Resolving the Discrepancy of Distance to M60, a Giant Elliptical Galaxy in Virgo

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Abstract

There is a well-known discrepancy in the distance estimation of M60, a giant elliptical galaxy in Virgo; the planetary nebula luminosity function (PNLF) distance moduli for this galaxy are, on average, 0.4 mag smaller than the values based on the surface brightness fluctuation (SBF) in the literature. We present photometry of the resolved stars in an outer field of M60 based on deep F775W and F850LP images in the Hubble Space Telescope obtained as part of the Pure Parallel Program in the archive. Detected stars are mostly old red giants in the halo of M60. With this photometry, we determine a distance to M60 using the tip of the red giant branch (TRGB). A TRGB is detected at $F850LP_{TRGB} = 26.70 \pm 0.06$ mag, in the luminosity function of the red giants. This value corresponds to $F814W_{0,TRGB} = 27.13 \pm 0.06$ mag and $QTRGB = 27.04 \pm 0.07$ mag, where $Q$ is a color-corrected F814W magnitude. From this we derive a distance modulus, $(m-M)_0 = 31.05 \pm 0.07$ (ran) $\pm 0.06$ (sys) ($d = 16.23 \pm 0.50$ (ran) $\pm 0.42$ (sys) Mpc). This value is 0.3 mag larger than the PNLF distances and 0.1 mag smaller than the SBF distances in the previous studies, which indicates that the PNLF distances to M60 reported in the literature have larger uncertainties than the suggested values.

Key words: galaxies: clusters: individual (Virgo, M60) – galaxies: distances and redshifts – galaxies: elliptical and lenticular, cD – galaxies: stellar content – stars: Population II

1. Introduction

Two of the popular distance indicators for nearby elliptical galaxies and early-type spiral galaxies are the surface brightness fluctuation (SBF; Tonry & Schneider 1988; Tonry et al. 2001; Blakeslee et al. 2009, 2010; Cantillo et al. 2011; Blakeslee 2012) and the planetary nebula luminosity function (PNLF; Jacoby 1989; Jacoby et al. 1990; Feldmeier et al. 2007; Teodorescu et al. 2011; Ciardullo 2012, 2013). The SBF method is based on the fact that the variance in the images of a galaxy depends on the distance to the galaxy. It can be applied to more distant galaxies compared with the tip of the red giant branch (TRGB) method, but its precision decreases for the galaxies with composite stellar populations (Blakeslee 2012). The PNLF method is based on the estimation of the [O\textsc{iii}] $\lambda 5007$ luminosity function of planetary nebulae (PNe), which is calibrated empirically. It is not supported by any theory, but it works well as a distance indicator. It is easy to apply, but does not work for galaxies with a small number of PNe (Ciardullo 2012).

There is a well-known discrepancy in the distance estimation based on these two methods, in the sense that PNLF distance moduli are, on average, 0.3–0.4 mag smaller than SBF values (Ciardullo et al. 2002; Blakeslee et al. 2009, 2010; Teodorescu et al. 2010; Ciardullo 2012, 2013). Ciardullo (2012, 2013) concluded in a review of the PNLF that this distance offset may be due to the combined result of several small effects, including the difference in the zero points and the dust effect in spiral bulges (see also Cantillo et al. 2013). The author pointed out that the main calibrators for the SBF and PNLF are intermediate-type spiral galaxies, while the targets are mostly early-type galaxies. It is also noted that the distance offset (between the SBF and PNLF distances) versus distance modulus diagram (see Figure 7 in Ciardullo 2012) shows a trend that the scatter of this difference becomes larger at $(m - M)_0 > 31.0$. To help resolve this discrepancy, distance estimation based on another independent method is needed for the common targets of the SBF and PNLF methods.

In this study, we selected M60 (NGC 4649, VCC 1978), which is a giant elliptical galaxy in Virgo, to resolve the distance discrepancy between PNLF distances and SBF distances. Basic parameters of M60 are listed in Table 1. M60 has been a target of numerous studies because it shows several interesting features. First, it is the third brightest elliptical galaxy in Virgo, and hosts a rich population of globular clusters, PNe, and low-mass X-ray binaries (Hwang et al. 2008; Lee et al. 2008a, 2008b; Teodorescu et al. 2011; Strader et al. 2012; Luo et al. 2013; Mineo et al. 2014; Pota et al. 2015). Second, it has a small spiral companion, NGC 4647 (SAB(rs)c), located at 25′ (12 kpc) in the northwest from the center of M60. Whether M60 and NGC 4647 are interacting or not has been controversial (de Grijs & Robertson 2006; Lanz et al. 2013; D’Abrusco et al. 2014; Mineo et al. 2014; Pota et al. 2015). Third, it hosts a bright ultracompact dwarf (UCD, M60-UCD1), which is one of the densest galaxies (Strader et al. 2013; Liu et al. 2015). A supermassive black hole (SMBH) with $M_{SMBH} = 2.1 \times 10^7 M_\odot$ was found in this UCD, and provides a strong evidence that this UCD is not a globular cluster, but instead is a stripped nucleus of a genuine galaxy (Seth et al. 2014). Fourth, in the central region of M60 (51′′6 west and 78′′7 south), an underluminous SN Ia (SN2004W), was discovered (Moore et al. 2004; Nielsen et al. 2012). Unfortunately, the full light curve of SN2004W is not available. Fifth, it is a main member of the M60 group, which includes M60, NGC 4647, M59 (NGC 4621), NGC 4660, and NGC 4638. This group may be the nearest compact group of galaxies, if its nature as a genuine group is confirmed (Mamon 1989, 2008).

In an extensive study of the PNe in M60, Teodorescu et al. (2011) determined a distance to this galaxy using a large sample of PNe, and presented $(m - M)_0 = 30.7 \pm 0.2$ (14.0 ± 1.0 Mpc). This value is 0.4 mag smaller than...
Table 1
Basic Parameters of M60

| Parameter                        | Value                  | References |
|----------------------------------|------------------------|------------|
| R.A. (J2000), Decl. (J2000)      | $12^h 43^m 40.0^s$, $+11^\circ 33^\prime 10^\prime$ | 1         |
| Morphological Type               | E2                     | 2         |
| Apparent total magnitude         | $B_F = 10.24 \pm 0.03$ | 2         |
| Apparent total color             | $(B_F - V_T) = 0.96 \pm 0.01$ | 2         |
| Ellipticity                      | 0.11                   | 3         |
| Position angle                   | $71^\circ$             | 3         |
| $D_{25}(B)$                      | 262$^\prime$           | 2         |
| Effective radius                 | $58^\prime 7$          | 2         |
| Systemic velocity                | 1110 km s$^{-1}$       | 1         |
| Foreground extinction            | $A_B = 0.096$, $A_V = 0.072$, $A_I = 0.040$ | 5         |
| Distance modulus                 | $(m - M)_0 = 31.05 \pm 0.07$ ran $\pm 0.06$ sys | 6         |
| Distance                         | $d = 16.23 \pm 0.50 \pm 0.42$ Mpc | 6         |
| Plate scale                      | 78.7 pc arcsec$^{-1}$  | 6         |
| Absolute total magnitudes        | $M_B^o = -20.92$, $M_V^o = -21.85$ | 2, 6  |
| Central velocity dispersion      | 213 km s$^{-1}$        | 4         |
| Dynamical mass for $R < 8R_{eff}$ | $M = 1.61 \pm 0.7 \times 10^{12}M_\odot$ | 7         |

References. (1) NED, (2) de Vaucouleurs et al. (1991), (3) Makarov et al. (2014), (4) Cappellari et al. (2013), (5) Schlafl & Finkbeiner (2011), (6) this study, and (7) Alabi et al. (2016).

the most recent value based on the SBF method, which is $(m - M)_0 = 31.1 \pm 0.2$ (16.6 \pm 1.0 Mpc) (Blakeslee et al. 2009). M60 is an elliptical galaxy, so the dust effect for the PNLF and SBF distance estimation must be negligible. Therefore, this discrepancy must be due to other effects, which remain to be explained.

In this study, we analyze deep high resolution images of M60 available in the Hubble Space Telescope (HST) archive, and use them to determine a distance to M60 applying the TRGB (Lee et al. 1993; Rizzi et al. 2007; Jang & Lee 2017a). Currently deriving TRGB distances to Virgo galaxies is difficult, but is possible with deep HST images. To date, TRGB distances have been estimated only for a small number of Virgo galaxies: M87 (Bird et al. 2010; M. G. Lee & I. S. Jang 2017, in preparation) and several dwarf galaxies (Caldwell 2006; Durrell et al. 2007; Jang & Lee 2014). M60 is one of the rare examples in Virgo for which SBF, PNLF and TRGB distances can be compared.

This paper is organized as follows. In Section 2 we describe the reduction of data used in this study. Section 3 presents the color–magnitude diagrams (CMDs) of the resolved stars detected in the images of an outer field of M60. This is the first CMD of the resolved stars in M60. Then, we estimate a TRGB distance to M60 from photometry of these resolved stars. Section 4 compares the TRGB distance determination results in this study and the PNLF and SBF distances in the previous studies, and discuss interaction between M60 and NGC 4647. In the final section, main results are summarized.

2. Data and Data Reduction

Figure 1 displays a finding chart for a $20^\prime \times 20^\prime$ field, including M60 based on the SDSS color map. It also shows NGC 4647, which is a spiral galaxy northwest of M60. We used the ACS/WFC F775W (SDSS $i'$) and F850LP (SDSS $z'$) images of an outer field to the north of M60, the location of which is marked in Figure 1. These images were obtained as part of the ACS Pure Parallel Program (PID:9575, PI: William Sparks) in 2002. In addition, they are very useful for the study of the resolved stars in M60 as well. Since the difference between the effective wavelengths of F775W and F850LP filters is small, the combination of these two filters is not effective for the study of colors (or metallicity) of stellar populations. However, this combination of filters is good enough to detect red giants in nearby galaxies.

The HST field is located at $\approx 8^\prime$ to the north from M60 in the sky. The effective radius of M60 is $R_{eff} = 58^\prime 7$ (de Vaucouleurs et al. 1991), so the projected galactocentric distance of the HST field is about $8R_{eff}$. Therefore, the crowding of the point sources in this field is much lower compared with inner fields, so this field is much more suitable
for the study of resolved stars in M60. We combined individual exposure images to produce deep master images using the AstroDrizzle package. Total exposure times are 15,407 s for F775W, and 9547 s for F850LP, so the images are deep enough to study the resolved stars in M60. A gray scale map of the F775W image for a 10′ × 10′ section of the entire field (marked by a small square in Figure 1) is shown in Figure 2. In the figure, many point sources are clearly seen. Most of them are red giant stars belonging to M60, and some of them may be compact background galaxies.

We obtained photometry of the point sources in the images using the latest version of DOLPHOT (Dolphin 2000). We used charge-transfer-efficiency-corrected and flat-fielded images (*_flc.fits images) with the synthetic Tiny Tim point spread functions (PSFs; Krist et al. 2011). The DOLPHOT parameters used in this study are the same as those given in DOLPHOT/ACS user’s guide (version 2.0).

We carried out artificial star tests using the artificial star routine (acsfakelist) in DOLPHOT. We generated a sample of artificial stars with a color range of F775W–F850LP = 0.3 ~ 0.9 mag and a magnitude range of F850LP = 23.0 ~ 29.0 mag. We added 10,000 artificial stars, which corresponds to ~ 10% of the total number of detected sources, in each image, and carried out PSF photometry as were done on the original frames. We iterated this procedure 50 times to reduce statistical uncertainties. Figure 3 displays the recovery rates of the input stars, and the difference in F850LP magnitudes and (F775W–F850LP) colors between the input and output values. It shows that the 50% completeness limit is F850LP ~ 26.9 mag. The mean values of the input minus output magnitudes and colors are ΔF850LP = −0.158 ± 0.007 mag and Δ(F775W–F850LP) = 0.057 ± 0.007 mag, for F850LP = 26.8 mag which is close to the TRGB magnitude.

Since the TRGB calibration is based on VI (or F606W and F814W in the HST system; Lee et al. 1993; Rizzi et al. 2007; Jang & Lee 2017a), we need to transform F775W and F850LP photometry to F606W and F814W photometry. For this purpose, we used the 12 Gyr isochrones in the Dartmouth model (Dotter et al. 2008). In Figure 4, we plotted the color–color relations for the TRGB of the isochrones for a range of metallicity (--2.3 ≤ [Fe/H] ≤ 0.0): (a) the (F606W–F814W) versus (F775W–F850LP) relation, and (b) the (F814W–F850LP) versus (F775W–F850LP) relation. The (F606W–F814W) versus (F775W–F850LP) relation is fit well by a double linear relation with a break at (F775W–F850LP) = 0.9 (corresponding to [Fe/H] = −0.5), while the (F814W–F850LP) versus (F775W–F850LP) relation is represented well by a single linear relation for (F775W–F850LP) < 1.35. From the linear fits for the data, we obtain

$$\text{(F606W–F814W) = (3.136 ± 0.014) × (F775W–F850LP) − (0.102 ± 0.007)},$$

(1)

with rms = 0.034 for (F775W–F850LP) ≤ 0.9, and

$$\text{(F606W–F814W) = (1.235 ± 0.021) × (F775W–F850LP) + (1.610 ± 0.019)},$$

(2)

with rms = 0.029 for (F775W–F850LP) > 0.9.

Similarly, we derive

$$\text{(F814W–F850LP) = (0.642 ± 0.006) × (F775W–F850LP) + (0.027 ± 0.004)},$$

(3)

with rms = 0.003.

On the other hand, from the comparison of SDSS photometry and Johnson–Cousins photometry of standard stars, Lupton (see footnote 3) derived a transformation relation between the two systems: $I = i − 0.3780 × (i − z) − 0.3974$ (rms = 0.0063), as plotted by the blue solid line in Figure 4(b). The second relation derived in this study is very similar to this transformation, except for the slight offset in the blue end.
Using the equations above, we can transform (F775W–F850LP) colors and F850LP magnitudes of the detected stars in the HST field of M60 into (F606W–F814W) colors and F814W magnitudes.

3. Results

3.1. CMDs of the Resolved Stars in M60

In Figure 5, we plotted the F850LP–(F775W–F850LP) CMD of the detected point sources in the HST field of M60. The most prominent feature in the CMD is a concentration of red stars with a broad range of colors, the mean value of which is (F775W–F850LP) ≈ 0.6. It is a red giant branch (RGB) of M60. The brightest part of this RGB is seen at F850LP ≈ 26.8 mag, which corresponds to the TRGB of M60. The number density of the stars above the TRGB is much lower than that below the TRGB. Our photometry of the resolved stars goes more than one magnitude below the TRGB, and it can be used for a reliable TRGB distance estimation of M60.

The width of the bright RGB with F850LP < 27.0 mag is much larger than the mean photometric errors of the colors, which is mainly due to a large range of metallicity of the RGB stars in M60. We overlayed 12 Gyr stellar isochrones with a range of metallicity ([Fe/H] = −2.2 to 0.0, in steps of 0.2) in the Dartmouth models (Dotter et al. 2008), which is shifted according to the distance to M60, by red lines. The broad RGB of M60 is roughly overlapped by the RGB part of the isochrones with a range of metallicity.

3.2. TRGB Distance Estimation

We determine a TRGB distance to M60 from photometry of the resolved stars, as done in our previous studies for other galaxies (Lee & Jang 2016; Jang & Lee 2017b). Table 2 lists a summary of the TRGB distance estimations for M60. First, we selected the blue red giant candidates inside the shaded region in the CMD of Figure 5. The TRGB magnitude is almost constant in this blue RGB. The data for M60 used in this study are not deep enough to cover the full range of colors of the RGB stars. In this case, using the blue RGB is the best way to avoid any complications due to redder stars. Then, we derived their luminosity function, as shown in Figure 6. Applying the edge-detection method with a Sobel kernel [−1, −2, −1, 0, 1, 2, 1] to this luminosity function, we calculated the edge-detection responses, as plotted by the red solid line in the figure. The edge-detection response clearly shows a major single peak at F850LP ∼ 26.8 mag.

A quantitative value for the TRGB magnitude and its error were estimated using the bootstrap resampling method, as done in Jang & Lee (2017b). We performed 10 thousand simulations of bootstrap resampling. In each simulation, we resampled a half number of stars randomly from the original sample and measured the TRGB as done for the original sample. Then we performed a Gaussian fit to the measured TRGB magnitudes and quoted the Gaussian mean for the mean TRGB magnitude and the width for the TRGB measurement error. This process gives a TRGB magnitude of F850LP_{TRGB} = 26.79 ± 0.06 mag. The median color
of the TRGB, \((F775W\text{--}F850LP)_{\text{TRGB}} = 0.63 \pm 0.02\), is measured using the RGB stars at ±0.02 mag range of the TRGB. We estimated the systematic offsets of the TRGB magnitude and color using the artificial stars that have a luminosity function with a logarithmic slope of \(\alpha = 0.3\) and \(F850LP_{\text{TRGB}} = 26.70\) mag and \((F775W\text{--}F850LP)_{\text{TRGB}} = 0.60\). We derived the TRGB magnitude and color from the recovered artificial stars using the same procedure. The mean values of the input minus output TRGB magnitudes and colors are \(\Delta F850LP_{\text{TRGB}} = −0.09 \pm 0.06\) mag and \(\Delta(F775W\text{--}F850LP)_{\text{TRGB}} = 0.06 \pm 0.02\) mag. By correcting the measured TRGB values with these systematic offsets, we obtain \(F850LP_{\text{TRGB}} = 26.70 \pm 0.06\) mag and \((F775W\text{--}F850LP)_{\text{TRGB}} = 0.69 \pm 0.02\).

Then we corrected these values for the foreground extinction effect, using the values in Schlafly & Finkbeiner (2011), \(A_{F775W} = 0.043\) and \(A_{F850LP} = 0.033\). M60 is a typical elliptical galaxy and our \(HST\) field is far from the M60 center so it is expected that our \(HST\) field contains little dust. Indeed no far-infrared emission is detected in M60 (Lanz et al. 2013). Thus we ignore internal reddening for M60 in this analysis. We converted the measured TRGB magnitude and color in the F775W and F850LP system to the F606W and F814W system using the photometric transformations described in Section 2, obtaining \(F814W_{\text{TRGB}} = 27.13 \pm 0.06\) mag and \((F606W\text{--}F814W)_{\text{TRGB}} = 2.03 \pm 0.06\).

The \(I\)-band TRGB has a known weak metallicity dependence, especially at the red color range \((F606W\text{--}F814W \gtrsim 1.5)\) (Bellazzini et al. 2001; Rizzi et al. 2007; Jang & Lee 2017a). Jang & Lee (2017a) introduced a color-dependence-corrected TRGB magnitude, called as the \(QT\) magnitude. It is described by \(QT = F814W_0 - 0.159(\text{Color} - 1.1)^2 + 0.047(\text{Color} - 1.1),\) where \(F606W\text{--}F814W\). The absolute zero-point of the \(QT\) is measured to be \(M_{QT,\text{TRGB}} = \,−4.015 \pm 0.056\) mag, from the combination of two distance anchors with known geometric distances (NGC 4258 and the Large Magellanic Cloud (LMC)). The systematic error of ±0.056 in this calibration is much smaller than the values given in the previous studies. The value of the \(QT\) magnitude and corresponding distance modulus for M60 we obtained are: \(QT_{\text{TRGB}} = 27.04 \pm 0.07\) mag and \((m - M)_0 = 31.05 \pm 0.07\) (random) mag \((d = 16.23 \pm 0.50\) Mpc). The systematic uncertainty of this distance modulus is ±0.056 mag (corresponding to the distance error of ±0.42 Mpc).

4. Discussion

4.1. Comparison of the TRGB Distance to M60 with PNLF and SBF Distances

We compared our TRGB distance estimate for M60 with those based on the PNLF and SBF in the literature, as summarized in Table 3 and plotted in Figure 7. Jacoby et al. (1990) presented a PNLF distance to M60 derived from a small sample of 16 PNe, \((m - M)_0 = 30.76 \pm 0.14\) \((d = 14.2 \pm 0.6\) Mpc), including a systematic error of 0.13, which was updated later to \((m - M)_0 = 30.73^{0.10}_{-0.13}\) by Ciardullo et al. (2002). They adopted the calibration for the PNLF given by Ciardullo et al. (1989), \(M_P^* = -4.48\), which is based on the Cepheid distance to M31, 710 kpc \((m - M)_0 = 24.26 \pm 0.10\), and foreground reddening \(E(B - V) = 0.11 \pm 0.02\). The distance to M31 adopted for this PNLF calibration is somewhat smaller than the values in more recent Cepheid distances to M31: \((m - M)_0 = 24.51 \pm 0.08\) and \((m - M)_0 = 24.32 \pm 0.09\) (e.g., in Wagner-Kaiser et al. 2015).

Later, Teodorescu et al. (2011) used a much larger sample of 218 PNe in M60 and obtained a similar value, \((m - M)_0 = 30.70 \pm 0.20\), which includes a systematic error of 0.13. They adopted the same calibration for the PNLF as used in Jacoby et al. (1990). If the metallicity dependence of the period–luminosity relation for Cepheids is adopted for bright galaxies, this calibration will be slightly brighter to \(M_P^* = -4.53 \pm 0.04\) (Ciardullo 2013). Ciardullo (2013) presented a similar calibration for metal-rich galaxies (with higher metallicity than that of the Large Magellanic Cloud),

| Parameter | Value |
|-----------|-------|
| Apparent TRGB magnitude in F850LP | 26.79 ± 0.06 |
| Apparent TRGB color in F775W–F850LP | 0.63 ± 0.02 |
| Systematic offset in F850LP | −0.09 ± 0.06 |
| Systematic offset in F775W–F850LP | 0.06 ± 0.02 |
| Corrected TRGB magnitude in F850LP | 26.70 ± 0.06 |
| Corrected TRGB color in F775W–F850LP | 0.69 ± 0.02 |
| Foreground extinction at F775W | 0.043 |
| Foreground extinction at F850LP | 0.033 |
| Intrinsic TRGB magnitude in F850LP | 26.67 ± 0.06 |
| Intrinsic TRGB color in F775W–F850LP | 0.68 ± 0.02 |
| Intrinsic TRGB magnitude in F814W | 27.13 ± 0.06 |
| Intrinsic TRGB color in F606W–F814W | 2.03 ± 0.06 |
| Intrinsic TRGB magnitude in QT | 27.04 ± 0.07 |
| Absolute TRGB magnitude | −4.015 ± 0.057 |
| Distance modulus, \((m - M)_0\) | 31.05 ± 0.07 (random) ± 0.06 (sys) |
| Distance, \(d [\text{Mpc}]\) | 16.23 ± 0.50 (random) ± 0.42 (sys) |
Comparison of Distance Estimates for M60

| Method | \((m - M)_0\) | References | Remarks |
|--------|----------------|------------|---------|
| TRGB   | 31.05 \(\pm\) 0.07 (ran) \(\pm\) 0.06 (sys) | This study |         |
| PNLF   | 30.76 \(\pm\) 0.15 (ran) \(\pm\) 0.13 (sys) | Jacoby et al. (1990) | N(PN) = 16, \(M^*_{PN}\) = \(-4.48\) |
|        | 30.73 \(\pm\) 0.10 | Ciardullo et al. (2002) |         |
|        | 30.7 \(\pm\) 0.1 | Teodorescu et al. (2011) |         |
|        | 30.8 \(\pm\) 0.1 | Ciardullo (2013) |         |
|        | 30.74 \(\pm\) 0.09 |         |         |
| SBF    | 31.06 \(\pm\) 0.11 | Neilsen & Tsvetanov (2000) | F814W   |
|        | 31.13 \(\pm\) 0.15 | Tonry et al. (2001) | I       |
|        | 31.19 \(\pm\) 0.07 (ran) \(\pm\) 0.15 (sys) | Mei et al. (2007) | F850LP  |
|        | 31.08 \(\pm\) 0.08 (ran) \(\pm\) 0.15 (sys) | Blakeslee et al. (2009) | F850LP  |
|        | 31.13 \(\pm\) 0.05 |         |         |

PNL value, and is 0.1 mag smaller than the mean SBF value. This indicates that the PNLF distances to M60 reported in the literature have larger uncertainties than the suggested values.

Ciardullo (2013) pointed out that two main causes for the discrepancy between the PNLF and SBF distances are zero points in the calibration and the extinction effect due to dust in spiral galaxies. In the case of M60, the dust extinction is negligible. Then, only the calibration problem remains for M60. Note that the galaxies used for the calibration of the PNLF and SBF are mostly late-type galaxies, while a significant fraction of the galaxies used for the comparison of the PNLF and SBF distances are early-type galaxies (Ciardullo 2013). In the future, it is needed to check any possible difference in the calibration of the PNLF and SBF method between the late-type galaxies and early-type galaxies.

The result of this study is based on only one galaxy, therefore it may be too early to resolve the discrepancy between the PNLF distances and SBF distances. However, the result for M60 in this study will serve as a precious data point to understand the causes for the discrepancy.

### 4.2. Interaction between M60 and NGC 4647

NGC 4647, a spiral galaxy, is located only 2′6 (corresponding to a projected distance of 12 kpc) northwest from the center of M60 in the sky. This pair of galaxies is called Arp 116 and is a rare example of a combination of an elliptical galaxy and a spiral galaxy. The heliocentric radial velocity of NGC 4647 (1409 \(\pm\) 1 km s\(^{-1}\), NED) is only about 300 km s\(^{-1}\) larger than that of M60 (1110 \(\pm\) 5 km s\(^{-1}\), NED). Because of the projected proximity and the small radial velocity difference of M60 and NGC 4647, several studies investigated any possibility of tidal interaction between these two galaxies (de Grijs & Robertson 2006; Lanz et al. 2013; D’Abrusco et al. 2014; Mineo et al. 2014; Pota et al. 2015). However whether NGC 4647 is interacting with M60 or not is still controversial (de Grijs & Robertson 2006; Pota et al. 2015 and references therein).

Optical images of this pair of galaxies, displayed in Figure 1, show little evidence for any significantly distorted structures around each galaxy, although they are close to each other in the sky. This indicates two possibilities. First, the relative distance along the line of sight in the space between the two galaxies is so large that they are not interacting. Second, they are relatively close to each other in the space, but their interaction is weak. Recently, Pota et al. (2015) found, from the study of kinematics...
of the globular clusters in M60, no strong evidence to support
the interaction between M60 and NGC 4647. They suggested
that M60 and NGC 4647 may be only in the beginning stage of
interaction, if they are interacting, as suggested earlier by de
Grijs & Robertson (2006), who noted the presence of a weak
young blue stellar population in the northwest direction of M60
in the HST/ACS images of the central region.

Strongly interacting galaxies are known to show relatively
stronger mid-infrared (MIR) and far-infrared (FIR) emission than
weakly interacting galaxies, so the spectral energy distributions
(SEDs) of galaxies are useful to estimate the stage of interaction
(Lanz et al. 2013). Dopita et al. (2002) presented a five-stage
classification scheme to estimate the stage of galaxy interaction.
According to this scheme, weakly interacting galaxies (Stage 2)
show minimal morphological distortions, and moderately inter-
acting galaxies (Stage 3) show stronger morphological distortion
including often tidal tails (Lanz et al. 2013). Lanz et al. (2013)
suggested, from the SEDs of NGC 4647 and M60 based on UV
to FIR data, that this pair of galaxies is in the moderately
interacting stage.

We need to know a relative distance between M60 and NGC
4647 to conclude on the possibility of tidal interaction between
the two galaxies. Unfortunately, there is not any TRGB distance
to NGC 4647 yet. There are several estimates for the distance
to NGC 4647 based on deep F775W and F850LP images. This is the
first photometry of the resolved giant stars in M60. Primary
results in this study are summarized as follows.

1. The CMD of the resolved stars in M60 shows a

   distinguishable broad RGB. A TRGB is detected at
   F850LP_{TRGB} = 26.70 ± 0.06 mag in the luminosity
   function of the red giants. This value corresponds to
   F814W_{TRGB} = 27.13 ± 0.06 mag

   3. The TRGB distance modulus for M60 derived in this

   study is 0.3 mag larger than the mean PNLF distance
   values, and is 0.1 mag smaller than the SBF distance
   values. This indicates that the PNLF distances to M60
   reported in the literature have larger uncertainties than
   the suggested values.

2. We checked the relative distance between M60 and
   NGC 4647, a nearby spiral galaxy, to investigate any
   tidal interaction between the two galaxies. The TRGB
distance to M60 and the Tully–Fisher distance to NGC
   4647 are found to be similar within the errors. However,
   absence of any significantly distorted structures around
each galaxy indicates that the relative distance between
the two is not close enough to show strong tidal interaction.

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References

Alabi, A. B., Forbes, D. A., Romanowsky, A. J., et al. 2016, MNRAS, 460, 3838
Bellazzini, M., Ferraro, F. R., & Pancino, E. 2001, ApJ, 556, 635
Bird, S., Harris, W. E., Blakeslee, J. P., & Flynn, C. 2010, A&A, 524, A71
Blakeslee, J. P. 2012, Ap&SS, 341, 179
Blakeslee, J. P., Cantilo, M., Mei, S., et al. 2010, ApJ, 724, 657
Blakeslee, J. P., Jordán, A., Mei, S., et al. 2009, ApJ, 694, 556
Caldwell, N. 2006, ApJ, 651, 822
Cantiello, M., Biscardi, I., Brocato, E., & Raimondo, G. 2011, A&A, 532, A154
Cantiello, M., Grado, A., Blakeslee, J. P., et al. 2013, A&A, 552, A106
Ciardullo, M., Mcdermid, R. M., Alatalo, K., et al. 2013, MNRAS, 432, 1862
Ciardullo, R. 2012, Ap&SS, 341, 151
Ciardullo, R., in IAU Symp. 289, Advancing the Physics of Cosmic
Distances, ed. R. de Grijs (Cambridge: Cambridge Univ. Press), 247
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., et al. 2002, ApJ, 577, 31
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, ApJ, 339, 53
D’Abrusco, R., Fabbiano, G., Mineo, S., et al. 2014, ApJ, 783, 18
de Grijs, R., & Robertson, A. R. I. 2006, A&A, 460, 493
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., et al. 1991, Third
Reference Catalogue of Bright Galaxies (New York: Springer)
Dolphin, A. E. 2000, PASP, 112, 1383
Dopita, M. A., Pereira, M., Kewley, L. J., & Capaccioli, M. 2002, ApJS, 143, 47
Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, ApJS, 178, 89
Durrell, P. R., Williams, B. F., Ciardullo, R., et al. 2007, ApJ, 656, 746
Feldmeier, J. J., Jacoby, G. H., & Phillips, M. M. 2007, ApJ, 657, 76
Hwang, H. S., Lee, M. G., Park, H. S., et al. 2008, ApJ, 674, 869
Jacoby, G. H. 1989, ApJ, 339, 39
Jacoby, G. H., Ciardullo, R., & Ford, H. C. 1990, ApJ, 356, 332
Jang, I. S., & Lee, M. G. 2014, ApJ, 792, 52
Jang, I. S., & Lee, M. G. 2017a, ApJ, 835, 28
Jang, I. S., & Lee, M. G. 2017b, ApJ, 836, 74
Kost, J. E., Hook, R. N., & Stoehr, F. 2011, Proc. SPIE, 8127, 81270J
Lanz, L., Zezas, A., Brassington, N., et al. 2013, ApJ, 768, 90
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, 553
Lee, M. G., Hwang, H. S., Park, H. S., et al. 2008a, ApJ, 674, 857
Lee, M. G., & Jang, I. S. 2016, ApJ, 822, 70
Lee, M. G., Park, H. S., Kim, E., et al. 2008b, ApJ, 682, 135
Liu, C., Peng, E. W., Côté, P., et al. 2015, ApJ, 812, 34
Luo, B., Fabbiano, G., Strader, J., et al. 2013, ApJS, 204, 14
Makarov, D., Prugniel, P., Terekhova, N., Courtois, H., & Vauclair, I. 2014,
A&A, 570, A13
Mamon, G. A. 1989, A&A, 219, 98
Mamon, G. A. 2008, A&A, 486, 113
Mei, S., Blakeslee, J. P., Côte, P., et al. 2007, ApJ, 655, 144

5. Summary

We present photometry of the resolved stars in an outer field
of M60 based on deep F775W and F850LP images. This is the
first photometry of the resolved giant stars in M60. Primary
results in this study are summarized as follows.

1. The CMD of the resolved stars in M60 shows a

   distinguishable broad RGB. A TRGB is detected at
   F850LP_{TRGB} = 26.70 ± 0.06 mag in the luminosity
   function of the red giants. This value corresponds to
   F814W_{TRGB} = 27.13 ± 0.06 mag

2. From the magnitude of the TRGB, we derive a distance modulus,

   (m − M)_0 = 31.05 ± 0.07 (ran) ± 0.06 (sys)

   (the total error is ±0.09). The corresponding linear distance is
d = 16.23 ± 0.50 (ran) ± 0.42 (sys) Mpc (the
total error is ±0.65 Mpc).
Mineo, S., Fabbiano, G., D’Abrusco, R., et al. 2014, ApJ, 780, 132
Moore, M., Li, W., Filippenko, A. V., Chornock, R., & Foley, R. J. 2004, IAUC, 8286, 2
Neilson, E. H., Jr., & Tsvetanov, Z. I. 2000, ApJ, 536, 255
Nielsen, M. T. B., Voss, R., & Nelemans, G. 2012, MNRAS, 426, 2668
Pota, V., Brodie, J. P., Bridges, T., et al. 2015, MNRAS, 450, 1962
Rizzi, L., Tully, R. B., Makarov, D., et al. 2007, ApJ, 661, 815
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Seth, A. C., van den Bosch, R., Mieske, S., et al. 2014, Natur, 513, 398
Solanes, J. M., Sanchis, T., Salvador-Solé, E., Giovanelli, R., & Haynes, M. P. 2002, AJ, 124, 2440
Strader, J., Fabbiano, G., Luo, B., et al. 2012, ApJ, 760, 87
Strader, J., Seth, A. C., Forbes, D. A., et al. 2013, ApJL, 775, L6
Teodorescu, A. M., Méndez, R. H., Bernardi, F., et al. 2011, ApJ, 736, 65
Teodorescu, A. M., Méndez, R. H., Bernardi, F., Riffeser, A., & Kudritzki, R. P. 2010, ApJ, 721, 369
Tonry, J. L., Dressler, A., Blakeslee, J. P., et al. 2001, ApJ, 546, 681
Tonry, J. L., & Schneider, D. P. 1988, AJ, 96, 807
Tully, R. B., Courtois, H. M., Dolphin, A. E., et al. 2013, AJ, 146, 86
Tully, R. B., Rizzi, L., Shaya, E. J., et al. 2009, AJ, 138, 323
Wagner-Kaiser, R., Sarajedini, A., Dalcanton, J. J., Williams, B. F., & Dolphin, A. 2015, MNRAS, 451, 724