Distance and Reddening of the Isolated Dwarf Irregular Galaxy NGC 1156

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Abstract

We present a photometric estimation of the distance and reddening values to the dwarf irregular galaxy NGC 1156, that is one of the best targets for the study of isolated dwarf galaxies in the nearby universe. We used imaging data sets of the Hubble Space Telescope (HST) Advanced Camera for Surveys, High Resolution Channel of the central region of NGC 1156 (26′ × 29′) available in the HST archive for this study. From the (U − B, B − V) color–color diagram, we first estimated the total (foreground + internal) reddening toward NGC 1156 of $E(B − V) = 0.35 ± 0.05$ mag, whereas only the foreground reddening was previously known to be $E(B − V) = 0.16$ mag (1984, ApJS, 54, 33) or 0.24 mag (1998, ApJ, 500, 525). Based on the brightest-star method, selecting the three brightest blue supergiants (BSG) stars with a mean $B$ magnitude of $(B(3B)) = 21.94$ and the three brightest red supergiants (RSG) stars with a mean $V$ magnitude of $(V(3R)) = 22.76$, we derived the distance modulus to NGC 1156 to be $(m − M)_0,BSG = 29.16$ mag and $(m − M)_0,RSG = 29.55$ mag. By using weights of 1 for BSGs and 1.5 for RSGs, we finally obtained a weighted mean distance modulus to NGC 1156, $(m − M)_0 = 29.39 ± 0.20$ mag (distance = 7.6 ± 0.7 Mpc), which is in agreement with previous estimates. Combining the photometry data of this study with those of Karachentsev, Musella, and Grimaldi (1996, A&A, 310, 722) gives a smaller distance to NGC 1156, which is discussed together with the limits of the data.

Key words: galaxies: dwarf irregular galaxies — galaxies: individual (NGC 1156) — galaxies: photometry — Galaxy: globular clusters: individual (NG104)

1. Introduction

Dwarf galaxies are an important class of galaxies in studying the evolution of galaxies as well as the cosmological evolution of the universe. They have much simpler structures than larger/giant galaxies, and are prone to be affected by small perturbations. It is also easy to observe and study the whole systems of dwarf galaxies because of their small sizes (Kim & Lee 1998; Kyeong et al. 2006, 2010; Cole et al. 2007). Isolated dwarf galaxies are even better targets for studying the evolution of the system, because they are not affected by any environmental effects, so that any kind of causes and effects reside in the system itself.

NGC 1156 (UGC 2455, Vorontsov-Velyaminov [VV] 531, PGC 11329, KIG 0121, IRAS F02567+2502) is an isolated, Magellanic-type dwarf irregular (dIrr) galaxy with the morphological type of IB(s)m V-VI (Sandage & Binggeli 1984; de Vaucouleurs et al. 1991). This galaxy has a boxy shape and bright blue patches, implying an active star-formation stage, though not triggered by any external tidal perturbations (Karachentsev et al. 1996). NGC 1156 is one of the highly isolated and less-disturbed galaxies; its nearest neighbors are UGC 2684 and UGC 2716, located more than 10° away from NGC 1156 (Karachentsev et al. 1996; Minchin et al. 2010). Studying the star-formation rate, the mass-loss rate, the current star-formation activity, etc. for NGC 1156 is very interesting, because this galaxy is not thought to be disturbed/triggered by any nearby objects (Hunter & Elmegreen 2004). Recently, using the 21 cm line of neutral hydrogen (H I) observed with the Arecibo L-band Feed Array, Minchin et al. (2010) found a new small dwarf galaxy, dubbed AGES J030039+254656, 35′ north-northeast of NGC 1156 (80 kpc in projection, $\alpha_{2000.0} = 03^h00^m38^s6$, $\delta_{2000.0} = +25^\circ47'02''$). This galaxy has a H I flux of 0.114 ± 0.032 Jy km s$^{-1}$, giving it a neutral hydrogen mass of (1.63 ± 0.46) $\times 10^8 M_\odot$. Minchin et al. (2010) estimated that the star-formation rate and H I mass of this galaxy both are by around three orders of magnitude lower than those in the case of NGC 1156, and concluded that it is unlikely that AGES J030039+254656, in its current position, could be exerting any significant tidal force on NGC 1156.

Although there have been many studies on NGC 1156 (especially the H II regions and CO content; see table 1 below), the distance estimate to this galaxy is only based on two studies of Karachentsev, Musella, and Grimaldi (1996) and Tully (1988). Karachentsev, Musella, and Grimaldi (1996) estimated the distance to NGC 1156 to be $d = 7.8 ± 0.5$ Mpc $(m − M)_0 = 29.46 ± 0.15$ mag] using the brightest-star method with $V$ (300 s exposure time) and $I$ (300 s) CCD images for the central $80′ × 120′$ area obtained through the Smithsonian Astrophysical Observatory (SAO) 6 m telescope. From the Tully–Fisher relation, Tully (1988) obtained the distance to NGC 1156 to be 6.4 Mpc $(m − M)_0 = 29.02 ± 0.40$ mag. * KASI-Carnegie Fellow.
Fig. 1. Gray-scale second-generation Digitized Sky Survey (DSS) image of NGC 1156. The size of the field of view is 5′ × 5′. North is at the top and east is to the left. The coordinates of NGC 1156 given by the NASA/IPAC Extragalactic Database (NED) are (∇_J2000:0, δ_J2000:0) = (02h59m42s19, +25°14′2), which are also the field center in this image. The inner box denotes the area (26″ × 29″) covered by the HST images in this study (also shown in figure 2), and the outer box shows the area (80″ × 120″) covered by Karachentsev, Musella, and Grimaldi (1996).

There is no estimate for the total (foreground + internal) reddening toward NGC 1156, and there are only two foreground reddening estimates to NGC 1156: E(B − V) = 0.16 mag and 0.24 mag, measured by Burstein and Heiles (1984) and Schlegel, Finkbeiner, and Davis (1998), respectively.

Thanks to the unprecedented resolving power of the Hubble Space Telescope (HST), we were able to resolve individual stars at the center of galaxy, NGC 1156. This allowed us to investigate the color–color diagram of the central stars of NGC 1156, and hence to make an accurate estimation of the reddening, and then the distance modulus to this galaxy. In this paper, we present a new estimate of the distance and (total) reddening to NGC 1156 using the photometry from the HST archive imaging data. This paper is arranged as follows. In section 2, we describe the data set used in this study, and present the data reduction and transformation into the standard UBVRI photometric system in section 3. In section 4, we show color–magnitude diagrams, and derive the reddening and distance to NGC 1156. We discuss the results in section 5, and finally summarize them in section 6.

2. Data

For this study, we used the imaging data sets of HST Advanced Camera for Surveys (ACS) High Resolution Channel (HRC) on NGC 1156 available in the HST archive. While Wide Field Channel (WFC) is the widely used camera of the ACS, HRC is one of the three electronic cameras of ACS together with Solar Blind Channel (SBC), and is designed for high angular resolution imaging and coronagraphy for the wavelength range of 2000–11000 Å. The field-of-view of HRC is 26″ × 29″ (1024 × 1024 SiTe CCD), with a pixel size of 0′025 × 0′028 (21μm/pixel).

The data used in this study were obtained on 2005 September 5–6 (UT) with F330W, F435W, F550M, F814W, and F658N filters through the HST observing program 10609 (P.I.: William Vacca). The accumulated exposure times were 1780 s (4 × 445 s) for the F330W band, 592 s (4 × 148 s) for the F435W band, 780 s (4 × 195 s) for the F550M band, 364 s (4 × 91 s) for the F814W band, and 240 s for the F658N band. For this study we used images obtained in the F330W, F435W, F550M, and F814W bands. Figure 1 displays the gray-scale
image of NGC 1156 ($5' \times 5'$) taken from the Digitized Sky Survey (DSS), and figure 2 shows the HST ACS/HRC $F814W$ image of NGC 1156 ($26'' \times 29''$), which is the very central region (inner box) of NGC 1156 in figure 1.

3. Data Reduction

3.1. Photometry

Photometry of NGC 1156 was carried out for the data taken by HST ACS/HRC using the DOLPHOT package developed by Dolphin (2000a, 2000b). The DOLPHOT routine performs point-spread function fitting to the stars, and gives the magnitudes in the standard Johnson system as well as instrumental magnitudes in the HST filter system. DOLPHOT uses zeropoints and transformation coefficients of Sirianni et al. (2005), which were recently revised (see HST ACS Web page).

Figure 3 shows the photometric errors from the DOLPHOT package as a function of magnitude. DOLPHOT gives five classifications for objects (type 1, good star; type 2, possible unresolved binary, two stars combined during photometry iterations; type 3, bad star, centered on saturated pixel or bad column; type 4, single-pixel cosmic ray or hot pixel; type 5, extended object); here, we plot only objects with reliable measurements (i.e., flagged as object type 1; $N = 5580$).

1 http://www.stsci.edu/hst/acs/analysis/zeropoints/.
3.2. Transformation to the UBVI system

We used the UBVI filter system for analyzing the photometric properties and determining the distance to NGC 1156. Although the DOLPHOT package effectively converts the ACS filter system into the UBVI one using the coefficients of Sirianni et al. (2005), the transformation from F550M to the V band is not provided. While the recent transformation relations between the HST ACS/WFC system (including F550M filter) and the BVRI photometry are given by Saha et al. (2011), their relations are solely based on the WFC, excluding the HRC. We, therefore, transform the F550M magnitude into the V magnitude, as described below, while the F330W, F435W, and F814W filters were converted to the U, B, and I bands, respectively, by the DOLPHOT package.

First, we transformed the F550M magnitude into the F555W using the equation

\[
F555W = F550M + 0.232(F550M - F814W)
\]

for \((F550M - F814W) < 1.337\) mag,

\[
F555W = F550M + 0.311
\]

for \((F550M - F814W) \geq 1.337\) mag. (1)

for using the transformation coefficients from F555W to V given by Sirianni et al. (2005) in the DOLPHOT package.

Equation (1) was derived by using the photometry of the stars in the globular cluster 47 Tucanae (NGC 104), obtained from the HST ACS/HRC images, and by using the Padova isochrones (Marigo et al. 2008). Figure 4a shows a color–color diagram of the stars in the globular cluster 47 Tuc obtained from the HST ACS/HRC images with F550M, F555W, and F814W filters. Small dots show the stars of 47 Tuc from the DOLPHOT package with object type 1 and F550M errors < 0.05 mag. Among these stars we selected stars with F550M errors < 0.006 mag, and performed the ordinary least-squares method (Isobe et al. 1990) with 3-sigma clipping for these stars, which are shown in circles and a blue slant line denoting the upper part of the equation (1). Since there was not a great number of stars enough to use at the red part (\((F550M - F814W) \geq 1.337\) mag), we used the Padova isochrones (Marigo et al. 2008), as shown in figure 4b. Saviane et al. (2008) found \(12 + \log(O/H) = 8.23\) for NGC 1156, and using the equations \([\text{Fe/H}] = \log(O/H) + 3.34 = -0.43\) dex (Bono et al. 2010) and \(\log Z = 0.977\) \([\text{Fe/H}] = -1.699\) (Bertelli et al. 1994) we assumed \(Z = 0.008\) for NGC 1156. The various ages (1, 2, 5, and 12 Gyr) used in figure 4b give little differences, and we thus used a constant value of 0.311 [lower part of the equation (1)] for the red part of \((F550M - F814W) \geq 1.337\) mag. Figure 4c is a composite of panels (a) and (b), showing the stars in the globular cluster 47 Tuc (dots for the stars with F550M errors < 0.05 mag and small circles for those with F550M errors < 0.006 mag), the Padova isochrones with \(Z = 0.008\) and with ages of 1 Gyr (triangles) and 12 Gyr (large circles),
and equation (1) plotted as a solid line.

To test the efficiency of this method, we compare \( V \) magnitudes transformed from \( F550M \) and from \( F555W \) for the stars in the globular cluster 47 Tuc in figure 4d, where the circles are for the stars with \( F550M \) errors < 0.006 mag, shown also as circles in panel (a). The two \( V \) magnitudes transformed from \( F550M \) and from \( F555W \) are in agreement with each other, as can be seen in figure 4d.

4. Results

4.1. Color–Magnitude Diagrams

Figure 5 displays the color–magnitude diagrams (CMDs) for the measured stars (\( N = 5248 \)) located in the central region of NGC 1156, only with the DOLPHOT object type 1. While blue supergiant (BSG)/blue main-sequence stars are clearly seen in the \(( V, U - B \)) (figure 5a) and \(( V, B - V \)) (figure 5b) CMDs reaching \( B = 21.6 \) mag and \( V = 21.3 \) mag, the \(( V, V - I)\) (figure 5c) and \(( I, V - I)\) (figure 5d) CMDs show both the BSG and red supergiant (RSG) stars well, the color of the latter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Information</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{2000.0}, \delta_{2000.0} )</td>
<td>( 02^h 59^m 42.19, +25^\circ 14' 14.92' )</td>
<td>NASA/IPAC Extragalactic Database (NED)</td>
</tr>
<tr>
<td>( l, b )</td>
<td>( 156^\circ 31, -29^\circ 20 )</td>
<td>NED</td>
</tr>
<tr>
<td>Morphological type</td>
<td>IB(s)m V-VI</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Position angle (from N through E)</td>
<td>( 39^\circ )</td>
<td>Hunter et al. (2002)</td>
</tr>
<tr>
<td>Angular diameter, ( D_0 )</td>
<td>( 3.3 )</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Axial ratio</td>
<td>( 7.4 )</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Kinematical axes of the ionized gas, neutral gas, and stellar disks</td>
<td>( 84^\circ )</td>
<td>Hunter et al. (2002)</td>
</tr>
<tr>
<td>Inclination, ( i )</td>
<td>( 42^\circ )</td>
<td>Bottinelli et al. (1984)</td>
</tr>
<tr>
<td>Radial velocity, ( v_r )</td>
<td>( 375 \pm 1 ) ( \text{km s}^{-1} )</td>
<td>NED</td>
</tr>
<tr>
<td>Redshift, ( z )</td>
<td>( 0.001251 )</td>
<td>NED</td>
</tr>
<tr>
<td>Distance modulus, ( (m - M)_0 )</td>
<td>( 29.02 \pm 0.40 ) mag (( d = 6.4 \pm 1.2 ) Mpc)</td>
<td>Tully (1988)</td>
</tr>
<tr>
<td>( B_0, M_{B,0} )</td>
<td>( 11.78 \pm 0.10 ) mag, ( -17.68 ) mag †</td>
<td>Barazz, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>( B_0, M_{B,0} )</td>
<td>( 11.56 ) mag ‡</td>
<td>Tully (1988)</td>
</tr>
<tr>
<td>( B_0, M_{B,0} )</td>
<td>( 11.61 ) mag †</td>
<td>Bottinelli et al. (1984)</td>
</tr>
<tr>
<td>( V_0 )</td>
<td>( 12.32 ) mag, ( -17.85 ) mag †, ‡</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>( M_V )</td>
<td>( -18.67 ) mag †</td>
<td>Barazza, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>( R_0 )</td>
<td>( 10.91 ) mag †</td>
<td>Hunter and Elmegreen (2004)</td>
</tr>
<tr>
<td>( R )</td>
<td>( 11.91 \pm 0.04 ) mag</td>
<td>Barazza, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>( (B - V)_0 )</td>
<td>( 0.47 ) ‡</td>
<td>James et al. (2004)</td>
</tr>
<tr>
<td>( (B - R)_0 )</td>
<td>( 0.87 ) ‡</td>
<td>Barazza, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>Effective radius, ( r^B_{\text{eff}}, r^V_{\text{eff}}, r^R_{\text{eff}} )</td>
<td>( 31.58, 34.28, 35.48 )</td>
<td>Barazza, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>Effective surface brightness, ( (\mu^B_{\text{eff}}, (\mu^V_{\text{eff}}, (\mu^R_{\text{eff}}) )</td>
<td>( 21.28, 20.98, 20.66 ) mag arcsec (^{-2} )</td>
<td>Barazza, Binggeli, and Prugniel (2001)</td>
</tr>
<tr>
<td>flux density at 12, 25, 60, 100 ( \mu )m</td>
<td>( 0.17, 0.55, 5.24, 10.48 ) Jy</td>
<td>Dale et al. (2000)</td>
</tr>
<tr>
<td>flux density at 6.75, 15 ( \mu )m</td>
<td>( 0.09 \pm 0.02, 0.14 \pm 0.03 ) Jy</td>
<td>Dale et al. (2000)</td>
</tr>
<tr>
<td>H( I ) flux</td>
<td>( 71.3 ) Jy km s (^{-1} )</td>
<td>Swaters et al. (2002)</td>
</tr>
<tr>
<td>H( I ) mass, ( M_{H I} )</td>
<td>( 1.02 \times 10^9 ) ( M_{\odot} )</td>
<td>Minchin et al. (2010)</td>
</tr>
<tr>
<td>H( I ) line width, ( W_{50} )</td>
<td>( 1.08 \pm 0.09 ) ( \times 10^9 ) ( M_{\odot} )</td>
<td>Minchin et al. (2010)</td>
</tr>
<tr>
<td>( M_{H II} / L_B )</td>
<td>( 0.56 ) ( M_{\odot} / L_{\odot} )</td>
<td>Swaters et al. (2002)</td>
</tr>
<tr>
<td>Star formation rate, SFR</td>
<td>( 0.71 \pm 0.07 ) ( M_{\odot} ) yr</td>
<td>James et al. (2004)</td>
</tr>
</tbody>
</table>

* Only the foreground extinction is corrected.
† Assuming \( d = 7.8 \pm 0.5 \) Mpc.
‡ Both foreground and internal extinctions are corrected.
§ Assuming \( A_g = 0.71 \) mag.
|| Profile width at a level of 50% of the peak value, corrected for instrumental broadening.
Fig. 4. (a) Color–color diagram of the stars in the globular cluster 47 Tuc (NGC 104) obtained from the HST ACS/HRC images. Small dots are for the stars with F550M errors < 0.05 mag. Stars with F550M errors < 0.006 mag are selected and used for the ordinary least-squares method (Isobe et al. 1990) with 3-sigma clipping, and are shown in circles and slant line for the blue part of $(F550M - F814W) \leq 1.3$ mag. (b) The Padova isochrones (Marigo et al. 2008) with $Z = 0.008$ and various ages (1, 5, 10, and 12 Gyr) are shown. The constant value determined at $(F550M - F814W) \leq 1.3$ mag is shown as a horizontal line. (c) Composite of panels (a) and (b), showing the stars of the globular cluster 47 Tuc (dots for the stars with F550M errors < 0.05 mag and small circles for the stars with F550M errors < 0.006 mag) and the Padova isochrones with $Z = 0.008$ and with ages of 1 Gyr (triangles) and 12 Gyr (large circles). The solid line shows the selected transformation with a slope of 0.232 (for the blue part of $F550M - F814W / DC4 \leq 1.337$ mag) and with 0 (for the red part of $F550M - F814W \geq 1.337$ mag). (d) Differences between the two $V$ magnitudes transformed from F550M and F555W. They are very little, especially for the stars with small errors (F550M error < 0.006 mag) shown in circles.

being $(V - I) \sim 2$ mag and reaching up to $V = 22.7$ mag and $I = 20.6$ mag. Red giant branch (RGB) stars are located below the tip of the RGB (TRGB), which might be much fainter than $I \sim 24$ (see figure 5d). There should be many asymptotic giant branch (AGB) stars between the RSG and RGB stars (see, e.g., Cioni & Habing 2005).

If we assume (i) the distance to NGC 1156 to be $d = 7.1 \pm 1.0$ Mpc [$M - M_0 = 29.24 \pm 0.31$ mag], given by the NASA/IPAC Extragalactic Database (NED), which is the mean of the two values from Tully [1988: $(m - M)_0 = 29.02 \pm 0.40$ mag] and Karachentsev, Musella, and Grimaldi [1996: $(m - M)_0 = 29.46 \pm 0.15$ mag], (ii) the total reddening toward NGC 1156 to be $E(B - V) = 0.35 \pm 0.05$ mag, as obtained in the following subsection, and (iii) the $I$-band absolute magnitude of the TRGB to be $M_{I, TRGB} \approx -4.0 \pm 0.1$ mag (Lee et al. 1993), then the $I$-band magnitude of the TRGB might be located at $I \sim 25.8$ mag. The $U$-magnitude calibration from Sirianni et al. (2005) is bifid above and below
(U - B) = 0.2 mag (see their table 23). At the very color of (U - B) = 0.2 mag, the derived U-magnitudes differ by 0.1 mag (see also their figure 22); this appears to be the reason for the vertical gaplike feature at (U - B) = 0.2 mag in the (V, U - B) CMD (figure 5a). The cross-identification results of the bright stars and the star clusters in the HST images and the Canada-France-Hawaii Telescope near-infrared images will be shown in a subsequent paper (J. Kyeong et al. in preparation).

4.2. Interstellar Reddening toward NGC 1156

Since NGC 1156 is a dIrr galaxy containing many star-forming regions (Barazza et al. 2001), the internal reddening in NGC 1156 might not be negligible, and the estimate of the total reddening toward NGC 1156 is important for photometric studies of this galaxy. However, there are only two foreground reddening values toward NGC 1156. Burstein and Heiles (1984) measured $A_B = 0.66$ mag using the 21 cm H I column density and the faint galaxy count method. On the other hand, Schlegel, Finkbeiner, and Davis (1998) determined $A_B = 0.968$ mag based on the COBE/DIRBE measurement of diffuse infrared emission. By adopting $R_V = 3.1$ and the interstellar extinction law of Cardelli, Clayton, and Mathis (1989), these reddening values are converted into…

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Fig. 5. CMDs of NGC 1156 obtained from the HST ACS/HRC images. Only the objects of type 1 (good star) are plotted from DOLPHOT photometry. The large circles in panels (a) and (b) are objects with U photometric errors smaller than 0.05 mag, which are used for estimating the total reddening value toward NGC 1156 in figure 6 below.
E(B − V) = 0.16 mag and 0.24 mag, respectively.

Using the color–color diagram produces a robust method for determining the interstellar reddening value only if UBV photometric data are available. Fortunately, our four filter photometry allows us to derive the interstellar reddening value for the total reddening value of NGC 1156, which is used to estimate the distance to galaxies without the necessity of repeated observations (Hubble 1936; Humphreys 1987; Sandage & Carlson 1988; Karachentsev & Tikhonov 1994; Rozanski & Rowan-Robinson 1994; Lyo & Lee 1997; Kudritzki et al. 2003, 2008; Bresolin 2003; Vaduvescu et al. 2005; Kudritzki 2010). Instead of the single brightest star, the average magnitude of the three brightest stars has been used for minimizing the effects of misidentifying the brightest individual star and for reducing the stochastic effect in obtaining the mean luminosity of the brightest stars (Rozanski & Rowan-Robinson 1994; Lyo & Lee 1997). While Rozanski and Rowan-Robinson (1994) claimed in this method rather larger errors of 0.58 mag for the brightest-red stars and 0.90 mag for the brightest-blue stars, Karachentsev and Tikhonov (1994) suggested that they are much smaller errors of 0.30 mag and 0.45 mag, respectively. Using new CCD-based data for 17 galaxies, Lyo and Lee (1997) showed that the uncertainties in the distance moduli determined by the brightest red and blue stars are 0.37 mag and 0.55 mag, respectively, concluding that the brightest RSGs might be useful in determining the distances to resolved late-type galaxies. They proposed new calibration equations:

\[
\langle M_V(3)_{\text{RSG}} \rangle = 0.21 M_B^\text{T} - 3.84, \quad \sigma(M_V) = 0.37 \text{mag} \quad (2)
\]

and

\[
\langle M_B(3)_{\text{BSG}} \rangle = 0.30 M_B^\text{T} - 3.02, \quad \sigma(M_B) = 0.55 \text{mag} \quad (3)
\]

In order to make it free from any contamination by foreground stars and to select the three brightest blue and red stars, we consider stars bluer than B − V = 0.4 mag [in (B, B − V) CMD] and stars redder than B − V = 2.0 mag [in (V, B − V) CMD] (Rozanski & Rowan-Robinson 1994). In

![Fig. 6. (U − B, B − V) color–color diagram of the stars in NGC 1156.](https://academic.oup.com/pasj/article-abstract/64/2/23/2898250/fig6)

The objects with U photometric errors smaller than 0.05 mag and with type 1 are plotted as open circles. The thin dotted line represents the unreddened ZAMS line given by the Padova isochrone (Marigo et al. 2008) with log t = 6.0 and Z = 0.008 (Saviane et al. 2008), and the thick solid line represents the ZAMS line reddened by the amount of E(B − V) = 0.35 ± 0.05 mag. The ZAMS lines for Z = 0.03 and Z = 0.019 (both for log t = 6.0) reddened by E(B − V) = 0.35 mag are also shown in thick short-dashed and long-dashed lines, respectively, for comparison, where the chosen metallicity gives little difference in obtaining the reddening value. The arrow at (B − V) ∼ 0 mag is the reddening vector with E(B − V) = 0.10 mag. The three, numbered stars with boxes are the BSGs selected in subsection 4.3 and shown in table 2 in the order named.
Table 2. Selected blue and red supergiant stars in NGC 1156.*

<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000.0)</th>
<th>Dec (J2000.0)</th>
<th>(U)</th>
<th>(U) err</th>
<th>(B)</th>
<th>(B) err</th>
<th>(V)</th>
<th>(V) err</th>
<th>(I)</th>
<th>(I) err</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSG1</td>
<td>2:59:41.96</td>
<td>25:14:33.6</td>
<td>21.130</td>
<td>0.017</td>
<td>21.598</td>
<td>0.013</td>
<td>21.263</td>
<td>0.014</td>
<td>20.827</td>
<td>0.015</td>
</tr>
<tr>
<td>BSG2</td>
<td>2:59:42.02</td>
<td>25:14:08.3</td>
<td>21.786</td>
<td>0.026</td>
<td>22.009</td>
<td>0.017</td>
<td>21.772</td>
<td>0.019</td>
<td>21.453</td>
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<tr>
<td>BSG3</td>
<td>2:59:41.48</td>
<td>25:14:13.8</td>
<td>21.834</td>
<td>0.028</td>
<td>22.221</td>
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<td>21.584</td>
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</tr>
<tr>
<td>RSG1</td>
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<td>25:14:33.7</td>
<td>26.942</td>
<td>3.690</td>
<td>25.184</td>
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<td>22.674</td>
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<tr>
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<td>2:59:42.12</td>
<td>25:14:27.9</td>
<td>25.513</td>
<td>0.607</td>
<td>24.757</td>
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<td>22.708</td>
<td>0.031</td>
<td>21.199</td>
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</tr>
<tr>
<td>RSG3</td>
<td>2:59:42.57</td>
<td>25:14:34.3</td>
<td>25.554</td>
<td>0.788</td>
<td>25.305</td>
<td>0.177</td>
<td>22.893</td>
<td>0.036</td>
<td>20.796</td>
<td>0.014</td>
</tr>
</tbody>
</table>

* BSGs are in the order of \(B\) magnitudes and RSGs are in the order of \(V\) magnitudes.
† Units of hours, minutes, and seconds.
‡ Units of degrees, arcminutes, and arcseconds.

Fig. 7. Location of the selected blue supergiants (BSGs) and red supergiants (RSGs) in (a) \((B, B - V)\) CMD, (b) \((V, B - V)\) CMD, (c) \((V, V - I)\) CMD, and (d) \((I, V - I)\) CMD. Pentagons and open circles are the BSG and RSG stars, respectively, selected in this study, while triangles and squares in panels (c) and (d) are the brightest blue and red stars selected in Karachentsev, Musella, and Grimaldi (1996), respectively. BSGs selected in the \((B, B - V)\) CMD [panel (a)] and RSGs selected in the \((V, B - V)\) CMD [panel (b)] are denoted boldly in each panel.
figure 7, we show the selected supergiant stars: pentagons are the three brightest blue stars and the open circles are the three brightest red stars, while the triangles and squares in panels (c) and (d) are the brightest blue and red stars selected in Karachentsev, Musella, and Grimaldi (1996), respectively. Table 2 lists the equatorial coordinates and photometry results of the selected BSG and RSG stars. While we denote V(3) as the average V-band magnitude of the three brightest stars selected in the V-band, it is worth noting here that the brightest RSG stars in V (3) or K (3) will not, in general, be the same stars as in I (3) or R (3), and this situation is the same for the brightest BSGs (Rozanski & Rowan-Robinson 1994). It is natural that similar, but not the same, stars are selected among our study and that of Karachentsev, Musella, and Grimaldi (1996) by considering the different areas of the studies; we use the HST images of the central 26′ × 29′ region of NGC 1156, while Karachentsev, Musella, and Grimaldi (1996) searched for supergiant candidates only outside the central/crowded areas in their 80′ × 120′ CCD images. The mean magnitudes of the three brightest BSGs are ⟨B(3B)⟩ = 21.943 mag and ⟨V (3B)⟩ = 21.680 mag, and the mean color is ⟨(B − V) (3B)⟩ = 0.263 mag, where 3B denotes the three brightest BSGs. The redder (V − I) colors of the BSGs in this study [(⟨V − I⟩) = 0.392 mag] over those of the BSGs in the study of Karachentsev, Musella, and Grimaldi 1996: ⟨(V − I)⟩ = 0.077 mag] might be due to the crowding of more dust and star-forming regions in the central area of NGC 1156 that caused more reddening. The mean magnitudes of the three brightest RSGs in this study, ⟨V (3R)⟩ = 22.758 mag and ⟨I (3R)⟩ = 20.871 mag, are somewhat fainter than those of the RSGs in Karachentsev, Musella, and Grimaldi (1996): ⟨V⟩ = 22.443 mag, ⟨I⟩ = 20.317 mag; ⟨V⟩This study − ⟨V⟩Karachentsev = 0.315 mag and ⟨I⟩This study − ⟨I⟩Karachentsev = 0.554 mag.

Using the total blue absolute magnitude of NGC 1156 (M_B = −18.64 mag) given by Barazza, Binggeli, and Prugniel (2001) (we redden M_B^{T1} into M_B^{T2} again using A_B = 0.96 mag as given in their study, where M_B^{T1} means the reddening-corrected total B-band magnitude) and equation (2), we obtained the mean total visual absolute magnitude of ⟨M_V(3RSG)⟩ = −7.75 mag. Using the average V magnitude of the three brightest RSGs derived in the previous paragraph [(⟨V(3R)⟩) = 22.758 mag], we obtained a distance modulus of (m − M)_0 = 22.758 + 7.75 − 3.1 E(B − V) = 29.423 mag. Using this value, to derive the total blue absolute magnitude of NGC 1156 assuming B_T = 11.78 mag (Barazza et al. 2001) and the total reddening of A_B = 1.45 mag (subsection 4.2), we calculated M_B^{T2} = −19.093 mag. Inserting this value into the equation (2) and iterating this process until the values converge, we obtained M_B^{T3} = −19.22 mag, ⟨M_V(3RSG)⟩ = −7.88 mag, and the distance modulus (m − M)_0 = 29.55 mag (d ≈ 8.1 Mpc).

Similarly, using the total blue absolute magnitude of NGC 1156 (M_B = −18.64 mag) given by Barazza et al. (2001) and equation (3), we derived the mean total blue absolute magnitude of ⟨M_B (3BSG)⟩ = −8.61 mag. Using the average B magnitude of the three brightest BSGs derived above [(B(3B)) = 21.943 mag], we found a distance modulus of (m − M)_0 = 21.943 + 8.61 − 4.14 E(B − V) = 29.104 mag. Using this value for deriving again the total blue absolute magnitude of NGC 1156 and iterating the process until the values converge, we obtained M_B^{T4} = −18.83 mag, ⟨M_B (3BSG)⟩ = −8.67 mag, and the distance modulus (m − M)_0 = 29.16 mag (d = 6.8 Mpc).

The average of the distance moduli obtained from using the BSGs and RSGs is (m − M)_0 = 29.36 ± 0.20 mag (d = 7.4 ± 0.7 Mpc). Since the uncertainties of the distances estimated by these two methods are different, we used different weights for each of them. The errors in the distances estimated by using BSGs and RSGs were 0.90 mag : 0.58 mag (1.55 : 1) in the study of Rozanski and Rowan-Robinson (1994), respectively, 0.45 mag : 0.30 mag (1.50 : 1) in that of Karachentsev and Tikhonov (1994), and 0.55 mag : 0.37 mag (1.49 : 1) in that of Lyo and Lee (1997). The mean values of the three estimates of the errors for the BSGs and RSGs are 0.63 mag and 0.42 mag, respectively, and their ratio is 1.50 : 1. Giving a single weight to the distance estimate from the BSGs and a weight of 1.5 to that from the RSGs, we finally obtained (m − M)_0 = 29.39 ± 0.20 mag (d = 7.6 ± 0.7 Mpc). This result is in agreement with that derived by Karachentsev, Musella, and Grimaldi (1996), while somewhat larger than that of Tully (1988). The result that the distance estimate of this study is very similar to that of Karachentsev, Musella, and Grimaldi (1996) could be considered to be reasonable because the magnitudes of the selected BSGs and RSGs are not much different, and the studied areas of the two studies are located close to each other.

5. Discussion

While de Vaucouleurs et al. (1991) lists the angular diameter of NGC 1156 to be 3.3, our and Karachentsev, Musella, and Grimaldi (1996)’s studies used only the HST data of the central 26′ × 29′ area and the SAO 6 m telescope data of the central 80′ × 120′ area, respectively. This means the present study covered only 2.5% of the area of NGC 1156 and that of Karachentsev, Musella, and Grimaldi (1996) 31.2%. In fact, in order to select the true brightest stars in a galaxy, we would need to observe the entire area of the galaxy. It, therefore, might be easily speculated that there could be brighter stars in NGC 1156 than the brightest stars selected in the two studies mentioned above.

Figure 1 shows that the area covered by Karachentsev, Musella, and Grimaldi (1996) includes most of the barlike main body and most of the star-forming regions of NGC 1156; it seems that there may not be many, if any, brighter stars outside the area studied by Karachentsev, Musella, and Grimaldi (1996). The fact that our study used a smaller area than that of Karachentsev, Musella, and Grimaldi (1996) is consistent with somewhat fainter (V) magnitudes for both the BSGs (ΔV = V_{This study} − V_{Karachentsev} ≈ 0.44 mag) and the RSGs (ΔV ≈ 0.32 mag) selected in this study, as shown in figure 7c. The (I) magnitude for the RSGs selected in this study is quite fainter than that of Karachentsev, Musella, and Grimaldi (1996) (ΔI = I_{This study} − I_{Karachentsev} ≈ 0.55 mag), but the (I) magnitude for the BSGs selected...
in this study is only a little fainter than that of Karachentsev, Musella, and Grimaldi (1996) ($\Delta I \sim 0.12$ mag; figure 7d). Although the smaller area covered by the HST images in this study compared to that of Karachentsev, Musella, and Grimaldi (1996) renders fainter mean magnitudes of the brightest stars, the new calibration for the brightest stars (from Lyo & Lee 1997) and the new estimate of the total reddening to NGC 1156 used in this study give almost the same distance. It is still possible, though, that we might obtain brighter magnitudes for the brightest stars (and a smaller distance modulus), if we observe a larger area ($r \geq 0.9$) than that of Karachentsev, Musella, and Grimaldi (1996).

Karachentsev, Musella, and Grimaldi (1996)'s and our studies used different observation data and different regions to search for the brightest stars: the former focused only on the outer regions in their $80' \times 120'$ images to avoid the central crowded areas, and the latter used only the central $26' \times 29'$ area of NGC 1156. Therefore, we can obtain more reliable results if we combine the data on the brightest stars from these two studies. The selection of the three brightest RSGs among the six RSGs in the two studies gives the same stars as in the study of Karachentsev, Musella, and Grimaldi (1996), since all of their stars are brighter than those of the present study. Using the three RSGs of Karachentsev, Musella, and Grimaldi (1996) with $\langle V(3R) \rangle = 22.44$ mag and equation (2), we obtain a distance modulus of $(m - M)_0 = 29.16$ mag ($d = 6.8$ Mpc).

Karachentsev, Musella, and Grimaldi (1996) used only the $V$ and $I$ bands for their study. They used these two bands to search for both BSGs and RSGs, and obtained the mean $B$ magnitude of the three BSGs [$\langle B(3B) \rangle = 21.31$ mag] from conversion of the mean $V$ magnitude and the $(V - I)$ color $\langle V(3B) \rangle = 21.24$ mag, $\langle V - I \rangle = 0.08$ mag. Although the $B$ magnitude of each of the three BSGs in the study of Karachentsev, Musella, and Grimaldi (1996) is not known, we might be able to assume that they all have brighter magnitudes than any of the BSGs used in the present study, considering the larger magnitude difference in $V$ (figure 7c) than in $I$ (figure 7d): $\Delta V = \langle V \rangle_{\text{this study}} - \langle V \rangle_{\text{Karachentsev}} \sim 0.44$ mag and $\Delta I = \langle I \rangle_{\text{this study}} - \langle I \rangle_{\text{Karachentsev}} \sim 0.12$ mag. Using the three brightest BSGs of Karachentsev, Musella, and Grimaldi (1996) among the six BSGs in the two studies and equation (3), we obtain $\langle B(3B) \rangle = 21.31$ mag, which gives us a distance modulus of $(m - M)_0 = 28.26$ mag ($d = 4.5$ Mpc).

The weighted mean of the distance estimates from using BSGs with a weight of 1 and RSGs with 1.5 is $(m - M)_0 = 28.80 \pm 0.20$ mag ($d = 5.8 \pm 0.5$ Mpc), while the unweighted mean is $(m - M)_0 = 28.71 \pm 0.50$ mag ($d = 5.5 \pm 1.4$ Mpc). Using the revised calibration of the BSGs and RSGs in Lyo and Lee (1997) and the newly obtained total reddening to NGC 1156 in this study, we derived a distance to this galaxy smaller than those obtained in subsection 4.3 and in Karachentsev, Musella, and Grimaldi (1996). Future wide-field imaging of NGC 1156 at least in the $B$ and $V$ bands might be helpful in resolving this issue and determining a more accurate distance to NGC 1156.

The mean magnitudes and color of the BSGs obtained in this study are $\langle V(3B) \rangle = 21.68$ mag, $\langle I(3B) \rangle = 21.29$ mag, and $\langle V - I(3B) \rangle = 0.39$ mag, and those of the RSGs are $\langle V(3R) \rangle = 22.76$ mag, $\langle I(3R) \rangle = 20.87$ mag, and $\langle V - I(3R) \rangle = 1.89$ mag. On the other hand, the mean magnitudes and color of the BSGs obtained by Karachentsev, Musella, and Grimaldi (1996) are $\langle V(3B) \rangle = 21.24$ mag, $\langle I(3B) \rangle = 21.17$ mag, and $\langle V - I(3B) \rangle = 0.08$ mag, and those of the RSGs are $\langle V(3R) \rangle = 22.44$ mag, $\langle I(3R) \rangle = 20.32$ mag, and $\langle V - I(3R) \rangle = 2.13$ mag. All of the magnitudes obtained in our study are 0.12–0.55 mag fainter than those of Karachentsev, Musella, and Grimaldi (1996), while the situation is different for the $(V - I)$ color: the mean $(V - I)$ color for the BSGs obtained in our study is 0.32 mag redder than that of Karachentsev, Musella, and Grimaldi (1996), while that for the RSGs is 0.24 mag bluer than that of Karachentsev, Musella, and Grimaldi (1996). It could be possible that there occurs larger absorption in the central part of NGC 1156, which affects more for the BSGs than the RSGs. Nevertheless, since we accurately estimated the reddening value in the central part of the galaxy, and applied it to determine the distance, the distance values obtained in this study are not much affected by any differences of the reddening values in our study and those in the study of Karachentsev, Musella, and Grimaldi (1996).

All of the studies performed in the 1990’s, including those of Karachentsev and Tikhonov (1994), Rozanski and Rowan-Robinson (1994), and Lyo and Lee (1997), used the $(B - V)$ color for selecting both the BSGs and RSGs. The wide use of CCDs since then has produced colors using longer wavelengths, such as $(V - I)$, thanks to the good sensitivities of CCD detectors at these wavelengths. It might be helpful if we could use this $(V - I)$ color in selecting or investigating the RSGs, rather than the $(B - V)$ color. Using the $(V - I)$ colors for the RSGs assembled in Lyo and Lee (1997) together with those for NGC 1156 selected in this study, we plot the $(V, V - I)$ and $(I, V - I)$ CMDs in figure 8 to show the $(V - I)$ color distribution of the RSGs. While many RSGs are gathered near $(V - I) \sim 2$ mag, the whole color range of the RSGs is $1.5$ mag $\lesssim (V - I) \lesssim 3.5$ mag.

Figure 7 shows that among the three selected RSGs, RSG2 is the bluest both in $(B - V)$ and $(V - I)$ colors. The $(V - I)$ color of this star $(V - I) = 1.51$ mag is almost at the blue edge in the color range shown in figure 8. If we ignore this star and select again three RSGs in figure 7c, the somewhat fainter and redder star with $V = 22.8$ mag and $(V - I) = 1.56$ mag will be chosen, and this does not much affect the resultant distance estimate to NGC 1156.

6. Summary

Using the $UBVI$ archive HST ACS/HRC images of the dIrr galaxy NGC 1156, we performed DOLPHOT photometry, constructed various combinations of CMDs, and estimated the total (foreground + internal) reddening and distance to this galaxy. Although the CMDs are not deep enough to detect the TRGB, due to the short-exposure time of the HST images, they are good enough to draw a $(U - B, B - V)$ color–color diagram to determine the total interstellar reddening of $E(B - V) = 0.35 \pm 0.05$ mag and to select the three BSGs and three RSGs, which allowed us to determine the distance to this galaxy, $d = 7.6 \pm 0.7$ Mpc [$\langle m - M \rangle_0 = 29.39 \pm 0.20$ mag].

The CMDs obtained in this study are quite similar to those of NGC 6822 (Gallart et al. 1996): $(V, B - V)$ CMD in
Fig. 8. (a) \((V, V-I)\) and (b) \((I, V-I)\) CMDs showing the RSGs assembled and used in Lyo and Lee (1997) and those selected in this study for NGC 1156. The symbols for the six galaxies including NGC 1156 are shown in box in panel (a).

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