

## NEAR-IR TRGB DISTANCE TO DWARF ELLIPTICAL GALAXY NGC 147

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### ABSTRACT

We report the distance modulus of nearby dwarf elliptical galaxy NGC 147 estimated from the Tip of Red-giant Branch (TRGB) method applying to the color-magnitude diagrams and luminosity functions in the near-infrared  $JHK$  bands. Apparent magnitudes of TRGBs in each band are obtained by applying Savitzky-Golay filter to the luminosity functions, and the theoretical absolute magnitudes are estimated from Yonsei-Yale isochrones. The derived values of distance modulus to NGC 147 are  $(m - M) = 23.69 \pm 0.12$ ,  $23.78 \pm 0.17$ , and  $23.85 \pm 0.22$  for  $J$ ,  $H$ , and  $K$  bands, respectively. Distance modulus in bolometric magnitude is also derived as  $(m - M) = 23.87 \pm 0.11$ . We compare the derived values of the TRGB distance modulus to NGC 147 in the near-infrared bands with the previous results in other bands.

*Keywords:* TRGB, distance modulus, near-infrared, NGC 147

### 1. INTRODUCTION

The estimation of accurate distance, which is one of the basic parameters in astronomy, is crucial for observational cosmology. The parallax, as an ideal geometrical method to determine distance, is successfully used only for the nearby stars. In extragalactic distance scale, the most useful and reliable method in astrophysics is the Cepheid period-luminosity relation, but it depends on the age and the metallicity of galaxy and can be applied to Population I systems of late-type galaxies. The tip of the red giant branch (TRGB) is indeed an excellent alternative distance indicator for older and more metal-poor early type galaxies.

In the TRGB method, the determination of the accurate TRGB location is a key point. Various methods to determine the brightness of TRGB are used in previous studies. Before 1990s, the method for measuring TRGB is not well established, so most astronomers found the TRGB positions in the color-magnitude diagram (CMD) by eyes. However, the qualities of those are not ideal and not reproducible (e.g., McConnachie et al. 2004). Lee et al. (1993a) applied a technique for distance determination using an edge detection with the Sobel filter to the luminosity functions (LFs) of resolved galaxies. This TRGB method was successfully confirmed thorough numerical simulations by Madore & Freedman (1995). Sakai et al. (1996) revised the method in order to reduce the dependency on bin size of the LF by Gaussian smoothing.

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The TRGB method as the distance indicator has been generally used in  $I$ -band observation, because  $I$  magnitude of TRGB is weakly sensitive to the metallicity of the stellar population than the other magnitudes (e.g., Da Costa & Armandroff 1990, Lee et al. 1993a, Salaris & Cassisi 1998). Lee et al. (1993b) suggested that  $I$  magnitude, obtained by both observation and theoretical calculation, of TRGB stars in globular clusters for metallicity range of  $-2.2 < [\text{Fe}/\text{H}] < -0.7$  shows only small difference within 0.1 mag. However, observations of infrared bands have rarely secured to determine the TRGB of resolved galaxies. Montegriffo et al. (1995) estimated the distance using TRGB in  $J$  and  $K$  bands for 47 Tucanae. Cioni et al. (2000) estimated the distances of LMC and SMC using TRGB in the  $I$ ,  $J$ , and  $K_S$  bands from the data of DENIS catalogue towards the Magellanic Clouds. Also, Cioni & Habing (2005) obtained a distance modulus of NGC 6822 from the position of TRGB in  $IJK_S$  bands using the Issac Newton Group Red Imaging Device (INGRID) on the William Herschel Telescope. Valenti et al. (2004) measured TRGB in the  $J$ ,  $H$ , and  $K$  bands for 24 Galactic globular clusters using the ESO-MPI 2.2 m telescope with the near infrared camera IRAC-2. Bellazzini et al. (2004) estimated the TRGB as distance indicator in  $I$ ,  $J$ ,  $H$ , and  $K$  bands for  $\omega$  Centauri and 47 Tucanae from 2MASS data.

In this paper, we measure the distance modulus of the nearby dwarf elliptical galaxy NGC 147 using the Savitzky-Golay filter to measure the brightness of the TRGB in the near-infrared CMDs and LFs. In Sect. 2, we describe the data for the near-infrared CMDs with  $J$ ,  $H$ , and  $K$  bands. Sect. 3 describes the method to estimate the observational and theoretical TRGB magnitudes. In Sect. 4, we present the determined distance modulus of NGC 147, and compare with the previous results.

## 2. THE DATA OF NEAR-INFRARED CMD

Our target for this study is dwarf elliptical galaxy NGC 147 which is a companion of the M 31. Near-infrared image data were obtained on June 3, 2004 using the CFHTIR infrared imager of the CFHT 3.6m telescope. The detailed information about observations and the process of data reduction could be found in our previous paper (Sohn et al. 2006). We detected 7303 stars for NGC 147 after all pre-processing and photometry, and presented the CMDs in Figure 1 of Sohn et al. (2006). The observed CMDs contain AGB population and RGB population in brighter parts, while the beginning of RGBs is not seen due to bright detection limit. In the paper, by applying the empirical relation between TRGB brightness in near-infrared bands and metallicity for stars in the galaxy (Valenti et al. 2004), we assigned the TRGB magnitude of NGC 147 as  $K = 18.0$ , which is a boundary to separate the AGB and the RGB populations. The completeness tests for the  $JHK$  images of NGC 147 were also carried out in the paper, and the results are applied to the luminosity functions for each band. As confirmed in the next section, we conclude that the brightness of TRGB is not affected by the results of completeness test, because the completenesses for the estimated TRGB magnitude of NGC 147 nearly have 90 ~ 100%.

## 3. THE APPARENT AND ABSOLUTE TRGB MAGNITUDES

The LF is a fundamental tool for understanding evolutionary events of a stellar population (Cioni et al. 2000). The TRGB which marks the violent onset of core helium burning in low-mass stars causes a distinct and abrupt termination of the bright end of the RGB LF (Makarov et al. 2006). This discontinuity of LFs of galaxies is just used as a distance indicator. However, the accuracy of the observed TRGB is led to the necessary condition that the observed RGB LF should be well populated with more than  $\sim 100$  stars within 1 mag from the TRGB (Madore & Freedman 1995,

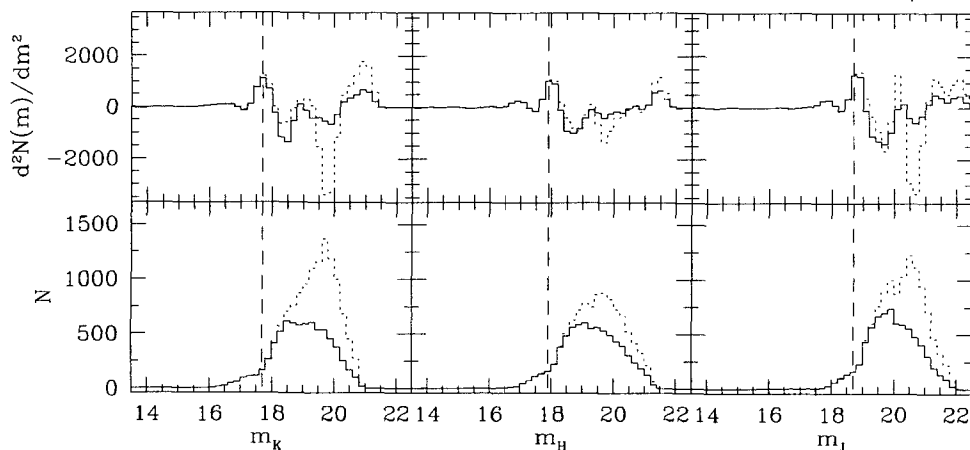


Figure 1. Lower: Luminosity functions in near-infrared  $JHK$  bands of NGC 147. The LFs with solid and dotted lines are for only detected stars and for completeness corrected number of stars, respectively. Upper: The second derivative of LF and completeness corrected LF. Vertical long-dashed lines in each panel indicate the TRGB magnitudes.

Bellazzini et al. 2002). Our data set for NGC 147 is satisfied this condition.

In this paper, the method for the detection of the TRGB is adopted from Cioni et al. (2000). Cioni et al. (2000) suggested that the TRGB discontinuity causes a peak in the second derivative of the observed stellar LF, and found that the set of the second derivatives provides a better handle on the brightness of TRGB. For the estimation of the second derivative, they used a Savitzky-Golay filter. The filter yields for bin number  $i$ ,  $[d^2N/dm^2]_i = \sum_{j=-J}^J c_j N(m)_{i+j}$ , where  $N(m)$  is number of stars with  $m$  magnitude and the  $c_j$  are Savitzky-Golay coefficients for the chosen value of  $J$  and the desired derivative order  $L = 2$ . The filter fits a polynomial of order  $M$  to the data points  $N(m)_j$  with  $j = i - J, \dots, i + J$ , and then evaluate the  $L$ th derivative of the polynomial at bin  $i$  to estimate  $d^2N/dm^2$ . We applied the same method to our sample.

Figure 1 shows near-infrared LFs of NGC 147 and the second derivative of the LFs after applying a Savitzky-Golay filter. The dotted lines of each box represent the completeness corrected LFs for NGC 147. Vertical dashed lines are the estimated TRGB apparent magnitudes which show the peaks of the second derivative LFs. As appeared in Figure 1, TRGB magnitudes in the apparent LFs are same as those in the completeness corrected LFs. Finally, the brightnesses of TRGBs in near-infrared bands of NGC 147 are derived as  $m_J = 18.7$ ,  $m_H = 17.9$ , and  $m_K = 17.7$ , respectively. After applying the reddening values to NGC 147 (i.e., Schlegel et al. 1998), we obtained the absorption corrected TRGB magnitudes of  $m_{J_0} = 18.544$ ,  $m_{H_0} = 17.800$ , and  $m_{K_0} = 17.636$ .

We note that the TRGB magnitudes in near-infrared  $JHK$  bands have more dependence on age and metallicity than  $I$ -band. Saris & Girardi (2005) shows  $M_K^{TRGB}$  as a function of age for various metallicities. On their study, the difference  $M_K^{TRGB}$  between  $[Fe/H] = 0.0$  and  $-1.68$  is approximately  $\sim 1$  magnitude at 12 Gyr, while that of  $M_{bol}^{TRGB}$  is just 0.3 mag at the same age. This indicates that the bolometric magnitude is less affected by metallicity and age as well as dust extinction (Cioni et al. 2000), and that we can obtain more accurate distance to the galaxy by using

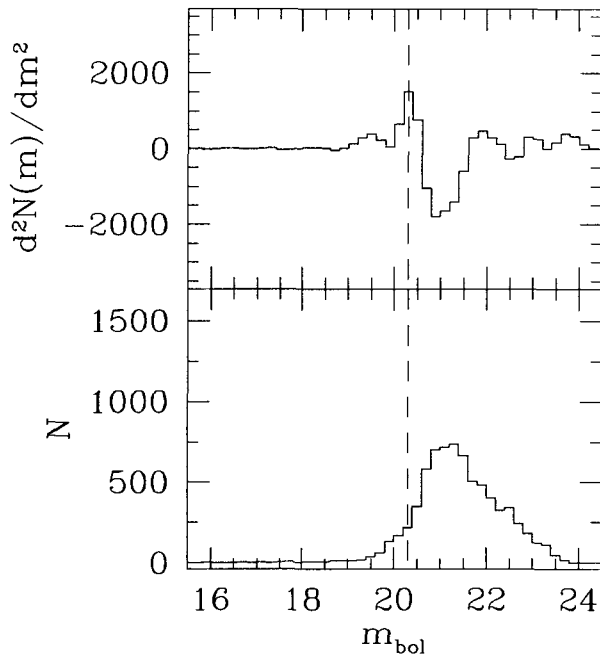


Figure 2. Lower: Luminosity function in bolometric magnitude for resolved stars in NGC 147. Upper: The second derivative of bolometric LF. The long-dashed line shows the TRGB magnitudes.

the bolometric magnitudes of stars.

In Sohn et al. (2006), we already calculated the observed bolometric  $m_{bol}$  magnitudes for AGB stars using the empirical relation between  $BC_K$  and  $(J - K)$  by Bessell & Wood (1984) and Costa & Frogel (1996). For  $m_{bol}$  magnitudes of RGB populations, we used the  $BC_K$  by Montegriffo et al. (1998), which provides the relation between  $BC_K$  and  $(J - K)$  from the infrared data of Population II stars. Figure 2 shows the bolometric LF and the second derivative of the LF for resolved stars in NGC 147. Finally, we determined the bolometric magnitude of the TRGB as  $m_{bol} = 20.3$  by detecting the peak of the second derivative of the bolometric LF for resolved stars in NGC 147.

To calculate the distance to galaxies with the derived apparent TRGB magnitudes, we need values for the absolute magnitudes of the TRGB in the near-infrared bands. Here, we determine the absolute magnitudes of TRGBs from the theoretical Yonsei-Yale ( $Y^2$ ) isochrones (Kim et al. 2002, Yi et al. 2003). Figure 3 shows the relation between metallicity and the absolute magnitudes of TRGB in the near-infrared and bolometric magnitudes derived from the  $Y^2$  isochrones. We note that the longer wavelength in near-infrared bands, the steeper slope of absolute magnitude to metallicity. The adopted metallicity range of NGC 147 is  $-1.3 < [\text{Fe}/\text{H}] < -0.7$  as shown in Sohn et al. (2006). Applying the metallicity range and the age of 12 Gyr to Figure 3, we estimate the theoretical TRGB magnitudes for NGC 147 to be  $M_J = -5.144 \pm 0.071$ ,  $M_H = -5.984 \pm 0.143$ ,  $M_K = -6.209 \pm 0.192$ , and  $M_{bol} = -3.565 \pm 0.047$ . The errors of the determined absolute magnitudes are mainly caused by the range of the metallicity.

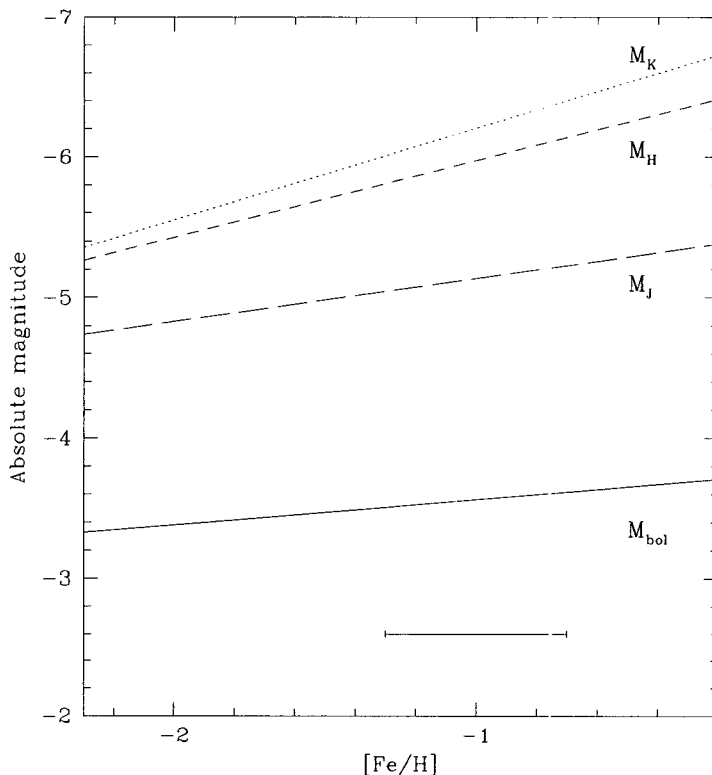


Figure 3. The relationship between the theoretical TRGB magnitude and  $[Fe/H]$  by  $Y^2$  isochrones. The solid line shows the relationship in bolometric magnitude, and the long-dashed, short-dashed, and dotted lines are those of  $JHK$  bands. Horizontal bar represents the adopted metallicity range of NGC 147.

#### 4. TRGB DISTANCE TO NGC 147

Using the observed magnitudes in near-infrared bands and theoretical magnitudes of TRGBs, we calculate distance modulus for NGC 147. The calculated values for each near-infrared band are  $(m - M)_J = 23.69 \pm 0.12$ ,  $(m - M)_H = 23.78 \pm 0.17$ ,  $(m - M)_K = 23.85 \pm 0.22$ , and  $(m - M)_{bol} = 23.87 \pm 0.11$  for the bolometric magnitude. Errors are estimated from the magnitude errors for both of the bin size in LF and the metallicity range.

There have been several distance determinations for NGC 147 by using the TRGB methods to the visible band CMDs and LFs, i.e.,  $24.0 \pm 0.15$  (Mould et al. 1983), 24.3 (Davidge 1994), and  $24.39 \pm 0.05$  (Han et al. 1997). Also, Lee et al. (1993a), who introduced that the  $I$  magnitude of TRGB is a good distance indicator for resolved stellar systems with broad range of metallicity, measured the distance modulus of 24.13 for NGC 147. Salaris & Cassisi (1998) also estimated the distance moduli of resolved galaxies using the re-evaluation of the TRGB method and determined  $24.27 \pm 0.14$  for NGC 147. In conclusion, distance modulus of NGC 147 estimated from the near-infrared band CMDs and LFs are comparable with previous values from other studies. At the point that near-infrared observations are getting important for the observational cosmology, we

need more observational studies for the distance modulus measurements of resolved galaxies in the near-infrared bands.

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