The Ratio of Total to Selective Extinction Toward Baade’s Window

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ABSTRACT

We measure the ratio of total to selective extinction, \( R_{VI} \equiv A_V/E(V-I) \), toward Baade’s Window by comparing the \( VIK \) colors of 132 Baade’s Window G and K giants from Tiede, Frogel, & Terndrup with the solar-neighborhood \((V-I), (V-K)\) relation from Bessell & Brett. We find \( R_{VI} = 2.283 \pm 0.016 \), and show that our measurement has no significant dependence on stellar type from G0 to K4. Adjusting the Paczyński et al. determination of the centroid of the dereddened Baade’s Window clump for this revised value of \( R_{VI} \), we find \( I_{0,RC} = 14.43 \) and \( (V-I)_{0,RC} = 1.058 \). This implies a distance to the Baade’s Window clump of \( d_{BW} = 8.63 \pm 0.16 \) kpc, where the error bar takes account of statistical but not systematic uncertainties.

Subject headings: distance scale – dust, extinction – Galaxy: center

1. Introduction

Paczyński & Stanek (1998) found that the \( VIK \) colors of clump giants in Baade’s Window were anomalous in the sense that at fixed \((V-K)_0\), they were redder in \((V-I)_0\) than clump giants in the solar neighborhood by 0.2 mag. Stutz, Popowski, & Gould (1999) found a similar offset (0.17 mag) for RR Lyrae stars in Baade’s Window compared to those in the solar neighborhood. Popowski (2000) showed that part of these offsets was simply due to errors in the original photometry used by both groups. When he incorporated the revised OGLE photometry of Paczyński et al. (1999), he found that the offset in \((V-I)\) shrank to \( \sim 0.11 \) mag in both cases.
Popowski (2000) then reviewed the various attempts to explain such an offset in terms of a difference between the intrinsic properties of stars in the two populations, an idea advanced by Paczyński (1998) and by Stutz et al. (1999). He argued that such an explanation was not impossible, but unlikely, and that a more plausible explanation is that the ratio of total to selective extinction $R_{VI} \equiv A_V/E(V-I) = 2.5$ adopted by both Paczyński & Stanek (1998) and Stutz et al. (1999) from Stanek (1996) was incorrect. Both color anomalies could be solved, he noted, by adopting $R_{VI} = 2.1$. Popowski (2000) used this re-evaluation to draw various conclusions about the extragalactic distance scale.

In the course of calibrating a $K$-band clump-giant distance indicator and applying it to measure the distance modulus of the Baade’s Window bulge field, Alves (2000) measured $R_{VI} = 2.26$. He did so by comparing the $VIK$ colors of his 20-star sample of Baade’s Window clump giants taken from Tiede, Frogel, & Terndrup (1995) with the $VIK$ colors of local clump stars.

Here we improve on the Alves (2000) measurement by incorporating a factor $\sim 7$ more stars into the analysis, i.e., all 138 G0-K4 giants with $VIK$ photometry from Tiede et al. (1995). We determine $R_{VI}$ by comparing these $VIK$ colors to the $VIK$ colors of nearby stars as determined by Bessell & Brett (1988). We find,

$$R_{VI} \equiv \frac{A_V}{E(V-I)} = 2.283 \pm 0.016. \quad (1)$$

This reduces the color anomalies to $\sim 0.05$ mag and so qualitatively confirms Popowski’s (2000) explanation of them.

2. Measurement of $R_{VI}$

To measure $R_{VI}$, we assume that the $VIK$ colors of giant stars in Baade’s Window as measured by Tiede et al. (1995) are intrinsically the same as those in solar neighborhood as determined by Bessell & Brett (1988). (We will partially test this assumption below.) Bessel & Brett (1988) give $VIK$ colors from G0 to M5, that is, over the color range $1.75 \leq (V-K)_0 \leq 5.96$. However, there is considerable evidence that the spectral energy distributions of M giants (at fixed spectral type) differ significantly between Baade’s Window and the solar neighborhood (Frogel & Whitford 1982, 1987; Tiede et al. 1995). This does not necessarily mean that the $(V-I), (V-K)$ color-color relation is different, and in fact we will present
evidence below that it is not. However, to be conservative, we restrict consideration to \((V - K)_0 \leq 3.5\), which eliminates all M giants and K5 giants as well. That is,

\[
1.75 \leq (V - K)_0 \leq 3.50. \tag{2}
\]

We begin with the sample of 509 stars with optical and infrared photometry from the BW4b field of Tiede et al. (1995). Note that the columns headed “\(V_0\)” and “\((V - I)_0\)” in that paper actually give \(V\) and \((V - I)\). We recover the original \(K\) magnitudes by adding \(K = K_{0,\text{Tiede}} + 0.14\), as indicated by Table 1 of Tiede et al. (1995). We then obtain \((V - K)_0\) using visual extinctions, \(A_V\), from Stanek’s (1996) extinction map together with the relation,

\[
A_K = 0.11 A_V. \tag{3}
\]

Note that the Stanek (1996) map (available by anonymous ftp at astro.princeton.edu, stanek/Extinction) has been corrected to the zero point found by Gould, Popowski, & Terndrup (1998) and Alcock et al. (1998). These authors made their zero-point determinations by comparing the \((V - K)\) colors of local K giants and RR Lyrae stars, respectively, with the \((V - K)\) colors of similar stars in Baade’s Window, making use of the extinction ratio given by equation (3). Hence, for consistency, we use the same ratio here.

Of the original 509 Tiede et al. (1995) stars, 185 lack \(VI\) photometry. Of the remainder, 86 lack \(A_V\) measurements because they fall within 2′ of NGC 6522 where Stanek (1996) found the \(A_V\) determinations to be unreliable. A further 96 stars are bluer than the color interval (2), and an additional 4 stars are redder. This leaves a total of 138 stars.

For each of these 138 stars, we use linear interpolation to estimate the \((V - I)_{0,\text{Bessel}}\) predicted from their measured \((V - K)_0\) and the Bessell & Brett (1988) \(VIK\) color-color relation. We then fit the data to a two-parameter model

\[
(V - I)_{\text{Tiede}} - (V - I)_{0,\text{Bessel}} = \alpha A_V + \beta [(V - K)_0 - 2.348], \tag{4}
\]

where the offset 2.348 is chosen to eliminate the correlation between \(\alpha\) and \(\beta\).

We remove outliers as follows. We do the fit using all the data, and determine the “errors” by forcing \(\chi^2\) per degree of freedom to unity. We find the largest \(\sigma\) outlier, eliminate it, and repeat the process. We stop when the largest outlier is less than 3\(\sigma\). This eliminates six outliers. We find,

\[
\alpha = 0.4380 \pm 0.0031, \quad \beta = -0.0023 \pm 0.0127 \quad [1.75 \leq (V - K)_0 \leq 3.50]. \tag{5}
\]
Since $R_{VI} = \alpha^{-1}$, we obtain equation (1). From the fact that $\beta$ is consistent with zero at the 1 $\sigma$ level, we conclude that the shift from $(V - I)$ to $(V - I)_0$ depends only on $A_V$ and not on the color of the star. We therefore set $\beta = 0$ and show our resulting fit in Figure 1. Note that since $R_{VI}$ will in general be a function of color or spectral type, our measurement should be taken as applying to stars at the mean of our sample, $(V - K)_0 = 2.35$, i.e., K0 giants. Our value, $R_{VI} = 2.28$, is in good agreement with the one found by Alves (2000), $R_{VI} = 2.26$, and the one adopted by Tiede et al. (1995), $R_{VI} = 2.25$.

Also plotted on Figure 1 are the four stars (open circles) that were excluded from the fit because they were too red. Note that they lie very close to the local $VIK$ curve of Bessell & Brett (1988). If we repeat the entire procedure including these four stars, we obtain

$$\alpha = 0.4384 \pm 0.0033, \quad \beta = 0.0073 \pm 0.0092 \quad [1.75 \leq (V - K)_0 \leq 5.96]. \quad (6)$$

with four outliers excluded. That is $R_{VI} = 2.281 \pm 0.017$, essentially identical to equation (1). In either case, the slope $\beta$ is consistent with zero, indicating that our determination is not a significant function of spectral type.

This non-dependence on $(V - K)_0$ color appears to be in strong conflict with Figure 14 of Tiede et al. (1995) which shows a large number of points in the range $4 < (V - K)_0 < 6$ that lie $\sim 0.3$ mag below the Bessell & Brett (1988) relation. In fact, all the points with CCD $VI$ photometry from Tiede et al. (1995) lie close to the line (as they do in our Fig. 1). The remaining points are from Frogel, Whitford & Rich (1984) and Frogel & Whitford (1987) who obtained their own single-channel infrared data, but relied on the earlier photographic data of Whitford & Blanco (1979) and Arp (1965) for the $VI$ photometry. From the small overlap between these older photographic data and the CCD photometry reported in Tiede et al. (1995), we estimate that the earlier photographic photometry may have a zero-point error of $\sim 0.3$ mag in $(V - I)$ in the sense of being too blue. If this zero-point error is confirmed by future observations, it would mean that the $(V - I), (V - K)$ color-color relation is the same for Baade’s Window and the solar neighborhood, but not necessarily the correspondance between colors anad spectral type. Nevertheless, to be conservative, we base our results only on the G0–K4 sample.
3. Discussion

As with essentially all methods for determining total and selective extinction, our measurement relies on the assumption that the colors of stars in Baade’s Window are the same as those in the solar neighborhood. If the mean $(V - I)_0$ color at fixed $(V - K)_0$ differed between the two populations by $\Delta(V - I)$, then our estimate of $\alpha$ would likewise be in error by $\Delta\alpha = \Delta(V - I)/\langle A_V \rangle$ where $\langle A_V \rangle = 1.496$ is the mean value of $A_V$ over our final sample of 132 stars. However, from the fact that $\beta$ is consistent with zero (eq. [5]), such an offset would have to be independent of spectal type from G0 to K4 (and arguably to M5). This seems quite implausible. In addition, approximately the same offset would have to apply to RR Lyrae stars (Stutz et al. 1999). Most probably, the fault lies not in the stars, but in the dust.

Popowski (2000) reexamined the Woźniak & Stanek (1996) method by which Stanek (1996) determined $R_{VI} = 2.5$. Making use of the original tests done by Woźniak & Stanek (1996), he found that this determination depends in part on an initial assumption about $R_{VI}$ so that values as low as $R_{VI} \sim 2.3$ would be consistent with the data.

Our measurement of $R_{VI}$ removes most, but not all, of the anomalous color problems found by Paczyński & Stanek (1998) and by Stutz et al. (1999). In the latter case, Popowski’s (2000) revised offset $0.11 \pm 0.02$ mag is now reduced to $0.04 \pm 0.02$, and so is only a $2\sigma$ discrepancy. However, for the clump giant anomaly found by Paczyński & Stanek (1998), the formal uncertainty is only $\sim 0.003$ mag, so statistical fluctuations do not provide a plausible explanation. Nevertheless, the remaining discrepancy is small and may be due to a combination of small offsets between the photometric zero points of the various measurement systems that are used to make the comparison.

Paczyński et al. (1999) used $R_{VI}^{\text{Stanek}} = 2.50$ from Stanek (1996) to deredden the observed centroid of the clump in their $VI$ color-magnitude diagram of Baade’s Window. The zero point of their $V$-band extinctions is based on Gould et al. (1998) and Alcock et al. (1998) and is not affected by the present paper. However, the $I$-band photometry should be adjusted fainter by $\Delta I_0 = (1/R_{VI}^{\text{Stanek}} - 1/R_{VI}^{\text{GSF}})\langle A_V \rangle = 0.056$, where $R_{VI}^{\text{GSF}} = 2.283$ is the value we determine here and $\langle A_V \rangle = 1.48$ is the mean extinction of clump stars measured by Paczyński et al. (1999). This adjustment yields a clump centroid of $I_{0,\text{RC}} = 14.43$ and $(V - I)_{0,\text{RC}} = 1.058$. The color is only 0.05 mag redward of the centroid of the Hipparcos clump (Paczyński et al. 1999).

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1999). Inserting the magnitude into Udalski’s (2000) $I$-band calibration of the clump standard candle, $M_I = (-0.26 \pm 0.02) + (0.13 \pm 0.07) ([\text{Fe/H}] + 0.25)$, we obtain a distance modulus to Baade’s Window

$$\mu_{BW} = 14.43 - M_I = 14.68 \pm 0.04,$$

where we have adopted $[\text{Fe/H}]_{BW} = -0.15 \pm 0.10$. The error bar takes account of all statistical uncertainties, 0.025 mag for $M_I$ (Udalski 2000), 0.02 mag for the observed brightness of the Baade’s Window clump (Paczyński et al. 1999), $0.04 \times (1 - R_{VI}) = 0.022$ mag for the zero-point uncertainty of the Stanek (1996) map (Alcock et al. 1998), and $0.0033 \times \langle A_V \rangle = 0.005$ mag for the uncertainty in $R_{VI}$ (this paper), but does not take account of systematic errors. Equation (7) is in good agreement with Alves’ (2000) determination using the $K$-band clump distance indicator, $\mu_{BW} = 14.58 \pm 0.11$.

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Fig. 1.— Color-color $(V - K)_0$ vs. $(V - I)_0$ plot of 142 Baade's Window giant stars (points) together with the color-color relation (solid curve) of solar-neighborhood stars taken from Bessell & Brett (1988). The $(V - K)_0$ color is determined from $VK$ photometry of Tiede et al. (1995) corrected for extinction according to Stanek (1996), assuming $E(V - K) = 0.89 A_V$. The $(V - I)_0$ color is determined in this paper by fitting for $R_{VI} = A_V / E(V - I)$, essentially by moving the points vertically until they straddle the curve. Four red stars (open circles) were excluded from the fit because of concerns that the spectral energy distributions of Baade’s Window M giants are different from those of M giants in the solar neighborhood. Six outliers (crosses) were also excluded from the fit. The arrow shows the effect of 1 magnitude of $V$ band extinction. Since this arrow is parallel to the color-color curve, even large errors in the extinction cannot affect the results.
$R_{VI} = 2.283 \pm 0.016$

$A_V = 1$