Further Evidence for Significant Luminosity Evolution in Supernova Cosmology

Young-Wook Lee1,2, Chul Chung1,2, Yijung Kang3, and M. James Jee1,4

1 Department of Astronomy, Yonsei University, Seoul 03722, Republic of Korea; ywlee@yonsei.ac.kr, chulchung@yonsei.ac.kr
2 Center for Galaxy Evolution Research, Yonsei University, Seoul 03722, Republic of Korea
3 Gemini Observatory/NSFs NOIRLab, Casilla 603, La Serena, Chile
4 Department of Physics, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

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Abstract

Supernova (SN) cosmology is based on the assumption that the corrected luminosity of SNe Ia would not evolve with redshift. Recently, our age dating of stellar populations in early-type host galaxies (ETGs) from high-quality spectra has shown that this key assumption is most likely in error. It has been argued though that the age–Hubble residual (HR) correlation from ETGs is not confirmed from two independent age data sets measured from multiband optical photometry of host galaxies of all morphological types. Here we show, however, that one of the data sets is based on highly uncertain and inappropriate luminosity-weighted ages derived, in many cases, under serious template mismatch. The other data set employs more reliable mass-weighted ages, but the statistical analysis involved is affected by regression dilution bias, severely underestimating both the slope and significance of the age–HR correlation. Remarkably, when we apply regression analysis with a standard posterior sampling method to this data set comprising a large sample (N = 102) of host galaxies, very significant (>99.99%) correlation is obtained between the global population age and HR with the slope (−0.047 ± 0.011 mag Gyr−1) highly consistent with our previous spectroscopic result from ETGs. For the local age of the environment around the site of SNe, a similarly significant (>99.96%) correlation is obtained with a steeper slope (−0.057 ± 0.016 mag Gyr−1). Therefore, the SN luminosity evolution is strongly supported by the age dating based on multiband optical photometry and can be a serious systematic bias in SN cosmology.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); Observational cosmology (1146); Dark energy (351)

1. Introduction

The inference of dark energy in supernova (SN) cosmology is based on the assumption that the SN luminosity, after empirical standardization, would not evolve with redshift (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). As recognized by early investigators (see Figure 3 of Schmidt et al. 1998; see also Riess et al. 1998 and Perlmutter et al. 1999), this key assumption can be best tested at low-z by looking for any correlation between the population age of a host galaxy and the Hubble residual (HR) of SNe. While the correlations between HR and host galaxy properties, such as stellar mass and star formation rate, are now well established (e.g., Kelly et al. 2010; Sullivan et al. 2010; Rigault et al. 2015; Kim et al. 2018), there is, however, a paucity of literature on robust measurements of stellar population ages for host galaxies. Recently, Kang et al. (2020) have obtained the direct and reliable estimates of population ages for a sample of local early-type host galaxies (ETGs) from exceptionally high-quality (signal-to-noise ratio ~175) spectra. Based on this new age data set, we found a correlation between population age and HR which indicates a nonnegligible luminosity evolution in SN cosmology. While this result is based on a sample of ETGs, there is no theoretical reason that the age–HR correlation observed in ETGs should not extend to other types of host galaxies. Nevertheless, since SNe Ia are discovered in all morphological types of galaxies, it is important to check whether this correlation is confirmed by a larger sample of host galaxies comprising all morphological types.

Rose et al. (2020) have claimed, however, that this age–HR slope obtained from ETGs is not confirmed from the two independent age data sets measured from multiband optical photometry of host galaxies of all morphological types. Based on this result, they argued that there is no evidence for SN Ia luminosity evolution. This ongoing debate further underscores that the age–HR slope would determine the significance of the luminosity evolution and, therefore, the validity of the key assumption in SN cosmology. Because of its important implication for the inference of dark energy from SN cosmology, the origin of this apparent disparity between Kang et al. (2020) and Rose et al. (2020) must be investigated thoroughly. The purpose of this paper is to show that, when the regression analysis of the Rose et al. (2020) data set is performed in a consistent and standard manner, very significant age–HR correlation is also obtained from a large sample of host galaxies comprising all morphological types with the slope highly consistent with our previous spectroscopic result from ETGs.

2. Reexamining Stellar Population Ages from Multiband Optical Photometry

One of the two age data sets employed by Rose et al. (2020, their Figure 3) originates from a low-z host galaxy sample from Jones et al. (2018). Jones et al. (2018) used the Pan-STARRS grizy and Sloan Digital Sky Survey (SDSS) u band photometry together with the code Z-PEG (Le Borgne & Rocca-Volmerange 2002), which was originally designed to estimate photometric redshift, but can also be used to derive other parameters including luminosity-weighted age, if properly employed. However, neither Rose et al. (2020) nor Jones et al. (2018) provide the age data and their uncertainties. Without the crucial error bars for ages in Figure 3 of Rose et al. (2020), it is impossible to assess the validity of their ages and
the statistical significance of their claim derived from these ages.

Therefore, in an effort to investigate the reliability of their ages, we have selected 13 ETGs by cross-matching the Jones et al. (2018) sample with the Kang et al. (2020) ETG sample for which reliable estimates for ages are available from high-quality spectra. For this ETG subsample, we have reenacted the procedures adopted by Jones et al. (2018) by deriving ages using Z-PEG and the same ugrizy photometric data. The redshift and morphological classification for this low-z sample was adopted from the NASA Extragalactic Database as listed in Kang et al. (2020). Out of these 13 ETGs in common with Jones et al. (2018), we found catastrophic spectral energy distribution (SED) template mismatches ($\chi^2 = 20$–254; rms error $\approx 1.15$ mag) for six galaxies, and therefore the derived ages of these galaxies should be highly uncertain, if not meaningless. The origin for this mismatch is not clearly identified, seriously questioning the validity of ages for a significant fraction of galaxies in the Jones et al. (2018) sample. For the remaining seven ETGs, we obtained the ages with $\chi^2 < 20$ (rms error $\approx 0.11$ mag), but the Z-PEG derived ages are still underestimated by $\approx 3$ Gyr compared to the spectroscopic ages derived by Kang et al. (2020), illustrating the well-known limitation of the luminosity-weighted ages from multiband optical photometry (see, e.g., Lee et al. 2007; Walcher et al. 2011).

For galaxies with ongoing or recent star formation (most cases in the Jones et al. 2018 sample), the luminosity-weighted age derived from the photometric SED would be further biased toward the younger age. This is because even a small fraction of very young stars in a galaxy can significantly affect its SED (see Lee et al. 2007; Gupta et al. 2011). The majority of stellar populations in such galaxies can still be markedly older than the determined mean age. That the ages of Jones et al. (2018) are highly uncertain and underestimated can also be assessed from a severe internal inconsistency in Rose et al. (2020) between their Figures 2 and 3. Figure 2 of Rose et al. (2020) shows the age distribution of host galaxies based on more reliable mass-weighted ages of Rose et al. (2019), which has a mean of $\approx 5$ Gyr at $z = 0.14$ ($\approx 5.7$ Gyr at $z = 0.0$). This should be compared to the age distribution in their Figure 3 based on the Jones et al. (2018) data set, which has a mean of only $\approx 2.3$ Gyr at the local universe. Therefore, when the population age is derived from photometric SED, the luminosity-weighted age is not appropriate for the present study requiring the true average age of stellar populations. Instead, we need carefully measured mass-weighted age which is more relevant to the SN progenitor age in a host galaxy (see Gupta et al. 2011; Rose et al. 2019).

In addition to these critical problems in their ages, the HRs in Jones et al. (2018) further include the host-mass correction. In the analysis for the age–HR correlation, this is a very inappropriate treatment because the host mass is most likely a proxy for the population age. Kang et al. (2020, see their Figure 9) found a very tight (>$99.99\%$) correlation between host mass and age from high-quality spectra for ETGs, while they found no correlation with metallicity at a similar mass range where Kelly et al. (2010) and Childress et al. (2013) found the correlation between host mass and HR. A similar correlation between galaxy mass and population age was also reported by van de Sande et al. (2018) for a large sample of nonhost galaxies. Because of this correlation, applying the host-mass correction by itself would further undermine the correlation between age and HR. It is therefore not surprising to see that the correlation between age and HR is smeared out in Figure 3 of Rose et al. (2020) by using this problematic data set.

3. Correlation between Age and Hubble Residual from All Types of Host Galaxies

In order to overcome the problems in age dating from photometric SED, Rose et al. (2019) have devised a clever and efficient technique for measuring the mass-weighted age, which can provide more reliable average age of stellar populations in a host galaxy. Their technique is based on a Markov chain Monte Carlo (MCMC) sampling method to determine the most probable star formation history (SFH), which was then implemented in the updated version of the population synthesis model of Conroy & Gunn (2010). As such, the Rose et al. (2019) age dating is a significant improvement over a similar age data set of Gupta et al. (2011). Using their technique applied to SDSS ugriz photometric SED, Rose et al. (2019) have measured, with adequate accuracy, mass-weighted ages for 102 host galaxies of all morphological types in $0.05 < z < 0.2$.

Figure 1 shows this data set for population age and HR from Rose et al. (2019) both for the global age of a host galaxy and for the local age measured in the vicinity (1.5–3 kpc radius) of the SN Ia site. Rose et al. (2019) used the SN sample of Campbell et al. (2013) for the HR information. Since the Rose et al. (2019) sample is confined to a narrow redshift range, the effect of redshift evolution is negligible within their sample. To properly account for both measurement errors and intrinsic scatter in the regression analysis, the MCMC posterior sampling method implemented in the LINMIX package (Kelly 2007) is most commonly used in SN host galaxy studies (e.g., Kelly et al. 2010; Gupta et al. 2011; Pan et al. 2014, 2020) including our previous investigation for ETGs (Kang et al. 2020). Kelly (2007) has shown that this maximum-likelihood estimator based on the Gaussian mixture model outperforms other common estimators and provides the least biased result for the regression analysis. Surprisingly, unlike the argument of Rose et al. (2020), when we apply this standard regression analysis method to the Rose et al. (2019) data set comprising a large sample of host galaxies, very significant (>99.99%) correlation is obtained between the global population age and HR with the slope ($0.047 \pm 0.011$ mag Gyr$^{-1}$) in excellent agreement with the result ($0.051 \pm 0.022$ mag Gyr$^{-1}$) of Kang et al. (2020) from high-quality spectroscopy of ETGs. Rose et al. (2019) suggested that this correlation might be more consistent with a step of $0.1$ mag in the HR at an age of $\approx 8$ Gyr, but we obtain more or less the same slope ($0.054 \pm 0.015$ mag Gyr$^{-1}$) even if we restrict the sample to host galaxies younger than 8 Gyr. This indicates that, unlike the star formation rate–HR correlation (Rigault et al. 2013), the potential effect of a nonlinearity is not significant in the age–HR correlation.

5 At a given redshift, this empirical correction for host mass can indeed reduce the scatter in HR. However, since the redshift evolution of host mass is small for the redshift range ($z < 1$–1.3) relevant to SN cosmology, this empirical treatment, unlike the direct correction based on age (Figure 16 of Kang et al. 2020), has no impact on cosmology (consistent with a zero slope; see Figure 13 of Betoule et al. 2014). Therefore, the current practice of using a correction based on host mass cannot correct for the SN luminosity evolution with redshift.

6 Nevertheless, the method implicitly assumes that the parent distribution of the independent variable follows a Gaussian mixture model.
correlation. While the global age of a host galaxy can be used to infer the SN progenitor age, the local age around the SN Ia site would serve as a better proxy for the SN progenitor age. The right panel is for the local age of the environment around the site of SN in a host galaxy. Again, a similarly significant (3.6σ) correlation is obtained with an even steeper slope (−0.057 mag Gyr\(^{-1}\)).

The main argument of Rose et al. (2020) is also based on this same data set from Rose et al. (2019), but they reached a very different conclusion for the slope much shallower than the one reported by Kang et al. (2020). In order to understand the origin of this apparent disparity, we have carefully followed the procedures adopted by Rose et al. (2019) for which Figure 2 of Rose et al. (2020) is based on. Figure 2 shows our reproduction of their procedures. Unusually, Figure 2 of Rose et al. (2020) only presents a probability density plot without showing the original individual 102 data points with error bars. Their density plot is based on a Monte Carlo resampling method by generating 100 random mock samples around each data point according to the measurement errors. In doing so, however, the age range has been substantially stretched and, therefore, the slope obtained from the ordinary least-squares (OLS) fitting has been severely underestimated. This is the well-known regression dilution bias, which arises as a consequence of the measurement error in the independent variable and leads to the attenuation of both the regression slope and significance of the correlation (see, e.g., Kelly 2007). Particularly, in the case of Rose et al. (2019, 2020) analysis, this effect has been doubled because the generation of the mock data stretches the distribution more horizontally than vertically\(^9\) and, more importantly, the OLS does not take into account the measurement errors of the mock data in the independent variable. In Figure 2 we reproduce this double dilution bias happened in Rose et al. (2019, 2020). Since the public data set of Rose et al. (2019) does not provide non-Gaussian error bars, we assume Gaussian errors here for mock data generation. However, as our experiment shows, the difference due to this non-Gaussianity is insignificant.

Figure 3 compares the slope obtained by us for the Rose et al. (2019) data set comprising all types of host galaxies with that of Kang et al. (2020) for ETGs. Also compared is the slope reported by Rose et al. (2019). A small HR shift of 0.07 mag is applied here to Rose et al. (2019) data to account for the difference in median redshift between the Kang et al. (2020), \(z \sim 0.04\) and Rose et al. (2019, \(z \sim 0.14\)) samples. After this correction, the HR values would be equivalent to those calculated with respect to the cosmological model without \(\Lambda\).

\(^9\) The mean error (\(\sim 1.9\) Gyr) for the age is \(\sim 20\%\) of the interval (\(\sim 9.5\) Gyr) whereas the mean error (\(\sim 0.079\) mag) for the HR is \(\sim 8\%\) of its interval (\(\sim 0.98\) mag).
It is clear from this comparison that, while the slopes obtained from the standard MCMC posterior sampling method for both Kang et al. (2020) and Rose et al. (2019) samples show excellent agreement with each other, the analysis of Rose et al. (2019) severely underestimates the slope because of the dilution bias. Note that most data points for ages older than $\sim 7$ Gyr are placed below the regression line of Rose et al. (2020), illustrating that their regression does not fairly represent the distribution of actual data points. Their scientific conclusion (no luminosity evolution in SN cosmology) based on this problematic method is therefore seriously flawed.

4. Discussion

While the result of Kang et al. (2020) is based on the most direct population ages ever obtained for host galaxies from extremely high-quality spectra, it is limited to a small sample of ETGs. The present result is based on the ages derived from SED fitting of Rose et al. (2019) which are not as precise as those measured from spectral features, but a larger sample size coupled with adequate age accuracy has provided a far more significant ($>99.99\%$, $4.3\sigma$) correlation between population age and HR. Importantly, this result is no longer limited to ETGs but is based on host galaxies of all morphological types. Furthermore, unlike the Kang et al. (2020) analysis, no extrapolation in age is now required below 2.5 Gyr, because the Rose et al. (2019) sample contains younger host galaxies. In addition to the global age of a host galaxy, this study also presents the local population age around the site of SN.

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8 When the regression line is obtained with the “FITEXY” estimator (Press et al. 1992), an even steeper slope ($-0.078$ mag Gyr$^{-1}$) is obtained, but Kelly (2007) has shown that the FITEXY estimator is biased away from zero, while the OLS estimator is biased toward zero.
is more relevant to the SN progenitor age, and therefore is not strongly affected by the possible difference between the global and local population ages within a host galaxy. In these respects, the present result provides an independent confirmation for, and a significant improvement over, the result of Kang et al. (2020). Therefore, the luminosity evolution stands up to scrutiny as a serious systematic bias in SN cosmology.

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ORCID iDs

Young-Wook Lee @ https://orcid.org/0000-0002-2210-1238
Chul Chung @ https://orcid.org/0000-0001-6812-4542
Yijung Kang @ https://orcid.org/0000-0002-5261-5803

References

Betoule, M., Kessler, R., Guy, J., et al. 2014, A&A, 568, A22
Campbell, H., D’Andrea, C. B., Nichol, R. C., et al. 2013, ApJ, 763, 88
Childress, M., Aldering, G., Antilogus, P., et al. 2013, ApJ, 770, 108
Childress, M. J., Wolf, C., & Zahid, H. J. 2014, MNRAS, 445, 1898
Conroy, C., & Gunn, J. E. 2010, ApJ, 712, 833
Gupta, R. R., D’Andrea, C. B., Sako, M., et al. 2011, ApJ, 740, 92
Jones, D. O., Riess, A. G., Scolnic, D. M., et al. 2018, ApJ, 867, 108
Kang, Y., Lee, Y.-W., Kim, Y.-L., et al. 2020, ApJ, 889, 8
Kelly, B. C. 2007, ApJ, 665, 1489
Kelly, P. L., Hicken, M., Burke, D. L., et al. 2010, ApJ, 715, 743
Kim, Y.-L., Smith, M., Sullivan, M., et al. 2018, ApJ, 854, 24
Le Borgne, D., & Rocca-Volmerange, B. 2002, A&A, 386, 446
Lee, H.-c., Worthey, G., Trager, S. C., et al. 2007, ApJ, 664, 215
Pan, Y.-C., Foley, R. J., Jones, D. O., et al. 2020, MNRAS, 491, 5897
Pan, Y.-C., Sullivan, M., Maguire, K., et al. 2014, MNRAS, 438, 1391
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Press, W. H., Teukolsky, S. A., Vetterling, W. T., et al. 1992, Numerical Recipes in FORTRAN: The Art of Scientific Computing (Cambridge: Cambridge Univ. Press)
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Rigault, M., Aldering, G., Kowalski, M., et al. 2015, ApJ, 802, 20
Rigault, M., Copin, Y., Aldering, G., et al. 2013, A&A, 560, A66
Rose, B. M., Garnavich, P. M., & Berg, M. A. 2019, ApJ, 874, 32
Rose, B. M., Rubin, D., Cikota, A., et al. 2020, ApJL, 896, L4
Schmidt, B. P., Suntzeff, N. B., Phillips, M. M., et al. 1998, ApJ, 507, 46
Sullivan, M., Conley, A., Howell, D. A., et al. 2010, MNRAS, 406, 782
van de Sande, J., Scott, N., Bland-Hawthorn, J., et al. 2018, NatAs, 2, 483
Walcher, J., Groves, B., Budavári, T., et al. 2011, Ap&SS, 331, 1

9 The SN progenitor age can be obtained by convolving the SFH of a host galaxy with the delay time distribution (DTD) of SNe Ia (Childress et al. 2014). The difference between the population age and SN progenitor age can be estimated by employing SFHs and the DTD in Figure 3 of Childress et al. (2014). For the Rose et al. (2019) sample, we confirm that, on average, progenitor age is younger than population age by ~1.3 Gyr, but this difference is larger at older ages and smaller at younger ages. Therefore, the slope in Figure 1 would be somewhat steeper if we had used progenitor ages instead of population ages.