Discovery of strong progenitor age dependence of type Ia supernova luminosity standardization process and discordance in cosmology

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ABSTRACT

Supernova (SN) cosmology is based on the assumption that the width-luminosity relation (WLR) and the color-luminosity relation (CLR) in the type Ia SN luminosity standardization would not vary with progenitor age. Unlike this expectation, recent age datings of stellar populations in host galaxies have shown significant correlations between progenitor age and Hubble residual (HR). It was not clear, however, how this correlation arises from the SN luminosity standardization process, and how this would impact the cosmological result. Here we show that this correlation originates from a strong progenitor age dependence of the WLR and the CLR, in the sense that SNe from younger progenitors are fainter each at given light-curve parameters $x_1$ and $c$. This is reminiscent of Baade’s discovery of two Cepheid period-luminosity relations, and, as such, causes a serious systematic bias with redshift in SN cosmology. Other host properties show substantially smaller and insignificant differences in the WLR and CLR for the same dataset. We illustrate that the differences between the high-$z$ and low-$z$ SNe in the WLR and CLR, and in HR after the standardization, are fully comparable to those between the correspondingly young and old SNe at intermediate redshift, indicating that the observed dimming of SNe with redshift is most likely an artifact of over-correction in the luminosity standardization. When this systematic bias with redshift is properly taken into account, there is no or little evidence left for an accelerating universe, posing a serious question to one of the cornerstones of the concordance model.

Keywords: UAT concepts: Type Ia supernovae (1728); Observational cosmology (1146); Dark energy (351); Distance indicators (394)

1. INTRODUCTION

Supernova (SN) cosmology has long been considered to provide the most direct and the strongest evidence for an accelerating universe. Based solely upon the Hubble diagram, it is a very simple method and is less dependent on the model compared to other cosmological probes (Frieman et al. 2008; Weinberg et al. 2013). Cosmic microwave background (CMB) provides crucial cosmological constraints, notably the geometry of the universe, but “it alone provides relatively weak constraints on dark energy” (Planck Collaboration et al. 2020). Therefore, SN cosmology is best suited for directly investigating an accelerating or decelerating universe. More than two decades ago, Riess et al. (1998) and Perlmutter et al. (1999) discovered that SNe at high redshift are fainter by 0.20 - 0.25 mag (≈20% in brightness) compared to the model without the dark energy, after the empirical SN luminosity standardization. This was interpreted as evidence for an accelerating universe with dark energy. An alternative interpretation is also possible, however, because stellar populations and SN progenitors in host galaxies get younger with redshift, and, as first pointed out by Tinsley (1968), there is a possibility of the luminosity evolution of standard candle in observational cosmology. Within the redshift range most relevant to SN cosmology (0 < z < 1), we expect ~6 Gyrs of variation in mean stellar population age, and a similar variation (~5 Gyrs) in median progenitor age (see Figures 1 and 2). Therefore it is possible that SNe at high redshift...
are fainter, not because of an accelerating universe, but because their progenitors are younger (more massive) compared to their counterparts at the local universe.

History tells us that we should be concerned about this. Soon after his discovery of two stellar populations in 1944, Baade (1956) realized that young population I Cepheids that Hubble discovered in M31 are in fact brighter, at a given period, than old population II counterparts based on which Hubble calibrated his observations. Because of this discovery of Hubble's mistake, distances to M31 and other galaxies have been doubled, and the value of the Hubble parameter has been decreased by a factor of two. This illustrates that the luminosity of a standard candle can depend on stellar population age because of the difference in stellar mass. If a similar shift with progenitor age is discovered among type Ia SNe (SNe Ia), this would also have a critical impact on cosmology because SN cosmology is based on the assumption that the width-luminosity and color-luminosity relations in the SN Ia luminosity standardization would not vary with progenitor age and redshift (Jha et al. 2019).

Recent age datings of stellar populations in host galaxies, however, have shown significant correlations between population age and the Hubble residual (HR, a measure of relative luminosity), indicating that this key assumption in SN cosmology may not be correct and requires more careful investigations. From the YONSEI (Yonsei nearby supernovae evolution investigation) project initiated 10 years ago, we obtained very high quality spectra for 59 nearby early-type host galaxies (ETGs). Excluding some abnormal ETGs with recent star formation (SF), Kang et al. (2020) found an important \( \Delta \sigma \) correlation between population age and HR, in the sense that SNe in younger host galaxies are fainter, which would indicate a luminosity evolution in SN cosmology because high-\( z \) SNe should be from younger progenitors. Rose et al. (2020), however, claimed that this result from ETGs is not confirmed from a larger sample of host galaxies comprising all morphological types. Their claim was based on the two age datasets, one by Jones et al. (2018) and the other by Rose et al. (2019), all measured from multi-band optical photometry. In our rebuttal paper (Lee et al. 2020), we have shown that the Jones et al. (2018) ages, in particular, are based on highly uncertain and inappropriate luminosity-weighted ages derived, in many cases, under serious template mismatch. The other dataset is based on the improved photometric age dating of Rose et al. (2019) for mass-weighted ages implemented in the updated version of the population synthesis model of Conroy & Gunn (2010), which, unlike luminosity-weighted ages, are not biased by on-going or recent SF. We found, however, that the statistical analysis of Rose et al. (2020) is seriously affected by the regression dilution bias, severely underestimating both the slope and significance of the age-HR correlation. When the regression analysis is performed with a standard MCMC posterior sampling method, a very significant (4.3\( \sigma \)) correlation is obtained between population age and HR for both global age and local age near the site of SN with the slope in excellent agreement with our previous spectroscopic result from ETGs (Kang et al. 2020). Recently, Zhang et al. (2021) confirms that this age-HR correlation is statistically significant (5\( \sigma \)), although they obtained a somewhat shallower slope from a posterior sampling method adopting full posterior for the age error instead of the Gaussian error. Therefore, even the dataset originally used by Rose et al. (2020) to oppose our claim is instead strongly supporting our result, and the luminosity evolution stands up to scrutiny as a serious systematic bias in SN cosmology. It was not clear, however, how this correlation arises from the SN luminosity standardization process, and how this would impact the cosmological result. The same dataset of Rose et al. (2019) for reliable mass-weighted ages, with a larger sample size (\( N = 102 \)) coupled with adequate age accuracy, makes it possible to look into the SN luminosity standardization process in a more detailed manner.

2. PROGENITOR AGE DEPENDENCE OF THE WIDTH-LUMINOSITY AND COLOR-LUMINOSITY RELATIONS

Type Ia SN luminosity standardization process is based on the light curve width (stretch) parameter \( \Delta m_{15} \), or \( x_1 \) together with color parameter \( c \) (Phillips 1993; Tripp 1998). In the modern SALT2 method (Guy et al. 2007), the distance modulus from SN Ia is given by

\[
\mu_{SN} = m_B - M_B + \alpha x_1 - \beta c, \tag{1}
\]

where \( m_B \) is an apparent magnitude, \( M_B \) is an absolute magnitude at the reference point \( (x_1 = 0.0, c = 0.0) \), and \( \alpha x_1 \) and \( \beta c \) are the correction terms depending on the light curve width \( (x_1) \) and color \( (c) \). Therefore, like the Cepheid period-luminosity relation, the SN luminosity standardization relies on the width-luminosity relation (WLR) and the color-luminosity relation (CLR), in which the absolute values of the slopes of the correlations are \( \alpha \) and \( \beta \), respectively. These relations are also called “brighter-broader” and “brighter-bluer” relations. The key assumption of SN cosmology is that these relations should not depend on progenitor age, because high-\( z \) SNe should be from relatively younger progenitors. This is well described in Jha et al. (2019),
“if SNe Ia are to be good standardizable candles over cosmic time, the calibrating relationships between SN luminosity and light-curve shape must be invariant with progenitor age”. Our finding of the correlation between population age and HR raises a question as to the validity of this key assumption in SN cosmology. In order to understand this, we have investigated below how the population age affects the WLR and CLR of the SN luminosity standardization process.

When the SN sample is confined to a narrow redshift range, as in the Rose et al. (2019) sample, the relative luminosities of SNe Ia can be compared to each other from the values of the HR, which is defined by

\[ HR = \mu_{SN} - \mu_{model}, \]

where \( \mu_{model} \) is the distance modulus at the redshift \( z \) according to an assumed cosmological model. In Figure 3, we plot the WLR and CLR for the SNe Ia in Rose et al. (2019) sample, which is a subset of the SDSS SN survey (Campbell et al. 2013) at 0.05 < \( z \) < 0.20 with a median \( z = 0.14 \). Following Astier et al. (2006), the left panel computes distance modulus \( \mu_{SN} \) without the width term \( \alpha x_1 \) (corrected only for \( c \)), while the right panel computes \( \mu_{SN} \) without the color term \( \beta c \) (corrected only for \( x_1 \)), to recover WLR and CLR, respectively. As adopted or suggested by Rose et al. (2019), the light curve data (\( x_0, x_1, & c \)) are from Campbell et al. (2013), and the HR’s are calculated with \( \alpha = 0.16, \beta = 3.12, \) and \( M_x = -29.65 \) (\( M_B = -19.01 \)) from the \( \Lambda \)CDM baseline model (\( h = 0.738, \Omega_M = 0.24, \Omega_\Lambda = 0.76 \)). It is clear that the Rose et al. (2019) sample well follows the “brighter-broader” and “brighter-bluer” relations. To investigate the progenitor age dependence, in Figure 4, we subdivide this sample into two according to the population age with a gray zone between, so that SNe from younger (age \( \leq 4 \) Gyr) and older (age \( \geq 6.1 \) Gyr) populations have nearly the same sample size (\( N = 36 \)) with 31 SNe in a gray zone. As described above, the population ages of host galaxies adopted for this analysis are from the improved and reliable photometric age dating for mass-weighted ages. Rose et al. (2019) measured both the global ages of host galaxies and the local ages near the sites of SNe, and we employed the local ages because they should be more relevant to the SN progenitor ages. The blue and red lines are the regression fits (with \( \pm 1\sigma \) intercept error) from MCMC posterior sampling method for young and old progenitors, respectively. Surprisingly, there is a strong population age dependence in the sense that SNe from younger progenitors are fainter each at given \( x_1 \) and \( c \). When measured at \( x_1 = 0.0 \), the difference between the two age subgroups is 0.167\pm0.037 mag for the population age difference of 4.2 Gyr (i.e., \( \Delta HR/\Delta age = -0.040 \) mag/Gyr). This result is significant at 4.5\( \sigma \) level as estimated from the intercept errors of two regression fits. The population ages can be roughly converted to the SN progenitor ages based on Figure 3 of Childress et al. (2014), according to which the difference in progenitor age would correspond to \( \sim 3.0 \) Gyr between the two subgroups (i.e., \( \Delta HR/\Delta age = -0.056 \) mag/Gyr).

The population age dependence of the WLR and CLR is reminiscent of Baade’s (1956) discovery of two Cepheid period-luminosity relations, and, as such, would be universal, and should have a critical impact on SN cosmology once and for all. This result is quite robust to the choices of \( \alpha \) and \( \beta \), and of SN catalog. For example, if we had adopted \( \beta = 3.69 \), as derived by Kim et al. (2018), the difference between the two age subgroups is slightly larger (0.177 \pm 0.041 mag) at \( x_1 = 0.0 \). If a larger value of \( \alpha \) was adopted, \( \alpha = 0.22 \) as originally derived by Campbell et al. (2013), the difference becomes similarly larger (0.184\pm0.036 mag) at \( c = 0.0 \). A smaller but still meaningful difference is also obtained when we use the Betoule et al. (2014) SN catalog for 77 SNe in common with Rose et al. (2019) sample. We have also tested this result with a less reliable mass-weighted age dataset by Gupta et al. (2011) based on an early version of the Conroy & Gunn (2010) model for a sample in a larger redshift range, but still obtained a 3.1\( \sigma \) difference between the young and old SN subsamples. The Rose et al. (2019) sample is confined to a narrow redshift range, and, therefore, the effect of redshift evolution is negligible within their sample.

What would be the origin of this shift in luminosity with progenitor age? It appears that an increasing progenitor mass (with younger age) produces a brighter SN with a broader light curve and bluer color, following the green arrows in schematic diagrams in Figure 5. Theoretical models for type Ia SN are still incomplete, but a leading theory suggests that the WLR is mostly due to the asymmetry of ignition and detonation (Kasen et al. 2009), while other studies show that the SN peak luminosity increases with Ni mass formed in the explosion, which in turn increases with progenitor mass (Woosley et al. 2007; Leung et al. 2020). Therefore, taken together, the trend we can infer from Figure 5 is qualitatively consistent with model predictions, while more detailed modeling is required for the quantitative comparison. As illustrated in Figure 5, the green vector would have a slope that is shallower than that of the WLR (or CLR) for old SNe (the red line), forming another WLR (or CLR) for younger SNe (the blue line). Therefore, younger SNe are intrinsically brighter, but, at given \( x_1 \) and \( c \), they are fainter. This is the main point of our
discovery which leads to the serious systematic bias in SN cosmology because the SN luminosity standardization is based on $x_1$ and $c$. After the standardization (see Figure 6), which is nothing but the rotation of the WLR (or CLR) in Figure 4 following the slope $\alpha$ (or $\beta$), SNe from younger progenitors are over-corrected and become relatively fainter. The whole process of SN Ia luminosity standardization is illustrated again in Figure 7, based on the WLR and CLR, respectively, where the left panels are added to show the WLR and CLR before $x_1$ and $c$ corrections. In the case of the WLR (upper panels), the split between the young and old progenitors is already visible in the left panel even before the $x_1$ and $c$ corrections, which becomes more pronounced after the $c$ correction in the middle panel. In the case of the CLR (lower panels), however, the split is not shown in the left panel before $x_1$ and $c$ corrections. It only becomes clear after the $x_1$ correction in the middle panel. When $\mu_{\text{SN}}$ is corrected for both $x_1$ and $c$ (after the luminosity standardization), SNe from younger progenitors become relatively fainter (right panels). The values of HR in Figures 3 - 7 would be fainter by 0.094 mag if they were calculated with respect to the non-$\Lambda$CDM model ($h = 0.70$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.00$).

3. COMPARISON WITH COSMOLOGY SAMPLE

The population age dependence of WLR and CLR discovered in the previous section is based on the Rose et al. (2019) sample at $z \sim 0.14$. Like Baade’s discovery of population age dependence of Cepheid period-luminosity relation, which was originally discovered at the local universe but is valid at all distances, this effect should be universal. Since the average age of stellar populations (SN progenitors) in host galaxies gets younger with redshift (see Figure 2), this progenitor age dependence of the WLR and CLR would naturally lead to the relative dimming of SNe with increasing redshift. To investigate this effect more directly with the cosmology sample, in Figure 8, we compare the Rose et al. (2019) sample at $z \sim 0.14$ with the JLA dataset from Betoule et al. (2014). Here, as in the discovery papers (Riess et al. 1998; Perlmutter & Schmidt 2003), the HR’s are calculated from the baseline model without the dark energy ($h = 0.70$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.00$, $M_B = -19.08$) using the same parameters adopted for the Rose et al. (2019) sample ($\alpha = 0.16$, $\beta = 3.12$). As compared in the upper panel of Figure 8, the high-$z$ subsample is chosen at $0.3 < z < 0.6$ so that the population age difference predicted between the low-$z$ (0.02 < $z$ < 0.055) and high-$z$ subsamples would be roughly comparable to that between the old and young subsamples of Rose et al. (2019) at intermediate redshift. This redshift range chosen for our high-$z$ subsample was also the redshift range for high-$z$ SNe of Riess et al. (1998; their Figure 4), and, therefore, provides a fair comparison with the early analysis in a discovery paper.

In the lower panel of Figure 8, we can see that the mean values of HR for the young and old SNe of Rose et al. (2019) sample agree well with those for the high-$z$ and low-$z$ SNe in the cosmology sample, respectively. Therefore, the difference in HR between the high-$z$ and low-$z$ subsamples is fully consistent with that between the similarly and correspondingly young and old SNe of Rose et al. (2019) sample at $z \sim 0.14$. Young SNe at any redshift, young SN subsample at $z \sim 0.14$ or high-$z$ sample as a whole, should be equally affected by the same progenitor age dependence of the WLR and CLR. Figure 9 confirms that the shifts in WLR and CLR between the high-$z$ and low-$z$ subsamples are similar to those between the young and old SNe of Rose et al. (2019) sample in Figure 4 (after an HR offset of 0.094 mag for the difference in the baseline model), and, therefore, after the standardization, the high-$z$ SNe become similarly fainter. The young SNe of Rose et al. (2019) sample are also similar to the high-$z$ cosmology sample in the distribution of light curve parameters $x_1$ and $c$. In the $x_1$ versus $c$ plot, they all have the median values in the 4th quadrant (positive $x_1$ and negative $c$).

In order to avoid the systematic bias from the progenitor age evolution with redshift, SNe from young and roughly coeval progenitors should be selected at all cosmological epochs. The lower panel of Figure 8 also offers a glimpse into this evolution-free cosmological test by using only the young SNe having more or less the same age at different redshifts (the blue and cyan circles), finding no dimming of high-$z$ SNe with respect to the equally young SNe at $z \sim 0.14$. Therefore, we can confirm the self-consistency of our argument in several different ways. This comparison and test indicate clearly and directly that an accelerating expansion of the universe, which was inferred from the observed dimming of SNe with redshift, is most likely an artifact of over-correction in the SN luminosity standardization caused by the negligence of stellar astrophysics and stellar population effect.

4. DISCUSSION

There are other well-established correlations between HR and host galaxy properties, such as stellar mass and local star formation rate (Kelly et al. 2010; Sullivan et al. 2010; Rigault et al. 2015; 2020), and it is important to understand the root cause of these correlations. Since the host mass and the physics of star formation cannot directly affect the luminosity of a SN in a host galaxy,
these correlations are most likely not directly originated from these host properties, but due to the progenitor age closely related to these properties. As an illustrative example of a similar case, we recall Baade’s discovery of two populations of Cepheid variable stars. The population I Cepheids are discovered mostly in the late-type galaxies, while the population II Cepheids are predominantly discovered in less massive and old stellar systems, such as globular clusters and dwarf spheroidal galaxies (Baade 1956; Wallerstein 2002). It would be illogical, however, if one argues that the population II Cepheids are fainter not because of the population age dependence of the period-luminosity relation, but because of the difference in host mass. Likewise, in SN cosmology, the SN progenitor age dependence of the WLR and CLR (Figure 4) should be universal and is most likely the root cause of the HR - host property correlation. When the Rose et al. (2019) sample is subdivided into two based on the host mass, unlike Figure 4, we find no clear difference between the two subgroups on the WLR and CLR. The difference in HR between these two host mass subgroups is at most 0.055±0.044 mag (1.3σ), only one-third of the difference found in Figure 6 between the two age subgroups. Even if the mass step correction (Betoule et al. 2014) is added in Equation (1), the magnitude difference between the two age subgroups in Figure 4 is reduced by only 8% (0.013 mag). This practically confirms that the apparent correlation with host mass is not directly originated from host mass, but is rather a reflection of a mild relationship between population age and host mass among galaxies (Thomas et al. 2010; Kang et al. 2016). Figure 7 of Childress et al. (2014) explains how the host mass step is driven by progenitor age. A similar test for the local star formation rate (SFR) would be impracticable, because our analysis on the GALEX UV color-magnitude diagram shows that most (95%) galaxies in the Rose et al. (2019) sample would be classified as star-forming (on-going or recent SF) galaxies of Rigault et al. (2015; 2020). However, we note that, while there is no apparent correlation between local SFR and HR among star-forming host galaxy subsample of Rigault et al. (2020), there is a strong correlation between population age and HR among similarly star-forming galaxies of Rose et al. (2019). This, together with the progenitor age dependence of WLR in the same sample galaxies, suggests that the progenitor age is more likely the root cause of the local SFR - HR correlation as well.

Recent studies (Brout & Scolnic 2021; Rose et al. 2021) suggest dust attenuation and metallicity may derive the intrinsic scatter of SN Ia HRs after standardization. Using the same Rose et al. (2019) dataset, we have tested these suggestions by subdividing the sample into two based on the dust attenuation parameter τ2 and the metallicity index of Rose et al. (2019). Similar to our analysis for population age in Figure 4, each subgroup had ~36 SNe with a gray zone between. When measured at x1 = 0.0, we find only 0.050 ± 0.041 mag (1.2σ) and 0.044 ± 0.045 mag (0.98σ) differences in the WLR between the two subgroups for the dust and metallicity, respectively. These differences are substantially smaller and not statistically significant, suggesting dust and metallicity are not likely the root cause of the host property dependence of HR. Kang et al. (2020) also find no correlation with metallicity from their high-quality spectroscopic sample of early-type host galaxies. The young and old SN subsamples of Rose et al. (2019) in Figure 8 directly show that most of the scatter in HR at a given redshift is due to population age, although we cannot rule out the possibility that dust and metallicity may play a secondary role.

In the cosmological application of this result, the most important information to recall is the population age distribution of host galaxies at low-z, for which Rose et al. (2019) and Kang et al. (2020) all show clearly that both young and old populations produce SNe Ia with the average age of ~6 Gyr at the local universe. As shown by Childress et al. (2014) and Kang et al. (2020), which is illustrated in Figure 1, the SN progenitor age distribution (SPAD) at a given redshift can be obtained by convolving the well-established cosmic SFH, which is an ensemble average of SFHs of all galaxies, with the empirically derived SN Ia delay time distribution (DTD). These models naturally predict that the median age of SN progenitors gets younger with increasing redshift, following the average age of stellar populations, as the old populations no longer contribute to the SPAD at high-z (see Figure 2). It is unavoidable to conclude from this reasoning that the population age dependence of the WLR and CLR discovered in this paper would lead to a significant luminosity evolution with redshift (look-back time) in SN cosmology. This possibility was also clearly pointed out and extensively discussed by investigators of the discovery papers and of the recent literature (Schmidt et al. 1998; Riess et al. 1998; Perlmutter et al. 1999; Jha et al. 2019). Previous investigations considered only the redshift evolution of host mass or local SFR (Scolnic et al. 2018; Rigault et al. 2020). Unlike population age, the variations of these host properties are either negligible or relatively small within the redshift range most relevant to SN cosmology (0 < z < 1), yielding only an insignificant or limited impact on cosmology.

In order to illustrate the level of significance of the luminosity evolution predicted from our finding, it is
heuristically useful to see what they would have found if, at the discovery time, they knew the $\Delta HR/\Delta \text{age}$ slope reported in this paper (see also Kang et al. 2020, Lee et al. 2020, and Zhang et al. 2021 for a similar slope). Table 1 lists our predictions of the magnitude corrections for the SN Ia luminosity evolution with redshift under two different assumptions for the cosmological model in Figure 2. The corrections are made based on the population ages with a slope $\Delta HR/\Delta \text{age} = -0.040 \text{ mag/Gyr}$ (Figure 4). Figure 10 shows the effects of these corrections for the SN Ia luminosity evolution in the residual Hubble diagram. The SN data over-plotted are from the binned values of Betoule et al. (2014). Case 1 is for the redshift-age relation obtained with $\Omega_\Lambda = 0.73$, while case 2 is for that with $\Omega_\Lambda = 0.00$. As expected from Figure 8, Figure 10 shows clearly that, when the luminosity evolution is properly corrected, the data points are distributed close to the non-accelerating model (the dotted line), rather than an accelerating universe with $\Omega_\Lambda = 0.73$ (the solid line). Specifically, for $z > 0.3$, each of the data points is, on average, $\sim 3.7\sigma$ away from the accelerating universe model, while it is within $\sim 0.8\sigma$ from the non-accelerating model. If we had used progenitor ages, instead of population ages, the deviation from the accelerating universe model would be even larger or similar because the $\Delta HR/\Delta \text{age}$ slope would be steeper, as described in Section 2, while the progenitor age variation with redshift is somewhat smaller (see Figure 2 insets). Therefore, taken at face values, there is no or little evidence left for an accelerating universe when the progenitor age dependence of the SN luminosity standardization is properly taken into account. It appears that the observed dimming of SNe with redshift is not due to the cosmological effect, but mostly due to the stellar astrophysics and stellar population effect.

The SN cosmology has long been considered as the first and most direct evidence for an accelerating universe with dark energy, and, as such, it forms one of the cornerstones of the concordance model (Frieman et al. 2008; Weinberg et al. 2013). This finding, therefore, poses a serious question to one of the cornerstones of the concordance model. While the present result is quite robust, to put this result on a firmer refined basis, reliable mass-weighted ages (a la Rose et al. 2019) would be required for a larger sample of host galaxies at different redshift bins. If the present result is further supported by these studies, an important avenue of future investigations would be to see how this result from SNe can be reconciled with other cosmological probes.

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Figure 1. The SN Ia progenitor age distributions (SPADs) at $z = 0.0, 0.5, 1.0, \& 1.5$ under two different cosmological models ($\Omega_\Lambda = 0.00 \& \Omega_\Lambda = 0.73$). Following Childress et al. (2014) and Kang et al. (2020), the SPAD at given redshift (the blue solid line) is derived by convolving the SN Ia delay time distribution (DTD, the green dotted line) with cosmic star formation history (SFH, the red dashed line). Note that the DTD has a peak at $\sim0.3$ Gyr but it also has a long tail towards older age, and since the cosmic SFH has a peak at $\sim9$ Gyr, the SPAD at $z = 0.0$ appears bimodal with a median age of $\sim6$ Gyr.
Figure 2. Evolution of stellar population age with redshift under two different cosmological models ($\Omega_\Lambda = 0.00$ & $\Omega_\Lambda = 0.73$). Stellar populations and SN progenitors in host galaxies get younger with redshift. The distribution functions (the blue lines) at $z = 0.0, 0.5, 1.0, \& 1.5$ are SPADs derived in Figure 1. The black dashed line is for the median age of SN progenitors, while the black solid line is for the mass-weighted mean age of stellar population obtained from cosmic star formation history. The red line is for the maximum age of stellar population. The inset is for the difference with respect to $z = 0$. Observed data compared are average values of mean population ages of host (Gupta et al. 2011; Rose et al. 2019; Kang et al. 2020) and non-host (Schiavon et al. 2006; Choi et al. 2014) galaxies of comparable stellar mass ($\log M/M_\odot = 10.3 - 11.0$) at different redshifts.
Figure 3. The width - luminosity relation (WLR) and color - luminosity relation (CLR) for 102 SNe Ia in Rose et al. (2019) sample at $0.05 < z < 0.20$ with a median $z = 0.14$. Like the Cepheid period-luminosity relation, the SN luminosity standardization is based on the WLR and CLR. Following Astier et al. (2006), the left panel computes distance modulus $\mu_{\text{SN}}$ without the width term $\alpha x_1$ (corrected only for $c$), while the right panel computes $\mu_{\text{SN}}$ without the color term $\beta c$ (corrected only for $x_1$), to recover WLR and CLR, respectively. As adopted and suggested by Rose et al. (2019), the light curve data $(x_0, x_1, & c)$ are from Campbell et al. (2013), and the HR’s are calculated with $\alpha = 0.16$, $\beta = 3.12$, and $M_x = -29.65$ ($M_B = -19.01$) from the $\Lambda$CDM baseline model ($h = 0.738$, $\Omega_M = 0.24$, $\Omega_\Lambda = 0.76$).

Figure 4. Same as Figure 3, but the sample is subdivided into two according to the population age. SNe from young and old populations have nearly the same sample size ($N = 36 & 35$) with a gray zone between. Strong progenitor age dependence is discovered in the sense that SNe from younger progenitors are fainter each at given light-curve parameters $x_1$ and $c$. This is reminiscent of Baade’s (1956) discovery of two Cepheid period-luminosity relations, and, as such, should be universal and have a critical impact on SN cosmology. The blue and red lines are the regression fits (with $\pm 1\sigma$ intercept error) from MCMC posterior sampling method for young and old progenitors, respectively. When measured at $x_1 = 0.0$, the difference between the two age subgroups is $0.167 \pm 0.037$ mag (i.e., $\Delta HR/\Delta age = -0.040$ mag/Gyr).
**Figure 5.** Same as Figure 4, but with a schematic indication for a most likely direction of the variation with progenitor age. Following the green arrow, an increasing progenitor mass (with younger age) would produce a brighter SN with a broader light curve and bluer color. The green vector has a slope that is shallower than that of WLR (or CLR) for old SNe (the red line), creating another WLR (or CLR) for young SNe (the blue line). Therefore, younger SNe are brighter, but, at given $x_1$ and $c$, they are fainter than old SNe.

**Figure 6.** Similar to Figure 4, but after the luminosity standardization, which is a rotation of the WLR (or CLR) in Figure 4 according to the slope $\alpha$ (or $\beta$). The dashed lines are the mean values of HR. Note that SNe from younger progenitors are over-corrected and become relatively fainter. SNe at high redshift are also from the younger population, and, therefore, should be equally over-corrected and become similarly fainter.
Figure 7. The whole process of SN Ia luminosity standardization is illustrated on the WLR (top panels) and CLR (bottom panels), respectively. The middle and right panels are the same as Figures 4 and 6, but the left panels are added to show the WLR and CLR before $x_1$ and $c$ corrections. When the $\mu_{SN}$ is corrected for $c$ ($x_1$), the WLR (CLR) shows a more clear split between the young and old progenitors (middle panels). After the luminosity standardization ($\mu_{SN}$ corrected for both $x_1$ and $c$), SNe from younger progenitors are over-corrected and become relatively fainter (right panels).
Figure 8. Comparison of Rose et al. (2019) sample with the cosmology sample (JLA dataset from Betoule et al. 2014). In the upper panel, the gray band is for the relative difference in average population age and its variation with redshift encompassing the two cosmological models of Figure 2, including the age uncertainty from ±5% error in $H_0$. The relative ages are with respect to $z = 0$ for the models and with respect to the old subsample for the Rose et al. (2019) sample. In the lower panel, the difference in HR between the high-$z$ and low-$z$ subsamples (cyan & magenta circles) is fully consistent with that between the similarly and correspondingly young and old SNe (blue & red circles) of Rose et al. (2019) sample at $z \sim 0.14$. This illustrates clearly that the observed dimming of SNe with redshift is not due to the cosmological effect, but due to the stellar astrophysics effect. As in the discovery paper (Riess et al. 1998), the HR’s are calculated from the baseline model without dark energy ($h = 0.70$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.00$).
Figure 9. The WLR and CLR for the cosmology sample. The shifts in the WLR and CLR between the high-z and low-z subsamples are similar to those between the young and old SNe of Rose et al. (2019) sample in Figure 4 after an HR offset of 0.094 mag for the difference in the baseline model.
Figure 10. The residual Hubble diagram before and after the correction for the luminosity evolution. The corrections for the luminosity evolution (Table 1) are made to the observational data (Betoule et al. 2014) using the $\Delta HR/\Delta age$ slope ($-0.040$ mag/Gyr) and the redshift evolution of the mean population age in the right (case 1) and left (case 2) panels of Figure 2. After the correction, there is no or little evidence left for an accelerating universe.
Table 1. Luminosity evolution with redshift

| z   | $\Delta age$ (Gyr) | $\Delta mag$ | $\Omega_\Lambda = 0.73$ | $\Delta age$ (Gyr) | $\Delta mag$ | $\Omega_\Lambda = 0.00$ |
|-----|---------------------|--------------|--------------------------|---------------------|--------------|--------------------------|
| 0.00| 0.00                | 0.000        | 0.00                     | 0.00                | 0.000        |
| 0.10| 1.11                | 0.044        | 1.07                     | 1.07                | 0.042        |
| 0.20| 2.07                | 0.082        | 1.94                     | 1.94                | 0.077        |
| 0.30| 2.89                | 0.115        | 2.65                     | 2.65                | 0.106        |
| 0.40| 3.60                | 0.144        | 3.24                     | 3.24                | 0.129        |
| 0.50| 4.21                | 0.168        | 3.73                     | 3.73                | 0.149        |
| 0.60| 4.73                | 0.189        | 4.14                     | 4.14                | 0.165        |
| 0.70| 5.17                | 0.206        | 4.49                     | 4.49                | 0.179        |
| 0.80| 5.55                | 0.222        | 4.78                     | 4.78                | 0.191        |
| 0.90| 5.88                | 0.235        | 5.03                     | 5.03                | 0.201        |
| 1.00| 6.16                | 0.246        | 5.24                     | 5.24                | 0.209        |
| 1.10| 6.40                | 0.256        | 5.42                     | 5.42                | 0.216        |
| 1.20| 6.60                | 0.264        | 5.57                     | 5.57                | 0.222        |
| 1.30| 6.77                | 0.270        | 5.70                     | 5.70                | 0.228        |
| 1.40| 6.92                | 0.276        | 5.81                     | 5.81                | 0.232        |
| 1.50| 7.04                | 0.281        | 5.90                     | 5.90                | 0.236        |

Note. $\Omega_M = 0.27$ and $h = 0.70$ for all cases.