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The Distance to the Galactic Center

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Abstract. The Optical Gravitational Lensing Experiment (OGLE) data on high-amplitude δ Scuti Stars (HADS) and RR Lyrae stars have been analyzed to determine the distance to the galactic bulge. We find a mean value of 14.47 ± 0.08 mag for the bulge distance modulus. A small additive correction leads to 7.9 ± 0.3 kpc as the best distance to the galactic center.

1. Introduction

Our discussion of the distance to the galactic center is based on recent observations of variable stars in the galactic bulge obtained primarily in the direction of Baade's window by the Optical Gravitational Lensing Experiment (OGLE). We have obtained the distance employing both RR Lyrae stars and high-amplitude δ Scuti variables (hereafter referred to as HADS, but frequently referred to as dwarf Cepheids). A description of the OGLE catalog, reductions, period-search technique employed, and other details are given by Udalski et al. (1994). Subsequent data that extend the catalog can be found in additional papers by Udalski et al. (1995a, 1995b, 1996, 1997). The catalog contains I magnitude light curves, $V-I$ color indices at light maximum, periods of variable stars with $\langle I \rangle$ in the $14-18$ magnitude range including variable stars with periods of $0.1-100$ d. The error of the zero point of the photometry is estimated to be ≤ 0.04 mag.

2. Intrinsic Color Indices, Color Excesses, and Absolute Magnitudes of the Variable Stars

a) *High-amplitude δ Scuti variables:*
The intrinsic color indices of the HADS on the $b-y$ color index scale are well-known from $uvby\beta$ photometry of 26 stars (McNamara, 1997b). The variables exhibit a P–C relation in the sense that the longer-period variables have more positive color indices. The intrinsic $b-y$ values at mean light (mag mean) were transferred to the $V-I$ color index system by the equation

$$(V-I)_0 = -0.002 + 2.070(b-y) - 1.113(b-y)^2 + 0.667(b-y)^3 \qquad (1)$$

given by Cousins (1987). It was found that the $(V-I)_0$ color indices of the field stars could by adequately represented by the equation:

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$$(V-I)_0 = 0.195 \log P + 0.514. \quad (2)$$

The mean color index $\langle V\rangle - \langle I\rangle$, was formed for all the HADS and the color excess calculated. We are assuming that the difference between $\langle V\rangle - \langle I\rangle$ and $\langle V-I\rangle$ is negligible. Following the suggestion of Woźniak & Stanek (1996) we calculated the visual absorption from the equation

$$A_V = 2.5E(V-I). \quad (3)$$

The P–L relation of the HADS given by McNamara (1997b)

$$M_V = -3.725 \log P - 1.933 \quad (4)$$

was used to calculate the absolute magnitudes of the variables. We assume that all of the variables are pulsating in the fundamental mode.

b) *RR Lyrae stars:*
The photometric parameters of the RR Lyrae variables measured in the OGLE experiment have been published by Olech (1997). The data of interest in our discussion are found in his Table 7. He gives in addition to the star catalog designation and period of the variables, the mean $\langle I\rangle$ and $\langle V\rangle - \langle I\rangle$ magnitudes of the variables along with the designation (i.e. RRab or RRc). He also lists the reddening-free magnitude V_{V-I} defined as:

$$V_{V-I} = V - 2.5(\langle V\rangle - \langle I\rangle). \quad (5)$$

To estimate the reddening of the variables we have adopted the equation

$$(V-I)_0 = 0.445 \log P + 0.594 \quad (6)$$

to calculate the intrinsic $\langle (V-I)_0\rangle$ values of the RRab variables. This equation is based on the reddening-free $\langle (V-I)_0\rangle$ values of RRab variables listed by McNamara (1997a). We have adopted $\langle (V-I)_0\rangle = 0.31$ for all the RRc variables. The color excess is given by the difference between $\langle V\rangle - \langle I\rangle$ and $(V-I)_0$. The absorption in V is given by $A_V = 2.5E(V-I)$. The typical residual of an individual data point from the $(V-I)_0$ values predicted by either equation (2) or equation (6) is ~ 0.015 mag.

3. Analysis and Discussion

a) *HADS:*
The distance moduli of the HADS were grouped into 0.1 mag interval bins. We divided the sample into the short-period, $\log P < -1.10$, and long-period, $\log P > -1.10$, variables. This is equivalent to dividing the sample according to abundance, since the short-period variables are metal poor, [Fe/H]< -0.07, and the longer-period variables tend to be more metal strong, [Fe/H]> -0.70. See McNamara (1997b) for a discussion of how the [Fe/H] values depend on period. The short-period (metal poor) variables exhibit a much larger spread in distance modulus than the long-period (more metal strong) variables. This is because some of the short-period variables are foreground objects.

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We find the best value of $\langle\langle V_0\rangle - \langle M_V\rangle\rangle$ is 14.47 magnitude. This corresponds to a distance of 7834 pc to the bulge in the direction of Baade's window.

If a considerable number of first overtone pulsators are present in the data set (for example $\frac{1}{4}$ the total) the distance modulus of the bulge would have to be increased by ~ 0.05 mag.

b) *RR Lyrae stars:*
In order to understand the dependence of the absolute magnitude of the RR Lyrae stars on period and on metal abundance, we have binned the variable stars in the bulge into period intervals and computed the mean reddening-free magnitude, $\langle V_{V-I}\rangle$, from the data given by Olech (1997). We have selected stars in the interval $V_{V-I} = 13.5 - 14.5$ mag where the data exhibits a Gaussian distribution with a well-defined maximum for this purpose. The run of absolute magnitude with $\log P$ must be similar to the dependence of $\langle V_{V-I}\rangle$ on $\log P$.

A solution for the galactic bulge distance is based on the three equations:

$$-0.29 < \log P < -0.22, \quad M_V = 0.55 \text{ mag} \tag{7}$$

$$\log P < -0.29, \quad M_V = -4.04 \log P - 0.62 \tag{8}$$

$$\log P > -0.22, \quad M_V = -0.91 \log P + 0.35\,. \tag{9}$$

These equations give the best fit to the slopes in the V_{V-I} data. A Gaussian fit to the data yields a maximum at $\langle V_0\rangle - \langle M_V\rangle = 14.45$ mag and a dispersion of 0.23 mag.

A second solution is based on the short distance scale. Fernley (1998) suggests that the absolute magnitudes of the RR Lyrae stars can be represented by the equation

$$M_V = 0.75 + 0.18([\text{Fe/H}] + 1.55). \tag{10}$$

If we translate this to the M_V, $\log P$ plane we find

$$M_V = -1.00 \log P + 0.54. \tag{11}$$

The distance modulus of each variable has been calculated with the aid of M_V values given by equation 11. The Gaussian fit yields a maximum at $\langle V_0\rangle - \langle M_V\rangle = 14.24$ mag ($d = 7.0$ kpc) and a dispersion of 0.27 mag. The fit is not as good as for solution (1) and yields a much smaller distance modulus.

We adopt 14.45 mag (7762 pc). As indicated previously, the HADS gave 14.47 mag (7834 pc). If we had used the Petersen (1999) $P-L$ relation we would have obtained 14.51 mag. We adopt the mean, 14.49 mag (7907 pc), as the best value. Finally, we adopt the mean of the RR Lyrae and HADS distance moduli $\langle V_0\rangle - \langle M_V\rangle = 14.47$ mag ($d = 7834$ pc) as our best value.

We regard the short distance ($R_0 = 7.0$ kpc) as simply too small – inconsistent with other data that indicate $R_0 \sim 8.0$ kpc. A contrary view regarding the luminosities of RR Lyrae stars and the viability of the short distance scale can be found in Fernley (1998).

To correct our bulge distance to the galactic center requires increasing the bulge distance by 30 pc. Our galactic center distance thus becomes $R_0 = 7.9 \pm 0.3$ kpc.

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Reid (1993) has discussed the various methods and investigations involved in determining the distance, R_0, to the galactic center. He concludes that the investigations cited in his review lead to a best value of $R_0 = 8.0 \pm 0.5$ kpc. This may be compared with our value of 7.9 ± 0.3 kpc.

We note that both long- and short-period HADS are found in the bulge. Their abundance [Fe/H] must cover the range ~ 0.00 to -1.5. This range may be compared with that found for other stars of -1.6 to 1.2 by Sadler, Rich, & Terndrup (1996).

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Discussion

Piotr Popowski: With the total A_V based on $V - K$ colors, which is superior to $V - I$, and the faint absolute magnitudes for RR Lyrae stars, we end up with the same distance to the Galactic center of about 8 kpc.

Harold McNamara: The Stanek absorption maps yield a $(\langle V \rangle - \langle I \rangle)_0 \approx 0.63$ for RR Lyrae stars. This is inconsistent with $(\langle V \rangle - \langle I \rangle)_0 \approx 0.47$ from other data. If absorption is calculated directly from RR Lyrae stars, the data give ≈ 7.0 kpc to galactic center. I am not familiar with the $V - K$ data.

Michael Reed: What are the errors associated with your P–M_V relationships?

Harold McNamara: Petersen estimates errors of ± 0.1 mag in predicting an M_V value from the P–L relation of the HADS.