On the relationship between Type Ia supernova luminosity and host-galaxy properties

Yukei S. Murakami,1,2,3 ★ Benjamin E. Stahl,1,2,4 Keto D. Zhang,1 Matthew R. Chu2, Emma C. McGinness2, Kishore C. Patra1,5, and Alexei V. Filippenko1,6,7

1 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
2 Department of Physics, University of California, Berkeley, CA 94720-7300, USA
3 Google Lick Predoctoral Fellow
4 Marc J. Staley Graduate Fellow
5 Nagaraj Graduate Fellow
6 Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720, USA
7 Miller Senior Fellow

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

A string of recent studies have debated the possible presence of an evolutionary trend between the peak luminosity attained by Type Ia supernovae (SNe Ia) and the properties of the galaxies that host them. We shed new light on the discussion by presenting an analysis of ~200 low-redshift SNe Ia in which we measure the separation of Hubble residuals (HR; as probes of luminosity) between two host-galaxy morphological types (as a probe of both age and mass). We show that this separation can test the predictions made by recently proposed models, using an independently and empirically determined distribution of each morphological type in host-property space. Our results are consistent with the previously known HR–mass step (or slope), but inconsistent with newly proposed HR–age slopes, which we find to significantly overstate what amounts only to a slight trend. In addition, we show that these two trends — HR–mass and HR–age correlation — need to be consistent with each other, given the significant correlation that we identify between age and mass in a sample of galaxies. While our result clearly rejects the recently proposed large HR–age slope, the correlations between mass, age, morphology, and HR values are evident, keeping the HR–age slope relevant as an interesting topic for discussion. Our results encourage further studies to determine the physical origin of this relation between host environments and luminosity of SNe Ia.

Key words: distance scale – cosmology: observations – supernovae: general – methods: data analysis – methods: statistical

1 INTRODUCTION

Type Ia supernovae (SNe Ia), brilliant explosions of white dwarfs (see, e.g., Maoz et al. 2014; Jha et al. 2019, for reviews), produce a remarkably small range of peak luminosities. Moreover, this range can be further narrowed through empirical relationships that quantify the correlated rate of photometric evolution (e.g., Phillips 1993; Riess et al. 1996; Jha et al. 2007). Consequently, SNe Ia are excellent standardisable candles for measuring extragalactic distances. Indeed, evidence for the accelerating expansion of the Universe was first found by studying distances derived in this way (Riess et al. 1998; Perlmutter et al. 1999) — a paradigm-shifting discovery that has been upheld and verified by independent observations at different redshift ranges (e.g., Planck Collaboration et al. 2020). Today, SNe Ia remain one of the best diagnostic tools for testing ΛCDM cosmology (for reviews, see, e.g., Filippenko 2005; Riess 2019).

In roughly the past decade, correlations have been discovered between the luminosity and host-galaxy environments of SNe Ia (e.g., Childress et al. 2013). Left unresolved, they could manifest as biases in the cosmological statements that follow from SN Ia observations; thus, understanding (and if necessary, correcting) them is essential. As a notable example, Childress et al. (2013) suggest that an offset in Hubble residuals1 (HR) values should be introduced to account for the differences that manifest — in aggregate — between SNe Ia in “light” and “heavy” galaxies. This “mass step” at ~10¹⁰ M☉, now commonplace in cosmological studies (e.g., Betoule et al. 2014; Scolicnic et al. 2018), makes SNe Ia in “heavier” galaxies appear brighter by ~0.05–0.1 mag. Alternatively, a more continuous model (“mass slope”) has also been proposed (e.g., Uddin et al. 2020) in the search for a more physical form of the mass-HR relation.

More recently, a study of SNe Ia with early-type host galaxies has proposed a large and significant correlation between the (spectroscopically determined) galaxy-luminosity-weighted age and HR (Kang et al. 2020, hereafter K20). That study, which is based on ~30 SNe from early-type galaxies (E–S0), finds a linear relationship between age and HR with a slope that (if correct) predicts a large luminosity offset between SN Ia populations from young and old

1 The deviation of each SN’s distance modulus from the cosmological value at its redshift. For details, see Sec. 2.1 and the lower panel of Figure 1.

* E-mail: sterling.astro@berkeley.edu

© 2020 The Authors
host galaxies. In response, another study (Rose et al. 2020, hereafter R20) points out that this result disagrees with their prior analysis that uses photometrically derived host-galaxy ages (Rose et al. 2019, hereafter R19) and finds a significantly smaller (if not zero) slope. R20 also suggest that a similar conclusion can be drawn from Jones et al. (2018). Responding to R20, Lee et al. (2020, hereafter L20) continue to disagree and claim a large slope comparable to their original result from K20 using the data from R19. In our separate work, Zhang et al. (2020, hereafter Z20L) demonstrated that the statistical analysis used by L20 in deriving a slope is considerably flawed.

In this Letter, we provide an independent test of some of the aforementioned relations between HR and host-galaxy properties (e.g., mass and age). As a proxy for direct measurements of host-galaxy age, we use Hubble morphology types which are known to be correlated with both the ages and the masses of the galaxies that they classify (for reviews, see, e.g., Roberts & Haynes 1994; Conselice 2014). By dividing a sample of cosmologically viable SNe Ia between two galaxy population groups — early-type (old galaxies) and late-type (young galaxies) — we evaluate the difference between their corresponding HR distributions. Using the separation between two galaxy types in HR distributions as a probe, we test the recently reported age–HR slope by K20 and the mass–HR slope by Uddin et al. (2020). This analysis takes advantage of spectroscopically determined host properties from a galaxy survey to construct the HR distribution for SNe Ia predicted by such slopes. We discuss our SN and galaxy dataset in Sections 2 and 3, and provide the results and conclusions in later sections.

2 DATA

2.1 Hubble Residuals from SNe Ia

We source our SN Ia dataset from the Second Amendment (A2) compilation (Boruah et al. 2020) of 465 objects, which is itself comprised of SNe Ia from numerous sources (Turnbull et al. 2012; Ganeshalingam et al. 2013; Krisciunas et al. 2017; Foley et al. 2018). In addition to convenience, our motivation for using A2 over directly sourcing observations from its constituent parts (and perhaps adding omitted sources, e.g., Stahl et al. 2019) is that (i) A2 carefully checks (and updates where necessary) all host-galaxy redshifts, and, more importantly, (ii) it adjusts the distances of each subsample to bring the entire sample onto a common relative distance scale. The small redshifts of the SNe in our sample not only minimise the observational bias in sampling, but also ensure clear and reliable classifications of host-galaxy morphologies (see Sec. 2.2).

Although this sample is already viable for a cosmological analysis (having had undesirable objects filtered out), we further filter based on redshift (keeping only those 416/450 with redshift $z > 0.01$ to mitigate the effect of peculiar velocities) and distance-modulus uncertainty (requiring $\sigma_\mu < 0.25$ mag; 413/416 objects satisfy this condition). We then fit a fiducial $\Lambda$CDM cosmology to the data to obtain Hubble residuals as $\text{HR}_i = \mu_i - \mu_{\text{cosmo}}(z_i)$, though given the low redshifts involved the model has negligible dependence on cosmological parameters. These derived HR values will henceforth be our probe for SN Ia luminosity. As is customary, the uncertainties ($\sigma_{\text{HR}}$) include an intrinsic scatter component that is determined simultaneously in fitting the cosmological model.

2.2 Host Galaxies and their Morphologies

To determine the host galaxy of each SN Ia in our sample, we queried the Transient Name Server (TNS)\(^2\). Those without a host listed were then searched for in the NASA/IPAC Extragalactic Database (NED)\(^3\) using a region centred at their coordinates and extending in a $0.1' \times 0.1'$ square in right ascension and declination. From the resulting lists, we take the closest galaxy to be the host. If no matches are found within this window, we iteratively increase the search radius until a galaxy is located.

Of the 465 total objects in the A2 sample (see Sec. 2.1), 429 SNe Ia are listed in TNS. Of these, 58 do not have hosts listed in TNS and have separations greater than $0.1'$ from their host galaxy assigned through our iterative search. Deeming such hosts as “suspicious,” we check for consistency with the originating SN publications (i.e., Jha et al. 2007; Hicken et al. 2009; Ganeshalingam et al. 2010; Krisciunas et al. 2017; Foley et al. 2018), and ultimately resort to visual inspection if the hosts are not listed or are marked as unknown. In five such cases, we manually override the host, resulting in host identifications for all objects except SN 2016dxy, whose host does not seem to be documented. Combined with the cuts described in Section 2.1, we obtain 366/465 objects with cross-matched host galaxies.

Following the acquisition of host-galaxy names, we obtained morphological types by cross-matching against HyperLEDA (Makarov et al. 2014). Conversion from numerical type to Hubble type is based on de Vaucouleurs (1977), and we limit the classification quality to the top two available groups (i.e., 0–1: “detailed classification”) to ensure reliability. In total, including this classification quality cut, we retain 297 SNe Ia with reliable host galaxies and corresponding morphological types as a result of this procedure.

3 EMPIRICAL PREDICTION OF HR DISTRIBUTION

To empirically determine the host properties for morphologically binned samples, we used data from the Calar Alto Legacy Integral Field Area (CALIFA) survey (for an overview, see Sánchez et al. 2010). The CALIFA survey is a large morphological and physical properties database that includes a wide range of galaxy types, and is particularly suited for studies of SN Ia host galaxies.

We use the CALIFA data to determine the host-galaxy distribution of SN Ia with reliable host galaxies and corresponding morphological types. We use this distribution to predict the HR distribution of SN Ia, taking into account the observed host-galaxy distribution and the observed HR distribution of SN Ia.

This prediction is based on a model that takes into account the observed HR distribution of SN Ia and the observed host-galaxy distribution of SN Ia. The model is based on a range of statistical techniques, including Bayesian inference and Monte Carlo simulations.

The predicted HR distribution is then used to test the observed HR distribution of SN Ia and to constrain the cosmological parameters.

This work is supported by the Institute of Technology.

\(^2\) This service is provided by the IAU supernova working group, free of charge to registered users.

\(^3\) The NASA/IPAC Extragalactic Database (NED) is funded by the National Aeronautics and Space Administration (NASA) and operated by the California Institute of Technology.
This operation is the conservative approach, favouring the overestimated slope if predicted separations are larger than the actual separation in the data, which is the case for our results. Removing bias will require more data, but doing so will only reject the hypothesis with those overestimated slopes.

4 The only exception is the Sd type, which has 13 samples. However, the number of Sd-type host galaxies in our SN Ia sample is small (see, e.g., Figure 2, and the effect of slight changes in Sd-type distributions along galaxy properties on our results is not significant.

5 This operation is the conservative approach, favouring the overestimated slope if predicted separations are larger than the actual separation in the data, which is the case for our results. Removing bias will require more data, but doing so will only reject the hypothesis with those overestimated slopes.

6 To minimise the possibility of accidentally including galaxies in the wrong bin due to observational ambiguity, we removed Sab and Sb types altogether. This minimises the possible bias in the predicted distributions.

Figure 2. Morphology-binned distributions from CALIFA and our process to empirically determine the HR distributions. Left: luminosity (flux)-weighted age of galaxies for each Hubble type, normalised to equal height. Mid: age distributions binned for early-type and late-type (solid), normalised to equal height. Contributions of original types for each bin (dashed), weighted by the number of host types in our SN Ia sample, are shown with dashed lines. Right: distributions in HR space projected from host luminosity-weighted age using relations reported by K20. The HR-axis is offset so that the mean value of the late-type population is fixed at HR = 0 mag. Dashed lines in the right panel represent the simulated Gaussian broadening due to intrinsic scatter in our SN Ia sample, which is used in our analysis in Section 4.
of $-207$ with a $p$-value much less than 0.1%, indicating that the $-0.070$ mag separation of the early-type HR distribution from the late-type distribution is statistically significant.

The empirical distributions are calculated with two age–HR slopes: “Slope by K20” refers to the slope reported by K20 ($-0.051 \pm 0.022$ mag Gyr$^{-1}$), while “Slope by Z20L” is calculated from R19’s data in a statistically proper method (Z20L$^7$: $-0.036 \pm 0.007$ mag Gyr$^{-1}$). These slopes predict mean early-type and late-type separations of $0.29 \pm 0.12$ and $0.20 \pm 0.04$ mag, respectively. The slope by K20 overestimates the separation by a factor of 4, and another independently measured slope (R19 + Z20L) also overestimates the trend. It should be noted, however, that the Z20L slope may not be accurately evaluated, since their analysis is based on R19’s data, which uses mass-weighted values for age estimation. As mentioned in Section 3, our analysis is based on luminosity-weighted age, consistent with K20 to ensure a valid comparison. We discuss our interpretation of these results, combined with the results from the following tests, in Section 5.

4.2 Test 2: Galaxy Stellar Mass on SN Ia Luminosity

Similarly to Test 1, we test the results from Uddin et al. (2020) in which a possible host-galaxy mass–HR relation for SNe Ia is reported. In this test, in accordance with the rule described in Section 3, we used a new binning of SN Ia data for early-type (E, S0, and Sa) and late-type (Sc and Sd), which provides a better separation. The S0a type was counted as the Sa type in CALIFA labels, and the remaining two types, Sab and Sb, were excluded. Since Uddin et al. (2020) report multiple slopes for different passbands, we take the mean of the reported values for the same age range as ours (i.e., $z > 0.01$), $-0.043 \pm 0.030$ mag dex$^{-1}$.

The resulting SN distributions, between 72 early-type and 109 late-type hosts, have a separation of 0.041 mag. This separation has a Welch $t$-statistic of $-125$ with a similarly small ($\ll 0.1\%$) $p$-value, and thus the separation is statistically significant. The separation between early-type and late-type hosts predicted by the Uddin et al. (2020) slope is $0.04 \pm 0.03$ mag, which is in good agreement with our SN distributions. In addition, the resulting separation in SN distributions is consistent with a mass step: the known size of the mass step, $0.08$–$0.09$ mag at $\log_{10}(M/M_\odot) \approx 10$ (e.g., Childress et al. 2013; Uddin et al. 2020), will split the late-type population (of which the majority are Sc types) into nearly equally sized groups, which results in a smaller separation $\Delta HR_{M}/2 \approx 0.040$–$0.045$ mag in our binning.

4.3 Test 3: Correlated Mass–Age on SN Ia Luminosity

In addition to the two tests above, where we compare predictions and observations, we can study the relation between predicted slopes in different parameters. The galaxy data with 256 samples suggests a significant correlation between age, mass, and morphology type. Known behaviour of SNe Ia as a function of galaxy mass (either mass step or slope) does, therefore, suggest a correlation between host-galaxy age and SN Ia luminosity, given the strong correlation between galaxy age and mass (see Fig. 4). Although more detailed analysis with a larger number of samples is required, the calculated
value of the mass–age slope $\Delta \text{mass}/\Delta \text{age} \approx 0.14 \text{dex Gyr}^{-1}$ with the CALIFA dataset provides us the mass–HR slope predicted from K20’s age–HR slope, $\Delta \text{HR}/\Delta \text{mass} \approx -0.39 \pm 0.15 \text{mag Gyr}^{-1}$. This predicted slope is an order of magnitude larger and more than $2\sigma$ apart from the mean slope for the similar condition ($z > 0.01$) in Uddin et al. (2020).

5 DISCUSSION AND CONCLUSION

Using $\approx 200$ low-$z$ SNe Ia, we have demonstrated that a small, yet nonzero separation in HR values exists between early-type and late-type bins of host-galaxy morphological types. Our analysis also shows that, based on empirically determined distributions of galaxy properties with 256 samples, the nonzero slopes between SN Ia luminosity and host-environment properties (e.g., age–HR, mass–HR) indeed predict such separations. In particular, the mass–HR slope/step predicted on Uddin et al. (2020) is able to accurately predict the distribution, while the Age–HR slope recently proposed by K20 clearly overestimates the separation. Another independently estimated slope, based on R19’s data with Z20L’s proper statistical method, shows a smaller, yet still significant disagreement (although this comparison uses ages derived in a manner different from those we use here).

In addition, we have shown that the correlation between age and mass in galaxy samples does predict an age–HR relation (and also morphology–HR relation), although K20’s age–HR slope is an order of magnitude larger than the size expected by Uddin et al. (2020). This may suggest that age-prediction methods for galaxies are not a reliable probe for the host environment—luminosity relation. This may be the result of current limitations with the fitting of multiparameter models, which is needed to estimate the age of galaxies.

We note that the known location of the mass step $\log_{10}(M/M_\odot) \approx 10$ coincides with the location where the number of early-type galaxies decreases (see Fig. 4). This is also consistent with another independent galaxy survey by Kelvin et al. (2014), in which the abundance of early-type and late-type galaxies switches its dominant group at $\log_{10}(M/M_\odot) \approx 10$. This may suggest that the morphological types, and thus galaxy evolution, could, at least in part, be the cause of the known mass step.

Despite the substantial disagreement of our work with, and therefore rejection of, the recently reported age–HR slope by K20, the discussion of the host environment and its effect on SN Ia luminosity remains an interesting topic. Further studies are required to reveal the origin of this phenomenon and account for the cosmological implications, if any.

ACKNOWLEDGEMENTS

We thank Thomas de Jaeger for discussions and Andrew Hoffman for proofreading. A.V.F.’s group at U.C. Berkeley acknowledges generous support from Marc J. Staley, the Christopher R. Redlich Fund, Sunil Nagaraj, the TABASGO Foundation, and the Miller Institute for Basic Research in Science (U.C. Berkeley).

DATA AVAILABILITY

The raw data used in our analysis are available from cited papers and upon requests to an author of this paper.

REFERENCES

Betoule M., et al., 2014, A&A, 568, A22
Boruah S. S., Hudson M. J., Lavaux G., 2020, MNRAS, 498, 2703
Childress M., et al., 2013, ApJ, 770, 108
ComerL C. J., 2014, ARA&A, 52, 291
de Amorim A. L., et al., 2017, MNRAS, 471, 3727
de Vaucouleurs G., 1977, in Tinsley B. M., Larson Richard B. Gehret D. C., eds, Evolution of Galaxies and Stellar Populations. p. 43
Filippenko A. V., 2005, Type Ia Supernovae and Cosmology, pp 97–133, doi:10.1007/1-4020-3725-2_12
Foley R. J., et al., 2018, MNRAS, 475, 193
Ganeshalingam M., et al., 2010, ApJS, 190, 418
Ganeshalingam M., Li W., Filippenko A. V., 2013, MNRAS, 433, 2240
González Delgado R. M., et al., 2015, A&A, 581, A103
Hicken M., et al., 2009, ApJ, 700, 331
Jha S. W., Maguire K., Sullivan M., 2019, Nature Astronomy, 3, 706
Jha S., Riess A. G., Kirshner R. P., 2007, ApJ, 659, 122
Jones D. O., et al., 2018, ApJ, 867, 108
Kang Y., Lee Y.-W., Kim Y.-L., Chung C., Ree C. H., 2020, ApJ, 889, 8
Kelvin L. S., et al., 2014, MNRAS, 444, 1647
Krisiunas K., et al., 2017, AJ, 154, 211
Lee Y.-W., Chung C., Kang Y., Lee M. J., 2020, ApJ, 903, 22
Makarov D., Prugniel P., Terekhova N., Courtois H., Vaught L., 2014, A&A, 570, A13
Maoz D., Mannucci F., Nelemans G., 2014, ARA&A, 52, 107
Perlmutter S., et al., 1999, ApJ, 517, 565
Phillips M. M., 1993, ApJ, 413, L105
Planck Collaboration et al., 2020, A&A, 641, A6
Riess A. G., 2019, Nature Reviews Physics, 2, 10
Riess A. G., Press W. H., Kirshner R. P., 1996, ApJ, 473, 88
Riess A. G., et al., 1998, AJ, 116, 1099
Roberts M. S., Haynes M. P., 1994, ARA&A, 32, 115
Rose B. M., Garnavich P. M., Berg M. A., 2019, ApJ, 874, 32
Rose B. M., et al., 2020, ApJ, 896, L4
Sánchez S. F., et al., 2012, A&A, 538, A8
Sánchez S. F., et al., 2016, A&A, 594, A36
Scolnic D. M., et al., 2018, ApJ, 859, 101
Stahl B. E., et al., 2019, MNRAS, 490, 3882
Turnbull S. J., Hudson M. J., Feldman H. A., Hicken M., Kirshner R. P., Watkins R., 2012, MNRAS, 420, 447
Uddin S. A., et al., 2020, ApJ, 901, 143
Walcher C. J., et al., 2014, A&A, 569, A1
Zhang K., et al., 2016, A&A, 594, A36
Zhang K., Murakami Y., Stahl B., Patra K., Filippenko A., 2020, submitted

This paper has been typeset from a $\LaTeX$ file prepared by the author.