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THE TIP OF THE RED GIANT BRANCH DISTANCES TO TYPE IA SUPERNOVA HOST GALAXIES. II. M66 AND M96 IN THE LEO I GROUP

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ABSTRACT

M66 and M96 in the Leo I Group are nearby spiral galaxies hosting Type Ia Supernovae (SNe Ia). We estimate the distances to these galaxies from the luminosity of the tip of the red giant branch (TRGB). We obtain VI photometry of resolved stars in these galaxies from $F555W$ and $F814W$ images in the *Hubble Space Telescope* archive. From the luminosity function of these red giants we find the TRGB I-band magnitude to be $I_{\rm TRGB} = 26.20 \pm 0.03$ for M66 and 26.21 ± 0.03 for M96. These values yield distance modulus $(m-M)_0 = 30.12 \pm 0.03$(random)± 0.12(systematic) for M66 and $(m-M)_0 = 30.15 \pm 0.03$(random)± 0.12(systematic) for M96. These results show that they are indeed the members of the same group. With these results we derive absolute maximum magnitudes of two SNe (SN 1989B in M66 and SN 1998bu in M96). V-band magnitudes of these SNe Ia are $\sim$0.2 mag fainter than SN 2011fe in M101, the nearest recent SN Ia. We also derive near-infrared magnitudes for SN 1998bu. Optical magnitudes of three SNe Ia (SN 1989B, SN 1998bu, and SN 2011fe) based on TRGB analysis yield a Hubble constant, $H_0 = 67.6 \pm 1.5$(random) ± 3.7(systematic) km s^{-1} Mpc^{-1}. This value is similar to the values derived from recent WMAP9 results, $H_0 = 69.32 \pm 0.80$ km s^{-1} Mpc^{-1}. and from Planck results, $H_0 = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1}, but smaller than other recent determinations based on Cepheid calibration for SNe Ia luminosity, $H_0 = 74 \pm 3$ km s^{-1} Mpc^{-1}.

Subject headings: galaxies: distances and redshifts — galaxies: individual (M66, M96) — galaxies: stellar content — supernovae: general — supernovae: individual (SN 1989B, SN 1998bu)

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) are a powerful tool to investigate the expansion history of the universe, because their peak luminosity is as bright as a galaxy and is known as an excellent standard candle. Since the discovery of the acceleration of the universe based on the observations of SNe Ia, higher than ever accuracy of their peak luminosity is needed to investigate various problems in cosmology (Freedman & Madore 2010; Riess et al. 2011; Lee & Jang 2012; Tammann & Reindl 2013).

We started a project to improve the accuracy of the calibration of the peak luminosity of SNe Ia by measuring accurate distances to nearby resolved galaxies that host SNe Ia. We derive accurate distances to the SN Ia host galaxies using the method to measure the luminosity of the tip of the red giant branch (TRGB) (Lee et al. 1993). We presented the result of the first target, M101, a well-known spiral galaxy hosting SN 2011fe that is the nearest SN Ia since 1972 (Lee & Jang 2012 (Paper I)). This paper is the second of the series, presenting the results for M66 and M96 in the Leo I Group.

M66 (NGC 3627, SAB(s)b) and M96 (NGC 3368, SAB(rs)ab) are nearby bright spiral galaxies hosting SNe Ia: SN 1989B in M66 (Evans & McNaught 1989; Wells et al. 1994) and SN 1998bu in M96 (Villi et al. 1998; Suntzeff et al. 1999; Jha et al. 1999; Hernandez et al. 2000; Spyromilio et al. 2004). M66 has been host to other three SNe as well: SN II 1973R (Ciatti & Rosino 1977), SN imposter SN 1997bs (Van Dyk et al. 2000), and SN II-L 2009hd (Elias-Rosa et al. 2011).

They are considered to be the members of the compact Leo I Group that includes three subgroups: the Leo Triplet (M66, M65, and NGC 3628), the M96 Group (including M96 (NGC 3368), M95 (NGC 3351), and M105 (NGC 3379)), and the NGC 3607 Group (de Vaucouleurs 1975; Saha et al. 1999). The Leo I Group has played an important role as a stepping stone for calibration of the secondary distance indicators, because it includes both early and late type galaxies at the distance closer than the Virgo cluster and because it hosts SNe Ia. In particular M66 and M96 have been used as important calibrators for the absolute magnitudes of SNe Ia and the Tully-Fisher relation (Saha et al. 1999; Suntzeff et al. 1999; Saha et al. 2006; Jha et al. 2007; Hislop et al. 2011; Tammann & Reindl 2013).

Harris et al. (2007a) derived a value for the distance to the Leo I Group, $(m-M)_0 \approx 30.10 \pm 0.05$ (≈ 10.5 Mpc), from the mean of the known distances to five brightest galaxies in the group (M66, M95, M96, M105, NGC 3351 and NGC 3377). Often the member galaxy candidates without known distances are assumed to be at the same distance, but it is still important to derive a precise distance to each member galaxy candidate for investigating various aspects of the member galaxies.

Unfortunately recent estimates of the distances to M66 and M96 based on resolved stars show a large range (Hislop et al. 2011; Tammann & Reindl 2013). Saha et al. (1999) found 68 Cepheids in M66 from $F555W$ and $F814W$ images obtained with the *Hubble Space Telescope (HST)*/Wide Field Planetary Camera 2 (WFPC2) and derived a distance modulus of $(m-M)_0 =$

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30.22 ± 0.12 from the photometry of 25 good Cepheids. Later Cepheid estimates range from $(m-M)_0 = 29.70 \pm 0.07$ (Willick & Batra 2001) to 30.50 ± 0.09 (Saha et al. 2006), showing as much as 0.8 mag differences. On the other hand, Mould & Sakai (2009a) presented a distance modulus $(m-M)_0 = 29.82 \pm 0.10$ using the TRGB method from $F555W$ and $F814W$ images obtained with the HST/Advanced Camera for Surveys (ACS) . Furthermore Tully et al. (2009) presented an even smaller TRGB distance estimate, $(m-M)_0 = 29.60 \pm 0.09$. Thus there is a significant difference between the Cepheid distances and TRGB distances as well as among the estimates of each method.

In the case of M96, Tanvir et al. (1995) found 7 Cepheids from HST/WFPC2 $F555W$ and $F814W$ images and derived a distance modulus of $(m-M)_0 = 30.32 \pm 0.16$. Later Cepheid estimates showed a significant spread, ranging from $(m-M)_0 = 29.94 \pm 0.13$ (Willick & Batra 2001) to 30.42 ± 0.15 (Kochanek 1997). Surprisingly Mould & Sakai (2009b) presented a much smaller TRGB distance estimate $(m-M)_0 = 29.65 \pm 0.28$ derived from the HST images. Thus the difference between the Cepheid distances and TRGB distance is as much as 0.3 to 0.7 mag and the range of the Cepheid distances is about 0.4.

In this study we use the well-known TRGB method to estimate the distances to M66 and M96 from the images available in the HST archive. The TRGB method is an efficient and precise primary distance indicator for resolved galaxies so that it is an excellent tool for calibration of more powerful distance indicators such as SN Ia and Tully-Fisher relations (Lee et al. 1993; Sakai et al. 1996; Jang et al. 2012; Tammann & Reindl 2013). Section 2 describes how we derive photometry of the point sources in the images and §3 presents color-magnitude diagrams of the resolved stars in each galaxy, and derive distances to each galaxy using the TRGB method. We discuss implications of our results in §4, and summarizes primary results in the final section.

2. DATA REDUCTION

Table 1 lists the information of the HST/ACS images we used for the TRGB analysis in this study: $F555W$ and $F814W$ images of M66 and M96 (Proposal ID: 10433). We made drizzled images for each filter combining the flat fielded images in the HST archive using Tweakreg and AstroDrizzle task in DrizzlePac provided by the Space Telescope Science Institute (http://www.stsci.edu/hst/HST_overview/drizzlepac/). Total exposure times for $F555W$ and $F814W$ are, respectively, 2224 s and 8872 s for M66, and 2280 s and 9112 s for M96. In Figure 1 we illustrate the locations of the HST fields in the gray scale maps of i-band Sloan Digital Sky Survey images of M66 and M96. The HST fields cover the west region of each galaxy off from the galaxy center. Two known SNe Ia (SN 1989B and SN 1998bu) are located close to the center of each galaxy and are not covered by these images, as marked in Figure 1.

Instrumental magnitudes of point sources in the images were obtained using the DAOPHOT package in IRAF (Stetson 1994), as done for M101 in Lee & Jang (2012). Details are described in Lee & Jang (2012). Mean values for the aperture correction errors are 0.02 mag for both filters. The instrumental magnitudes were converted into the standard Johnson-Cousins VI magnitudes, using the information in Sirianni et al. (2005). The average errors for this transformation are 0.02 mag. We adopted the standard Johnson-Cousins VI magnitudes for transformation to compare our results with others in the literature and combine our results with those for other galaxies sometimes based on F606W images.

3. RESULTS

3.1. *Photometry of Resolved Stars*

The HST/ACS fields cover disk regions with spiral arms in each galaxy. We need to select resolved old red giants for the analysis of the TRGB method. Therefore we selected an outer region avoiding arms in each field, as marked by the hatched region in Figure 1. Thus chosen regions have the lowest sky background level in the images.

Color-magnitude diagrams (CMDs) of the resolved stars in the selected regions in M66 and M96 are plotted in Figure 2. It shows that most of the resolved stars in each galaxy are red giants belonging to the thick slanted feature, which is a red giant branch (RGB). The brightest part of the RGB is seen at $I \approx 26.2$ mag in each galaxy, which corresponds to the TRGB. We adopted the foreground reddening values, $E(B-V) = 0.028$ for M66 and 0.022 for M96 in Schlegel et al. (1998); Schlafly & Finkbeiner (2011). These values yield $A_I = 0.049$ and $E(V-I) = 0.040$ for M66 and $A_I = 0.038$ and $E(V-I) = 0.031$ for M96. We assumed that internal reddening for the old red giants is zero.

3.2. *TRGB Distance Measurement*

We estimated the distances to M66 and M96 from the photometry of the resolved stars using the TRGB method, as described in Lee & Jang (2012). Figure 3(a) and (c) plot the I-band luminosity functions of the red giants obtained counting the stars inside the box as marked in Figure 2. In Figure 3 an abrupt discontinuity is seen at $I \approx 26.2$ mag for each galaxy, which is also noticed in the CMDs. This matches the TRGB in each galaxy.

We performed a quantitative analysis of the TRGB measurement using the edge-detecting algorithm (Sakai et al. 1996; Méndez et al. 2002; Mouhcine et al. 2010). When the I-band luminosity function of the stars is given by $N(I)$ and σ_I is the mean photometric error, the edge-detection response function is given by $E(I)$ $(= N(I+\sigma_I) - N(I-\sigma_I))$. The values of the TRGB magnitudes were determined from the peak values of the edge-detection response function. Figure 3(b) and (d) illustrate the edge-detection response functions for M66 and M96, respectively. The edge-detection response function for each galaxy shows a strong peak at the position corresponding to the TRGB. We estimated the measurement errors for the TRGB magnitudes using bootstrap resampling method as described in Lee & Jang (2012). Thus estimated TRGB magnitudes are $I_{\rm TRGB} = 26.20 \pm 0.03$ for M66 and 26.21 ± 0.03 for M96, both of which are almost the same. We obtained a median color value of the TRGB from the color of the brightest part of the RGB: $(V-I)_{\rm TRGB} = 1.97 \pm 0.05$ for

TABLE 1
A Summary of *HST* Observations for M66 and M96

Target	R.A. (J2000.0)	Dec (J2000.0)	Instrument	Exposure time *F555W*	Exposure time *F814W*	Prop. ID.
M66	11 20 00.00	12 59 28.0	ACS/WFC	2224 s	8872 s	10433
M96	10 46 32.89	11 48 16.0	ACS/WFC	2280 s	9112 s	10433

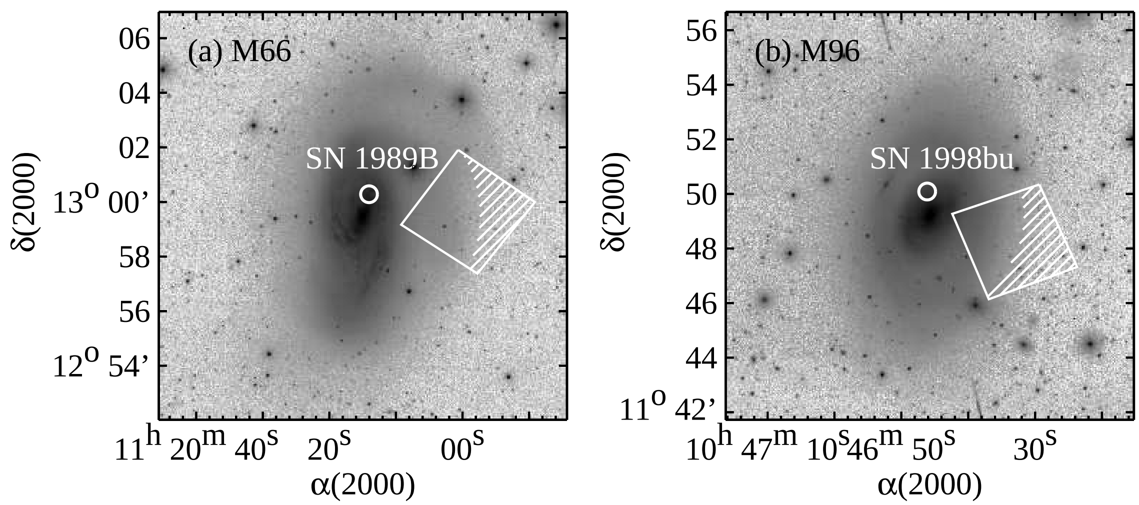

Fig. 1.— Finding charts for the *HST* fields of M66 (a) and M96 (b) (boxes). Gray scale maps represent *i*-band Sloan digital sky survey images. The hatched regions represent the regions used in the analysis for distance determination. Positions of SN 1989B and SN 1998bu are marked by circles.

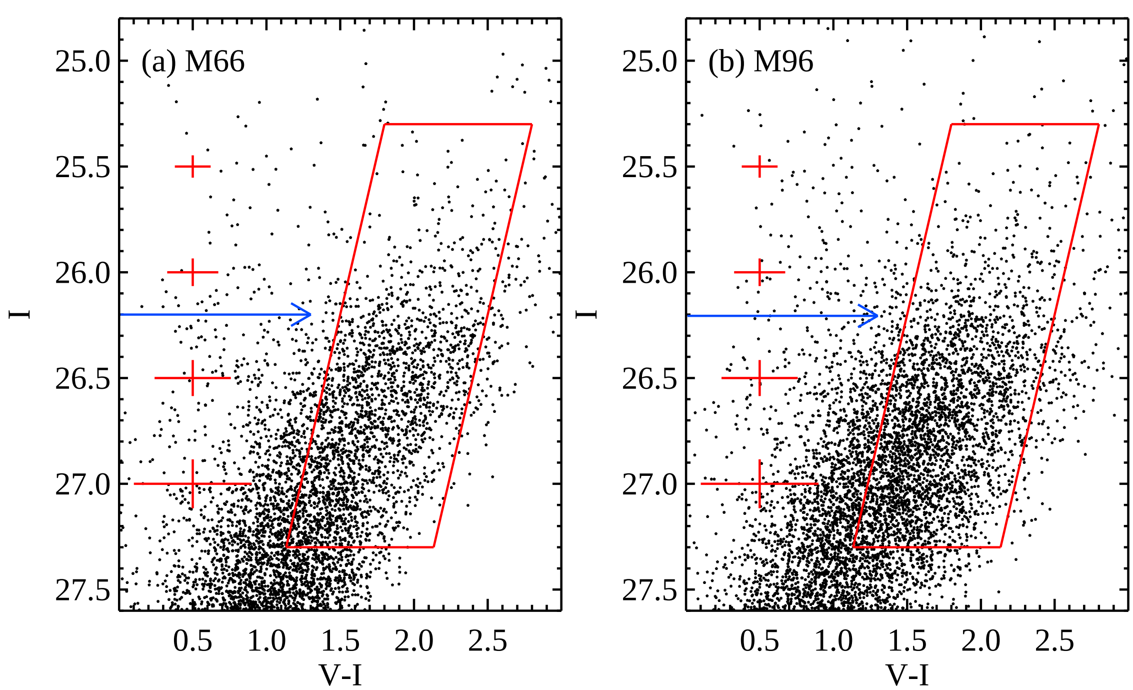

Fig. 2.— $I-(V-I)$ color-magnitude diagrams of the detected stars in the selected regions of M66 (a) and M96 (b). Boxes denote the boundary of the red giants used for distance determination. Arrows indicate the magnitudes of the TRGB. Mean photometric errors for given magnitude bins are plotted by error bars.

M66 and 1.93 ± 0.04 for M96. For calculating distance moduli from apparent TRGB magnitudes we adopted a relation Rizzi et al. (2007) derived: $M_{\rm I,TRGB} = -4.05(\pm 0.02) + 0.217(\pm 0.01)((V-I)_{0,TRGB} - 1.6)$.

After correction for foreground reddening, we derived distance modulus : $(m-M)_0 = 30.12 \pm 0.03$ for M66 and $(m-M)_0 = 30.15 \pm 0.03$ for M96 (where 0.03 is a measurement error). We derived a value of the systematic error to be 0.12, from the combination of the TRGB magnitude error, aperture correction error, and standard transformation error, as described in Lee & Jang (2012). Thus derived distance to these galaxies are $10.57 \pm 0.15 \pm 0.58$ Mpc for M66 and $10.72 \pm 0.15 \pm 0.59$ Mpc for M96. Our distance estimates for M66 and M96 are summarized in Table 2.

4. DISCUSSION

4.1. *Comparison with Previous Distance Estimates*

There are numerous previous estimates for the distances to M66 and M96 based on various methods (TRGB, Cepheids, Tully-Fisher relations, surface brightness fluctuation (SBF), planetary nebula luminosity functions (PNLFs), and SNe Ia), as listed in Tables 3 and 4. We compare our estimates for the distances to M66 and M96 with these previous estimates. Figure 4 shows a comparison of distance measurements for each galaxy in this study and previous studies. We derived a probability density curve for each measurement with a normalized Gaussian function centered at the distance modulus value with a width equal to the measurement error.

Comparison of the TRGB distances derived in this study and previous studies (Mould & Sakai 2009a; Tully et al. 2009) shows significant differences. Our distance estimate for M66 is 0.3 mag larger than that of Mould & Sakai (2009a) ($(m-M)_0 = 29.82 \pm 0.10$) and 0.5 mag larger than that of Tully et al. (2009) ($(m-M)_0 = 29.60 \pm 0.09$). In the case of M96, our distance estimate is 0.5 mag larger than that of Mould & Sakai (2009b) ($(m-M)_0 = 29.65 \pm 0.18$). These differences are explained in terms of the TRGB magnitude differences: the two previous studies derived much brighter magnitudes for the TRGB than this study. Mould & Sakai (2009a) and Tully et al. (2009) presented $I_{\rm TRGB} = 25.83$ and 25.56, respectively, for M66, which are, respectively, 0.37 mag and 0.64 mag brighter than the our value. Similarly Mould & Sakai (2009b) presented $I_{\rm TRGB} = 25.66$ for M96, which is 0.55 mag brighter than our value. What caused these differences is not clear, but the previous measurements might have been affected by younger stars in the disk of each galaxy. Note that we used only the stars in the arm-free regions in each galaxy to reduce the contamination due to younger stars for our analysis.

Our distance estimate is consistent with some of the previous estimates based on other distance indicators (Cepheids, Tully-Fisher relations, SBF, and SN Ia). However, the spread in the previous measurements for each method is significant and the errors for each measurement are mostly larger than ours. It is expected that our results will be useful for improving the calibration of these other distance indicators in the future.

4.2. *The Membership of the Leo I Group*

The distance estimates derived in this study show that M66 and M96 are at the same distance and that they are located at the same distance as the mean distance to the Leo I Group (Harris et al. 2007a). These confirm that M66 and M96 are indeed the members of the Leo I Group.

M96 is the brightest member of the Leo I Group. However it is not located at the center of the M96 Group. An E1 galaxy M105 resides at the center of the M96 Group, and M96 is $48'$ at the south-west of the group center. M96 has a large pseudo bulge (Nowak et al. 2010), and appears to be connected to a tidal feature extended out from the well-known giant HI ring surrounding a pair of M105 and NGC 3384 (SB0) (Schneider et al. 1983; Schneider 1989). Whether this giant gas ring around M105/NGC 3384 is primordial or formed via collision of disk galaxies (M105/NGC 3384 and M96) has been controversial (Thilker et al. 2009; Michel-Dansac et al. 2010). Precise distance estimates of M96 and M105/NGC 3384 will be useful to investigate the origin of this giant ring, because the relative distances (as well as velocities) are critical constraints for simulation models (Michel-Dansac et al. 2010).

Here we compare the distance to M96 with that of M105. Harris et al. (2007b) estimated the I-band magnitude of the TRGB for M105 to be $I_{TRGB} = 26.10 \pm 0.10$ from the HST/ACS $F606W$ and $F814W$ images of a field $630''$ west and $173''$ north of the galaxy center, and derived a distance modulus $(m-M)_0 = 30.10 \pm 0.16$ adopting the foreground reddening of $A_I = 0.05 \pm 0.02$ and the absolute TRGB magnitude given in Bellazzini et al. (2004), $M_{I,TRGB} = -4.05 \pm 0.12$. This value is nearly the same as the TRGB distance to M96 derived in this study, showing that M105 and M96 are at the same distance. The radial velocities of M96 and M105 are also very similar (897 ± 4 km s^{-1}and 911 ± 2 km s^{-1}, respectively), while they are $\sim$200 km s^{-1} larger than that of NGC 3384, 704 ± 2 km s^{-1}. These results indicate that the three galaxies (M96, M105, and NGC 3384) are close enough to interact with each other. This supports the collisional scenario that the giant gas ring was formed when M96 collided with NGC 3384/M105 (Michel-Dansac et al. 2010).

4.3. *The Calibration of the Absolute Magnitudes of SNe Ia and the Hubble Constant*

The distances to M66 and M96 derived in this study can be used to improve the calibration of the absolute magnitudes of SNe Ia. Tables 5 and 6 list, respectively, the V-band maximum magnitudes of SN 1989B and SN 1998bu derived in this study and previous studies (Gibson et al. 2000; Sandage et al. 2006; Tammann & Reindl 2013).

Recently Tammann & Reindl (2013) derived $M_{V,\rm max} = -19.45 \pm 0.15$ for SN 1989B and $M_{V,\rm max} = -19.38 \pm 0.16$ for SN 1998bu from the photometry in the literature (Suntzeff et al. 1999; Jha et al. 1999; Hernandez et al. 2000; Wells et al. 1994), adopting a mean TRGB distance of the Leo I Group, $(m-M)_0 = 30.39 \pm 0.10$. These values were obtained after correcting for the Galactic extinction, host galaxy extinction, and decline rates (Δm_{15}). These values will become fainter by 0.27 and 0.24 mag if the

TABLE 2
A Summary of TRGB Distance Measurements for M66 and M96

Parameter	M66	M96
TRGB magnitude, I_{TRGB}	26.20 ± 0.03	26.21 ± 0.03
TRGB color, $(V-I)_{TRGB}$	2.01 ± 0.05	1.96 ± 0.04
Foreground extinction at V, A_V	0.089	0.069
Foreground extinction at I, A_I	0.049	0.038
Foreground reddening, $E(V-I)$	0.040	0.031
Intrinsic TRGB magnitude $I_{0,TRGB}$	26.15 ± 0.03	26.17 ± 0.03
Intrinsic TRGB color, $(V-I)_{0,TRGB}$	1.97 ± 0.05	1.93 ± 0.04
Absolute TRGB magnitude, $M_{I,TRGB}$	-3.97 ± 0.12	-3.98 ± 0.12
Distance modulus, $(m-M)_0$	$30.12 \pm 0.03 \pm 0.12$	$30.15 \pm 0.03 \pm 0.12$
Distance	$10.57 \pm 0.15 \pm 0.58$	$10.72 \pm 0.15 \pm 0.59$

TABLE 3
A List of Distance Measurements for M66

ID	Reference	Method	Distance Modulus	Remarks
1	Pierce (1994)	Tully-Fisher	29.40 ± 0.30	
2	Russell (2002)	Tully-Fisher	30.10 ± 0.09	I band calibration
3		Tully-Fisher	30.07 ± 0.06	B band calibration
4	Tully et al. (2009)[a]	Tully-Fisher	29.67 ± 0.35	
5	Ciardullo et al. (2002)	PNLF[b]	29.99 ± 0.08	N(PNe)=40
6	Mueller & Hoeflich (1994)	SN Ia (Opt)	29.60 ± 0.05	
7	Reindl et al. (2005)	SN Ia (Opt)	30.50 ± 0.14	$H_0 = 60.0$ km s^{-1} Mpc^{-1}
8	Jha et al. (2007)	SN Ia (Opt)	30.04 ± 0.14	$H_0 = 65.0$ km s^{-1} Mpc^{-1}
9	Takanashi et al. (2008)	SN Ia (Opt)	30.89 ± 0.17	$H_0 = 70.8$ km s^{-1} Mpc^{-1}
10	Saha et al. (1999)	Cepheids (LMC)	30.22 ± 0.12	N(Cep)=25, $(m-M)_{0,\mathrm{LMC}} = 18.50$
11	Gibson et al. (2000)	Cepheids (LMC)	30.15 ± 0.08	N(Cep)=21, $(m-M)_{0,\mathrm{LMC}} = 18.50$
12		Cepheids (LMC)	30.06 ± 0.17	N(Cep)=17, $(m-M)_{0,\mathrm{LMC}} = 18.50$
13	Freedman et al. (2001)	Cepheids (LMC)	30.01 ± 0.15	N(Cep)=16, $(m-M)_{0,\mathrm{LMC}} = 18.50$
14		Cepheids (LMC)	29.86 ± 0.08	N(Cep)=16, $(m-M)_{0,\mathrm{LMC}} = 18.22$
15		Cepheids (LMC)	29.88 ± 0.08	N(Cep)=35, $(m-M)_{0,\mathrm{LMC}} = 18.50$
16		Cepheids (LMC)	29.71 ± 0.08	N(Cep)=35, $(m-M)_{0,\mathrm{LMC}} = 18.22$
17	Gibson & Stetson (2001)	Cepheids (LMC)	29.94 ± 0.17	N(Cep)=17, $(m-M)_{0,\mathrm{LMC}} = 18.45$
18		Cepheids (LMC)	29.79 ± 0.17	N(Cep)=17, $(m-M)_{0,\mathrm{LMC}} = 18.45$
19	Willick & Batra (2001)	Cepheids (LMC)	29.70 ± 0.07	N(Cep)=36, $(m-M)_{0,\mathrm{LMC}} = 18.50$
20	Dolphin & Kennicutt (2002)	Cepheids (LMC)	30.09 ± 0.10	N(Cep)=28, $(m-M)_{0,\mathrm{LMC}} = 18.50$
21		Cepheids (LMC)	30.03 ± 0.11	N(Cep)=28, $(m-M)_{0,\mathrm{LMC}} = 18.50$
22		Cepheids (LMC)	29.97 ± 0.09	N(Cep)=28, $(m-M)_{0,\mathrm{LMC}} = 18.50$
23	Paturel et al. (2002)	Cepheids (MW)	29.80 ± 0.06	N(Cep)=25
24		Cepheids (MW)	29.77 ± 0.07	N(Cep)=25
25	Kanbur et al. (2003)	Cepheids (MW)	30.31 ± 0.08	N(Cep)=25
26		Cepheids (MW)	30.24 ± 0.08	N(Cep)=25
27		Cepheids (MW)	30.21 ± 0.08	N(Cep)=25
28		Cepheids (LMC)	30.24 ± 0.08	N(Cep)=25, $(m-M)_{0,\mathrm{LMC}} = 18.50$
29		Cepheids (LMC)	30.16 ± 0.08	N(Cep)=25, $(m-M)_{0,\mathrm{LMC}} = 18.50$
30		Cepheids (LMC)	30.13 ± 0.08	N(Cep)=25, $(m-M)_{0,\mathrm{LMC}} = 18.50$
31		Cepheids (LMC)	30.13 ± 0.08	N(Cep)=25, $(m-M)_{0,\mathrm{LMC}} = 18.50$
32	Saha et al. (2006)	Cepheids (LMC)	30.50 ± 0.09	N(Cep)=22, $(m-M)_{0,\mathrm{LMC}} = 18.50$
33	Tully et al. (2009)[a]	TRGB	29.60 ± 0.09	$I_{TRGB} = 25.56, M_{\mathrm{I,TRGB}} = -4.10$
34	Mould & Sakai (2009a)	TRGB	29.82 ± 0.10	$I_{TRGB} = 25.83, M_{\mathrm{I,TRGB}} = -4.05$
35	This study	TRGB	30.12 ± 0.03	$I_{TRGB} = 26.20, M_{\mathrm{I,TRGB}} = -3.97$

[a] The Extragalactic Distance Database (EDD) (Tully et al. 2009).
[b] The Planetary Nebula Luminosity Function (PNLF).

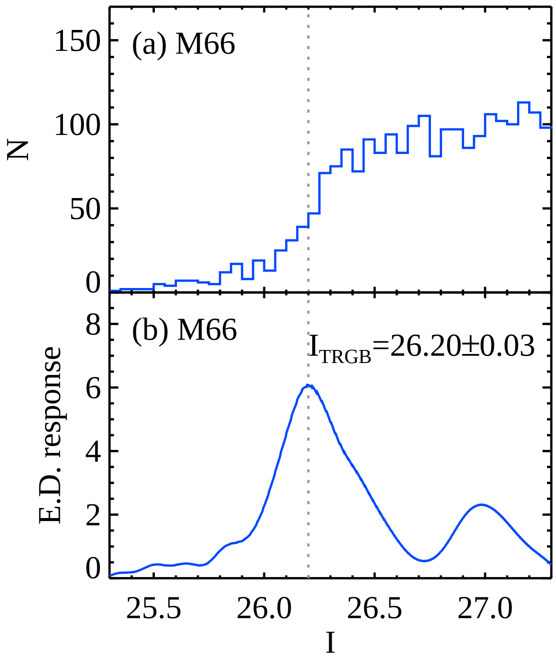

FIG. 3.— (a) and (c) denote I-band luminosity functions of the red giants in the selected regions of M66 and M96, respectively. (b) and (d) plot corresponding edge-detection responses ($E(I)$) for M66 and M96, respectively. Note that (b) and (d) show clearly a dominant single peak for each galaxy at the magnitude corresponding to the TRGB position (dotted lines).

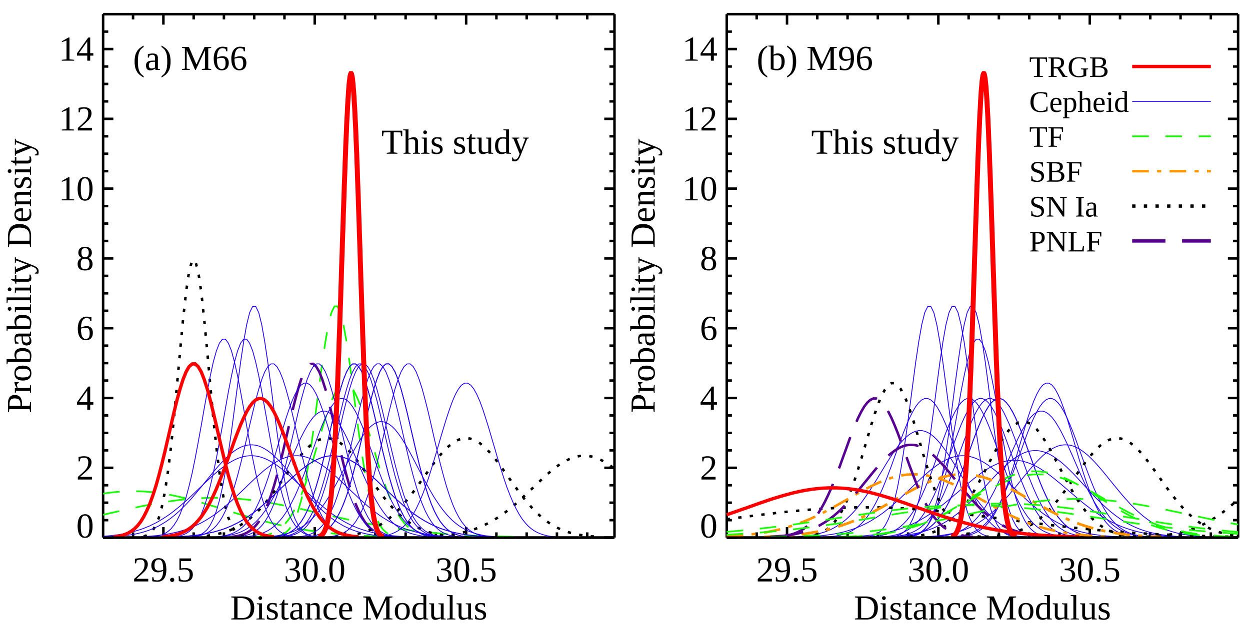

FIG. 4.— Comparison of the distance measurements for M66 (a) and M96 (b) derived in this study and previous studies based on the TRGB (thick solid lines), Cepheids (thin solid lines), Tully-Fisher relations (dashed lines), SBF (dot-dashed lines), SN Ia (dotted lines) and PNLF (long-dashed lines). A probability density curve for each measurement was derived from a Gaussian function centered at the distance modulus value with a width equal to the measurement error.

TABLE 4
A List of Distance Measurements for M96

ID	Reference	Method	Distance Modulus	Remarks
1	Russell (2002)	Tully-Fisher	30.32± 0.21	B band calibration
2		Tully-Fisher	30.33± 0.22	I band calibration
3	Springob et al. (2009)	Tully-Fisher	30.10± 0.43	
4		Tully-Fisher	30.21± 0.41	
5	Tully et al. (2009)[a]	Tully-Fisher	30.46± 0.36	
6	Feldmeier et al. (1997)	PNLF[b]	29.91± 0.15	N(PNe)=74
7	Ciardullo et al. (2002)	PNLF[b]	29.79± 0.10	N(PNe)=74
8	Reindl et al. (2005)	SN Ia (Opt)	30.59± 0.14	$H_0 = 60.0$ km s^{-1} Mpc^{-1}
9	Jha et al. (2007)	SN Ia (Opt)	30.28± 0.12	$H_0 = 65.0$ km s^{-1} Mpc^{-1}
10	Takanashi et al. (2008)	SN Ia (Opt)	31.20± 0.17	$H_0 = 70.8$ km s^{-1} Mpc^{-1}
11	Wood-Vasey et al. (2008)	SN Ia (NIR)	29.76± 0.46	$H_0 = 72.0$ km s^{-1} Mpc^{-1}
12	Mandel et al. (2009)	SN Ia (NIR)	29.85± 0.09	$H_0 = 72.0$ km s^{-1} Mpc^{-1}
13	Ajhar et al. (2001)	SBF[c]	30.08± 0.22	
14	Tonry et al. (2001)	SBF[c]	30.08± 0.22	
15	Jensen et al. (2003)	SBF[c]	29.92± 0.22	
16	Tanvir et al. (1995)	Cepheids (LMC)	30.32± 0.16	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
17	Kochanek (1997)	Cepheids (LMC)	30.14± 0.10	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
18		Cepheids (LMC)	30.42± 0.15	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
19	Tanvir et al. (1999)	Cepheids (LMC)	30.13± 0.07	N(Cep)=16, $(m-M)_{0,\mathrm{LMC}} = 18.50$
20		Cepheids (LMC)	30.25± 0.18	N(Cep)=16, $(m-M)_{0,\mathrm{LMC}} = 18.50$
21	Kelson et al. (2000)	Cepheids (LMC)	30.37± 0.10	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
22	Gibson et al. (2000)	Cepheids (LMC)	30.20± 0.10	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
23		Cepheids (LMC)	30.36± 0.09	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
24	Willick & Batra (2001)	Cepheids (LMC)	29.94± 0.13	N(Cep)=11, $(m-M)_{0,\mathrm{LMC}} = 18.50$
25	Gibson & Stetson (2001)	Cepheids (LMC)	29.96± 0.10	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
26		Cepheids (LMC)	30.10± 0.10	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.50$
27	Freedman et al. (2001)	Cepheids (LMC)	29.97± 0.06	N(Cep)=9, $(m-M)_{0,\mathrm{LMC}} = 18.22$
28		Cepheids (LMC)	30.11± 0.06	N(Cep)=9, $(m-M)_{0,\mathrm{LMC}} = 18.50$
29		Cepheids (LMC)	29.95± 0.08	N(Cep)=11, $(m-M)_{0,\mathrm{LMC}} = 18.22$
30		Cepheids (LMC)	30.10± 0.08	N(Cep)=11, $(m-M)_{0,\mathrm{LMC}} = 18.50$
31	Paturel et al. (2002)	Cepheids (MW)	30.05± 0.06	N(Cep)=7
32		Cepheids (MW)	30.17± 0.10	N(Cep)=7
33	Saha et al. (2006)	Cepheids (LMC)	30.34± 0.11	N(Cep)=7, $(m-M)_{0,\mathrm{LMC}} = 18.54$
34	Mould & Sakai (2009b)	TRGB	29.65± 0.28	$I_{TRGB} = 25.66, M_{\mathrm{I,TRGB}} = -4.04$
35	This study	TRGB	30.15± 0.03	$I_{TRGB} = 26.21, M_{\mathrm{I,TRGB}} = -3.98$

[a] The Extragalactic Distance Database (EDD) (Tully et al. 2009).
[b] The Planetary Nebula Luminosity Function (PNLF).
[c] The Surface Brightness Fluxuation (SBF).

TRGB distances to M66 and M96 derived in this study are used: $M_{V,\max} = -19.18 \pm 0.11$ for SN 1989B and -19.14 ± 0.12 for SN 1998bu. Other previous estimates (Gibson et al. 2000; Sandage et al. 2006) are affected in the similar way, yielding $M_{V,\max} = -19.46 \pm 0.17$ for SN 1989B and -19.38 ± 0.11 for SN 1998bu in Gibson et al. (2000), and $M_{V,\max} = -19.17 \pm 0.06$ for SN 1989B and -19.11 ± 0.06 for SN 1998bu in Sandage et al. (2006).

SN 2011fe in M101 is the nearest recent SN Ia with modern photometry so that it is an excellent object for calibration of SNe Ia. Lee & Jang (2012) derived maximum magnitudes of SN 2011fe from the photometry in the literature, adopting a new TRGB distance derived from the weighted mean of nine fields in M101, $M_{V,\max} = -19.38 \pm 0.05(\mathrm{random}) \pm 0.12(\mathrm{systematic})$. Thus V-band magnitudes of SN 1989B and SN 1998bu are ~ 0.2 mag fainter than that of SN 2011fe. This difference is similar to the dispersion of the absolute magnitudes of SNe Ia, 0.14 (Tammann & Reindl 2013). It is noted that the internal extinction for SN 2011fe is known to be negligible, $A_V = 0.04$ (Patat et al. 2011), while those for SN 1989B and 1998bu are not, as listed in Tables 7 and 8, respectively. The values for A_V derived in the previous studies range from 0.82 ± 0.08 to 1.33 ± 0.14 for SN 1989B and from 0.74 ± 0.11 to 1.06 ± 0.11 for SN 1998bu (Reindl et al. 2005; Wang et al. 2006; Jha et al. 2007; Tammann & Reindl 2013). Therefore the errors due to internal extinction for SN 1989B and SN 1998bu are expected to be larger than that for SN 2011fe. Further studies to derive better estimates for internal extinction for both SNe are needed in the future.

Near-infrared (NIR) photometry of SN 1998bu in M96 is available in the literature so that SN 1998bu plays as one of the important calibrators for NIR magnitudes of SNe Ia. Tammann & Reindl (2013) derived JHK_s maximum magnitudes at each band of SN 1998bu from the previous photometry (Jha et al. 1999; Suntzeff et al. 1999; Hernandez et al. 2000; Wood-Vasey et al. 2008) : $J = 11.55\pm0.03$, $H = 11.59\pm0.03$, and $K_s = 11.42\pm0.03$. They adopted a value for internal extinction of $A_V = 0.74 \pm 0.11$. Corresponding extinctions in NIR bands are $A_J = 0.19 \pm 0.03$, $A_H = 0.12 \pm 0.02$, and $A_{K_S} = 0.08 \pm 0.01$. If we apply internal extinctions presented above and adopt our new TRGB distance, we obtain NIR absolute magnitudes of SN 1998bu : $M_{J,\rm max} = -18.79\pm0.05$, $M_{H,\rm max} = -18.68 \pm 0.05$, and $M_{K_s,\rm max} = -18.81 \pm 0.04$. Lee & Jang (2012) derived JHK_s magnitudes of SN 2011fe in M101 from the photometry in Matheson et al. (2012), adopting a new TRGB distance they derived: $M_{J,\rm max} = -18.79 \pm 0.04(\rm random) \pm 0.12(\rm systematic)$, $M_{H,\rm max} = -18.55\pm0.04(\rm random)\pm0.12(\rm systematic)$, and $M_{K_s,\rm max} = -18.66 \pm 0.05(\rm random) \pm 0.12(\rm systematic)$. Thus absolute J magnitude of SN 1998bu is the same as that of SN 2011fe, while H, K_s magnitudes of SN 1998bu are $\sim$ 0.14 mag brighter than those of SN 2011fe. We derive weighted mean values of SN 1989bu and SN 2011fe from these: $M_{J,\rm max} = -18.79 \pm 0.03$, $M_{H,\rm max} = -18.60 \pm 0.03$, and $M_{K_s,\rm max} = -18.75 \pm 0.03$. It is noted that these values are 0.2 $\sim$ 0.4 mag brighter than recent calibrations of the NIR magnitudes for SNe Ia available in the literature (Krisciunas et al. 2004; Folatelli et al. 2010; Barone-Nugent et al. 2012; Kattner et al. 2012). Recently several calibrations of the NIR absolute magnitudes of SNe Ia were published, but they show a large spread with $\sim$ 0.2 mag differences (Wood-Vasey et al. 2008; Folatelli et al. 2010; Burns et al. 2011; Mandel et al. 2011; Kattner et al. 2012; Barone-Nugent et al. 2012; Matheson et al. 2012). Further studies are needed to understand these large differences in the NIR magnitudes of SNe Ia.

The relations between the Hubble constant and the absolute magnitude of SNe Ia are given by log $H_0 = 0.2M_{V,max} + 5 + (0.688 \pm 0.004)$ in Reindl et al. (2005) or by the equations (2) and (4) in Gibson et al. (2000). Using these relations we derive the Hubble constant : $H_0 = 69.1 \pm 3.2$(random) km s^{-1} Mpc^{-1}for SN 1989B, $H_0 = 71.0 \pm 2.6$(random) km s^{-1} Mpc^{-1}for SN 1998bu, and $H_0 = 65.0 \pm 2.1$(random) km s^{-1} Mpc^{-1}for SN 2011fe. A weighted mean of these three measurement is $H_0 = 67.6 \pm 1.5$(random) $\pm$ 3.7(systematic) km s^{-1} Mpc^{-1}. Note that this value for the Hubble constant is similar to the recent estimates based on the cosmic microwave background radiation maps in WMAP9 data, $H_0 = 69.32 \pm 0.80$ km s^{-1} Mpc^{-1}(Bennett et al. 2012) and Planck data $H_0 = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1}(Planck Collaboration et al. 2013), but smaller than other recent determinations based on Cepheid calibration for SNe Ia luminosity, $H_0 = 74\pm3$ km s^{-1} Mpc^{-1} (Riess et al. 2011; Freedman et al. 2012) .

5. SUMMARY

We present VI photometry of the resolved stars in two spiral galaxies M66 and M96 that host SNe Ia in the Leo I Group, derived from HST/ACS $F555W$ and $F814W$ images. Then we estimate the distances to these two galaxies applying the TRGB method to this photometry. We summarize main results in the following.

- Most of the resolved stars in the selected regions of M66 and M96 are red giants, allowing us to determine the distances to these galaxies.

- The I-band magnitudes of the TRGB are found to be $I_{\rm TRGB} = 26.20 \pm 0.03$ for M66 and 26.21 ± 0.03 for M96. These TRGB magnitudes yield distance modulus $(m - M)_0 = 30.12 \pm 0.03(\rm random) \pm 0.12(\rm systematic)$ for M66 and $(m - M)_0 = 30.15 \pm 0.03(\rm random) \pm 0.12(\rm systematic)$ for M96. This result shows that M66 and M96 are the members of the same group.

- The absolute maximum magnitudes of the SNe Ia are derived from the previous photometry and the distance measurement in this study, as listed in Tables 5 and 6. Similarly we derive NIR magnitudes for SN 1998bu: $M_{J,\rm max} = -18.79\pm0.05$, $M_{H,\rm max} = -18.68 \pm 0.05$, and $M_{K_s,\rm max} = -18.81 \pm 0.04$.

- Combining the results for SN 1989B and SN 1998bu with those for SN 2011fe in M101 based on the same method given in Lee & Jang (2012), we obtain an estimate of the Hubble constant, $H_0 = 67.6 \pm 1.5 \pm 3.7$ km s^{-1} Mpc^{-1}.

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TABLE 5
A Summary of Optical Luminosity Calibrations for SN 1989B in M66

ID	References	$(m-M)_0$	$V_{corr}{}^a$	$M_V{}^a$	$H_0[km/s/Mpc]$
(1)	Tammann & Reindl (2013)	30.39 ± 0.10	10.94 ± 0.11	-19.45 ± 0.15	62.8 ± 4.3
(2)	Gibson et al. (2000)	30.06 ± 0.17	10.66 ± 0.16^b	-19.40 ± 0.24^b	68.9 ± 7.5
(3)	Sandage et al. (2006)	30.50 ± 0.10	10.95 ± 0.05	-19.55 ± 0.11	60.0 ± 3.1
(4)	This study	30.12 ± 0.03	Tammann & Reindl (2013)	-19.18 ± 0.11	71.1 ± 3.8
(5)	This study	30.12 ± 0.03	Gibson et al. (2000)	-19.46 ± 0.17^b	67.1 ± 5.2
(6)	This study	30.12 ± 0.03	Sandage et al. (2006)	-19.17 ± 0.06	71.4 ± 2.0
(7)	This study	30.12 ± 0.03	Straight mean of (4) and (5)		69.1 ± 3.2
(8)	This study	30.12 ± 0.03	Weighted mean of (4) and (5)		69.7 ± 3.1

[a] Corrected for the Galactic extinction, host galaxy extinction and decline rate (Δm_{15}).
[b] We applied decline rate (Δm_{15}) correction using equation (21) of Phillips et al. (1999).

TABLE 6
A Summary of Optical Luminosity Calibrations for SN 1998bu in M96

ID	References	$(m-M)_0$	$V_{corr}{}^a$	$M_V{}^a$	$H_0[km/s/Mpc]$
(1)	Tammann & Reindl (2013)	30.39 ± 0.10	11.01 ± 0.12	-19.38 ± 0.16	64.9 ± 4.7
(2)	Gibson et al. (2000)	30.20 ± 0.10	10.77 ± 0.11^b	-19.43 ± 0.15^b	68.0 ± 4.7
(3)	Sandage et al. (2006)	30.34 ± 0.11	11.04 ± 0.05	-19.30 ± 0.12	67.3 ± 3.8
(4)	This study	30.15 ± 0.03	Tammann & Reindl (2013)	-19.14 ± 0.12	72.4 ± 3.9
(5)	This study	30.15 ± 0.03	Gibson et al. (2000)	-19.38 ± 0.11^b	69.6 ± 3.6
(6)	This study	30.15 ± 0.03	Sandage et al. (2006)	-19.11 ± 0.06	73.5 ± 2.1
(7)	This study	30.15 ± 0.03	Straight mean of (4) and (5)		71.0 ± 2.6
(8)	This study	30.15 ± 0.03	Weighted mean of (4) and (5)		70.9 ± 2.6

[a] Same as Table 5.
[b] Same as Table 5.

TABLE 7
A Summary of Internal Extinction Values for SN 1989B in M66

References	$E(B-V)$	A_V	R_V	Remarks
Suntzeff et al. (1999)	0.37 ± 0.03	1.15 ± 0.09	3.1	BVI
Jha et al. (2007)	0.47 ± 0.07	1.33 ± 0.14	2.86 ± 0.29	$UBVRI$
Wang et al. (2006)	0.42 ± 0.06	0.97 ± 0.14	2.30 ± 0.11	$UBVI$
Reindl et al. (2005) & Tammann & Reindl (2013)	0.31 ± 0.03	0.82 ± 0.08	2.65 ± 0.15	BVI

TABLE 8
A Summary of Internal Extinction Values for SN 1998bu in M96

References	$E(B-V)$	A_V	R_V	Remarks
Suntzeff et al. (1999)	0.34 ± 0.03	1.05 ± 0.09	3.1	BVI
Jha et al. (2007)	0.34 ± 0.05	1.06 ± 0.11	3.13 ± 0.36	$UBVRI$
Wang et al. (2006)	0.36 ± 0.04	0.83 ± 0.10	2.30 ± 0.11	$UBVI$
Reindl et al. (2005) & Tammann & Reindl (2013)	0.28 ± 0.04	0.74 ± 0.11	2.65 ± 0.15	BVI

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