B-V}\) at infrared wavelengths. We also note that the extinction law they derived in the wavelength range \(L, M, 8\mu\)m is inconsistent with those obtained toward the GC, in particular by spectroscopy with the Infrared Space Observatory (ISO) for \(\lambda \geq 2.4\mu\)m [14]. Therefore, although the inconsistency might be the result of spatial variation of the extinction law [7], it is also quite possible that the inconsistency was caused by...
Figure 2. Derived wavelength dependence of the interstellar extinction \( \frac{A(\lambda)}{A(J)} \) in the range of 1 to 10 \( \mu m \) toward the Galactic center. The results of our study [7] and Lutz et al. [14] are shown by filled and open circles, respectively. \( \frac{A(\lambda)}{A(V)} \) by Lutz et al. [14] is converted to \( \frac{A(\lambda)}{A(J)} \) by assuming a \( \lambda^{-1.99} \) extinction law for \( K_S \) and \( \lambda = 2.625 \mu m \).

4. A Distinct Structure Inside the Galactic Bar [16]

The existence of a bar structure in our Galaxy is by now established. However, its parameters (size, axis ratio, alignment, etc.) have not been well determined yet. Bulge RC stars are good standard candles, and the distribution of their apparent magnitude along the Galactic plane shows an asymmetry which presents clear evidence for the Galactic bar. Large scale surveys are important to determine the detailed structure of the Galactic bar, and deep infrared observations are also required because of the large extinction near the Galactic plane. The limiting magnitude of 2MASS \( (m_{K_S} \sim 13 \text{ mag}) \) is too shallow to detect the whole RC stars near the GC.

We surveyed a strip extending over \( |l| \leq 10^\circ.5 \) at \( b = +1^\circ \), with a latitude width of \( \sim 8^\prime \) [16]. To analyze the distribution of RC stars, (1) color-magnitude diagrams were constructed using the \( H \) and \( K_S \) bands, (2) stars on the red giant branch were extracted, (3) the extinction free magnitude \( K_{H-K} \) was defined as \( K_{H-K} \equiv K_S - 1.44 \times E_{H-K_S} \), where \( A_{K_S}/E_{H-K_S} = 1.44 \) and \( (H - K_S = 0.07 [6] \), and (4) de-reddened luminosity \( (K_{H-K}) \) functions were constructed and fitted with the sum of exponential (red giant branch) plus Gaussian (RC stars) functions.

The dependence of the RC peak magnitude on the Galactic longitude \( l \) is shown in Fig. 3. Assuming the absolute \( K_S \) magnitude of the Bulge RC stars to be \( M_{K_S} = -1.52 \text{ mag} \), the absolute peak distances are shown using the scale on the right in Fig. 3. The distance modulus to the Bulge RC stars is given by \( (m - M) = K_{H-K} - M_{K_S} + \Delta M_K \), where \( \Delta M_K \) is the population correction calculated from theoretical stellar evolution models. Here we adopt
\[ \Delta M_K = -0.07 \text{ (scaled to solar metalicity [5]).} \]

As shown in Fig. 3, the RC peak becomes progressively brighter at greater \( l \) from \( K_{H-K} \sim 13.5 (l = -10^\circ) \) to \( K_{H-K} \sim 12.3 (l = +10^\circ) \), indicating the non-axisymmetric Bulge structure in support of previous studies. However, the slope of the data points is not constant, becoming shallower at \( |l| < 5^\circ \). This variation suggests the presence of an inner structure inside the large-scale bar. Since the inner structure seems to be straight and the RC peak magnitude changes only slightly, the inner structure may well be an inner bar.

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Figure 3. Dependence of the peak of \( K_{H-K} \) on the Galactic longitude \( l \). This figure is slightly different from Fig. 4 of Nishiyama et al. [16] because \( K_{H-K} \) and distance were re-calculated by using a more realistic RC absolute magnitude and color.