RECONSIDERING THE EFFECTS OF LOCAL STAR FORMATION ON TYPE Ia SUPERNOVA COSMOLOGY

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ABSTRACT

Recent studies found a correlation with ~3σ significance between the local star formation measured by GALEX in SN Ia host galaxies and the distances or dispersions derived from these SNe. We search for these effects by using data from recent cosmological analyses to greatly increase the SN Ia sample; we include 179 GALEX-imaged SN Ia hosts with distances from the Joint Light-curve Analysis (JLA) and Pan-STARRS SN Ia cosmology samples and 157 GALEX-imaged SN Ia hosts with distances from the Riess et al. H₀ measurement. We find little evidence that SNe Ia in locally star-forming environments are fainter after light curve correction than SNe Ia in locally passive environments. We find a difference of 0.000 ± 0.018 (stat+sys) mag for SNe fit with SALT2 and 0.029 ± 0.027 (stat+sys) mag for SNe fit with MLCS2k2 (Rᵥ = 2.5), which suggests that proposed changes to recent measurements of H₀ and w are not significant and numerically smaller than the parameter measurement uncertainties. We measure systematic uncertainties of ~0.01–0.02 mag by performing several plausible variants of our analysis. We find the greatly reduced significance of these distance modulus differences compared to Rigault et al. results from two improvements with fairly equal effects, our larger sample size and the use of the JLA and Riess et al. sample selection criteria. Without these improvements, we recover the results of Rigault et al. We find that both populations have similar dispersions in distance than found by Rigault et al. and Kelly et al., with slightly smaller dispersions for locally passive (log(Σ𝓢FR) < −2.9 dex) SNe Ia fit with MLCS2k2, the opposite of the effect seen by Rigault et al. and Kelly et al. We caution that measuring the local environments of SNe Ia in the future may require a higher resolution instrument than GALEX and that SN Ia sample selection has a significant effect on local star formation biases.

Key words: cosmology: observations – distance scale

1. INTRODUCTION

SNe Ia have been a key component in measuring the dark energy equation of state, w, with ≤6% uncertainty (Betoule et al. 2014) and the Hubble constant, H₀, with 3.3% uncertainty (Riess et al. 2011, hereafter R11). With such small error budgets, unknown systematic uncertainties affecting SNe Ia shape- and color-corrected absolute magnitudes could have serious consequences for our understanding of dark energy, neutrino properties, and the global geometry of space.

Although SNe Ia remain accurate distance indicators with ~10% uncertainty per SN, there are concerns about their ability to remain standardizable in galaxies that vary in mass, metallicity, star formation, age, and dust properties (e.g., Sullivan et al. 2010; Childress et al. 2013; Johansson et al. 2013; Rigault et al. 2013). Even a small dependence of SN Ia luminosities on host galaxy properties may have a non-negligible effect on w due to the redshift evolution of galaxies or differences in sample selection. Such an effect could also bias H₀ due to the different demographics of Cepheid host galaxies compared to SN Ia hosts. The lack of detection of such an effect at >3σ with samples of ~10⁵ SNe suggests that such effects are ≲10⁻⁴ × 3 ≲ 0.06 mag, or that they result from galaxy properties that are difficult to measure robustly. These investigations are hampered by an inability to define the nature of the SN Ia correction a priori, complicating the interpretation of the significance of the correlations found a posteriori. If enough sources for a possible correlation are examined, a 3σ result will always be found.

The first widely accepted effect of host galaxy properties on SNe Ia was confirmed by the detection of a ~0.07 mag difference in mean corrected magnitude of SNe Ia with host masses >10⁰M☉. Identified by several independent studies including Lampeitl et al. (2010), Sullivan et al. (2010), and Kelly et al. (2010), this effect has now been detected at >5σ by Betoule et al. (2014) with a sample of 740 SNe Ia.

Because it is unclear how the physics of SN Ia distances could depend on its host galaxy mass, the most likely explanation is that host galaxy mass is merely tracing another physical property that could affect SN luminosity, such as metallicity, stellar age, or dust. Dominguez et al. (2001) suggested that progenitor metallicity could affect the SN luminosity by changing the carbon–oxygen ratio in the progenitor white dwarf, thus resulting in a lower nickel mass synthesized in the explosion. Hayden et al. (2013) found that a correction using a star-formation-based metallicity indicator reduced Hubble diagram residuals more than a simple host mass correction. Childress et al. (2013) found that dust and stellar age are also plausible explanations because they evolve with host galaxy mass.

Different SN Ia progenitor ages could also exhibit systematic differences in corrected magnitude due to the effects of metallicity or explosion mechanism on ⁵⁶Ni production (Maoz et al. 2014). Childress et al. (2014) suggested that progenitor age could be the source of the host mass step, as older progenitors preferentially occur in non-star-forming host galaxies. Because progenitor age evolves with redshift, Childress et al. (2014) modeled a potential redshift-dependent bias in cosmological analyses.

SN Ia light curve fitters may also create biases by assuming a universal relationship between color and absolute magnitude,
independent of the dust composition of different SN Ia hosts. Some preliminary evidence has supported these ideas; Scolnic et al. (2014b) found that the correlation between SN Ia color and absolute magnitude has two different slopes for bluer and redder SNe, which may in part be due to dust properties.

If the host mass step is indicative of one or more of these biases, galaxy properties in the vicinity of SN explosions could be more strongly correlated with SN corrected magnitude than properties of the galaxies as a whole. Three recent studies used \( \sim 60–85 \) nearby SNe Ia to look at such properties and found that they affect the distances derived from SNe Ia. Rigault et al. (2013, 2015) found a correlation between local star formation and SN Ia Hubble residuals from the Nearby Supernova factory (Aldering et al. 2002) and the CfA3 SN survey (Hicken et al. 2009b, hereafter H09) by using the local star formation rate (SFR) density (\( \Sigma_{\text{SFR}} \)) to separate SNe Ia into those with locally passive (SN Ia) and locally star-forming (SN Ia) environments. Rigault et al. (2015, hereafter R15) found a mean difference in Hubble residuals between SN Ia and SN Ia pass (hereafter referred to as the LSF step) of \( \sim 0.09–0.17 \) mag at \( 2–4 \sigma \) significance with different light curve fitters.

The fraction of SNe Ia is different in the nearby Cepheid-calibrated SN Ia sample compared to the Hubble flow SN Ia sample, and R15 found that SNe Ia have mean corrected magnitudes \( \sim 0.15 \) mag brighter than SN Ia when fit with the MLCS light curve fitter and assuming the same \( R_V \) as the R11 \( H_0 \) baseline analysis. They derived a correction to \( H_0 \):

\[
\log(H_0^{\text{corr}}) = \log(H_0) - \frac{1}{5}(\psi^{\text{HF}} - \psi^C) \times \delta(M_0^{\text{corr}})_{\text{SF}},
\]

where \( \psi^{\text{HF}} \) is the fraction of SN Ia in the Hubble flow SN sample and \( \psi^C \) is the fraction of SN Ia in the Cepheid-calibrated sample. \( \delta(M_0^{\text{corr}})_{\text{SF}} \) is the LSF step of 0.155 mag. By estimating \( \psi^{\text{HF}} (52.1 \pm 2.3\%) \) and \( \psi^C (70\%) \), R15 estimate that the true value of \( H_0 \) is reduced by \( \sim 3\% \).

R15 also found that SNe in highly star-forming regions fit by MLCS (Riess et al. 1996; Jha et al. 2007) have lower dispersion in their Hubble residuals than SNe in locally passive environments. Kelly et al. (2015) came to the same conclusion by examining SNe Ia with high local star formation (their \( \Sigma_{\text{SFR}} \) boundary is \( \sim 0.7 \) dex higher than the R15 Ia/Ia boundary cut-off). R13 first found this effect using the SALT2 light curve fitter (Guy et al. 2007), but they could not reproduce this result with the H09 data.

Both R15 and Kelly et al. (2015) used GALEX FUV data to measure the SFR within a few kiloparsecs (kpc) of SN Ia positions. In this work, we use a similar method to examine whether the significance of the LSF step and reduced dispersion from SNe in locally star-forming host galaxies is reduced when we use the most current vintage SN Ia distance estimates, a much larger sample size, and vary the priors and assumptions used in the original analyses.

Table 1 shows the sizes of the SN samples used in Rigault et al. (2013), R15, Kelly et al. (2015), and this work, along with the light curve fitters used, the SALT2 color parameters, and the MLCS prior on \( A_V \). Rigault et al. (2013) used 82 SNfactory SNe with star formation estimated using local H0 from integral field spectroscopy. Rigault et al. (2015) used \( \sim 100 \) SNe from the CfA3 sample of H09, with \( \sim 80 \) passing GALEX sample cuts. Kelly et al. (2015) used several surveys but made strict sample cuts and only used SNe with Hubble residuals \( < 0.3 \) mag, which would amount to a \( \sim 1.3 \sigma \) cut for the R11 data.

By using a sample size \( \sim 2–3 \) times as large as those in the analyses above, we hope to obtain a robust measurement of the magnitude and uncertainty of the effect of local star formation on SN Ia corrected magnitudes. Section 2 presents our sample selection, and Section 3 discusses our LSF step and dispersion analysis. In Sections 4 and 5 we present our results and discuss their significance, and our conclusions are in Section 6.

2. DATA

We used two samples of SNe for this analysis, one from the R11 measurement of \( H_0 \) and the other from the dark energy equation of state measurements of Betoule et al. (2014) and Pan-STARRS (PS1; Rest et al. 2014; Scolnic et al. 2014a, D. M. Scolnic et al. 2015, in preparation). These two samples rely on many of the same SNe, but R11 use the MLCS light curve fitter to perform their baseline analysis while Betoule et al. (2014) and PS1 use SALT2 (Guy et al. 2010; Betoule et al. 2014, version 2.4). Each sample is \( \sim 2–3 \) times as large as the R15 and Kelly et al. (2015) GALEX-imaged host samples and removes the possibility of a bias between our sample and the samples used in the most recent measurements of cosmological parameters.

2.1. Riess et al. (2011) SNe

The \( H_0 \) determination of R11 use the MLCS2k2 light curve fitter for their baseline analysis. We use only their MLCS2k2 distance moduli, as JLA+PS1 consists of a larger SALT2-fit SN Ia sample with more robust light curve cuts and an updated SALT2 model and color parameter, \( \beta \). The R11 sample consists of 140 SNe between 0.023 < \( z \) < 0.1 from Hicken et al. (2009a) and Ganeshalingam et al. (2010). As one of the variants in their systems section, R11 extend the lower bound of the redshift range to 0.01 after making peculiar velocity corrections (using results from Neill et al. 2007 and the Pike & Hudson 2005 dipole), giving 240 SNe (with peculiar velocity uncertainties added in quadrature to the distances). Adopting this redshift range raises \( H_0 \) by 0.8 km s\(^{-1}\) Mpc\(^{-1}\), or 0.26\( \sigma \). We adopt this lower redshift limit of 0.01 as it allows us to add more SNe Ia to our sample, although these nearby SNe have less weight in the likelihood approach outlined in Section 3 due to their included peculiar velocity uncertainties. In Section 4.1, we examine the effect of restricting the redshift range to \( z > 0.023 \). R11 remove 4\( \sigma \) Hubble diagram outliers but make no sample cuts based on light curve shape, \( A_V \), or MLCS \( \chi^2 \).

MLCS2k2 determines the distance modulus for each SN Ia by fitting for the light curve shape and extinction assuming an extinction prior and a value for the total to selective extinction ratio, \( R_V \). Common extinction priors include exponential distributions \( (e^{-A_V}/r); \) see Table 1), exponential distributions convolved with gaussians, a flat prior (with or without negative \( A_V \) allowed), and priors based on host galaxy information. R11 consider the latter two priors in their systematic uncertainty analysis, and use an exponential with a scale length of 0.457 mag for their baseline analysis. R11 consider dust reddening laws with \( R_V = 1.5, 2.0, 2.5 \), and 3.1, using \( R_V = 2.5 \) for their baseline analysis. \( R_V = 3.1 \) corresponds to...
the Milky Way reddening law (Cardelli et al. 1989). We exclude $R_V = 1.5$ from our analysis as such a low value is not typically used in cosmological analyses (e.g., Kessler et al. 2009a adopt $R_V = 2.18 \pm 0.5$ for SDSS cosmology); although highly reddened SNe Ia tend to favor low values of $R_V$ (Burns et al. 2014), these SNe are usually excluded from samples used to measure cosmological parameters. H09, for example, use only SNe with $A_V < 0.5$.

We queried GALEX\(^4\) for FUV images at the locations of these SNe, keeping only those with an angular distance from the field of view center (FOV radius) $<$ 0.55 to ensure accurate photometry and avoid reflection artifacts and distortion of the point-spread function (PSF) near the detector edge. Of the 240 SNe used in R11, we found 187 SN host images meeting this condition.

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Table 1

| SN Surveys | SNe | $\mu_{\text{version}}$ | $\beta$ | SNe | $\mu_{\text{version}}$ | $P(A_V)$ | $R_V$ |
|------------|-----|------------------------|--------|-----|------------------------|----------|-------|
| Rigault+13 | SNe | 82 | G07\(^b\) | ... \(^c\) | ... | ... | ... |
| Rigault+15 | CfA3 | 77 | G07\(^b\) | 2.48 \pm 0.10 \pm 0.12 | 84 | v0.06 | $e^{-A_V/0.457}$ | 1.7, 2.5, 3.1 |
| Kelly+15 | LOSS\(^d\), CfA2-4, CSP | ... | ... | ... | 61 | v0.07\(^e\) | $e^{-A_V/0.3} \times N(\sigma = 0.02)^f$ | 1.8, 3.1 |
| This work | CfA1-4, CSP, CT\(^g\), SDSS, SNLS, PS1 | 187 | G10\(^b\) | 3.097 \pm 0.062 | 154 | v0.06 | $e^{-A_V/0.457}$ | 2.0, 2.5, 3.1 |

Notes.

\(^a\) Aldering et al. (2002).
\(^b\) Guy et al. (2007).
\(^c\) The value of $\beta$ was blinded in Rigault et al. (2013).
\(^d\) The Lick Observatory Supernova Search (Li et al. 2011).
\(^e\) MLCS v0.07 used new spectral templates from Hsiao et al. (2007). This version was implemented in the SNANA software (Kessler et al. 2009b, SNANA).
\(^f\) An exponential convolved with a normal distribution having $\sigma = 0.02$ mag.
\(^g\) Calan/Tololo (Hamuy et al. 1996).
\(^h\) Guy et al. (2010) had improved uncertainty propagation and handling of residual scatter, a new SN Ia spectral energy distribution regularization scheme, and used a larger training sample with higher $z$ SNe (see their Appendix A for details).

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Figure 1. Hubble diagrams and Hubble residual diagrams for the JLA+PS1 sample (SALT2 light curve fitter; left) and the R11 sample (MLCS light curve fitter with $R_V = 2.5$; right), with the GALEX FUV-imaged hosts in red and the SNe without GALEX FUV host images in blue. Out of a total of 249 SNe in the JLA+PS1 sample, 207 were imaged by GALEX within 0.55 of the field center. In the R11 sample, 177 out of 239 SNe fit with $R_V = 2.5$ had GALEX FUV images. The MLCS data have slightly higher scatter, but both samples have intrinsic dispersions $\lesssim 0.2$. 

\(^4\) http://galex.stsci.edu/GalexView/
2.2. Betoule et al. (2014) and Pan-STARRS SNe

The most recent measurements of $w$ (Betoule et al. 2014; Rest et al. 2014) use the SALT2 light curve fitter, and compute distance moduli using the equation (Tripp 1998):

$$\mu = m_B^\ast + \alpha \times X_1 - \beta \times C - M,$$

where $\mu$ is the SN distance modulus, $m_B^\ast$ is the peak SN $B$ band magnitude, $X_1$ is the light curve stretch parameter, and $C$ is the light curve color parameter. SALT2 adopts a linear relation between SN Ia color and luminosity with no prior. For consistency with the Joint Light-curve Analysis (JLA) cosmological analysis, we only use the SALT2 fitter with these data.

The nuisance parameters $\alpha$, $\beta$, and $M$ (in this analysis, a single value independent of host galaxy mass) are simultaneously fit to the full supernova sample. In recent work, the value of $\beta$ has risen due to changes in the SALT2 model and larger SN Ia samples. The value found by Betoule et al. (2014) is $\beta = 3.102 \pm 0.075$, a difference of ~0.6 relative to the H09 value of 2.48 $^{+0.10}_{-0.12}$ (used by R15). This could have an important impact on measuring the LSF step, which we discuss further in Section 5.1. In this analysis, we simultaneously fit JLA and PS1 data together, finding $\beta = 3.097 \pm 0.062$. In contrast to Betoule et al. (2014) and following the R15 claim that the LSF step replaces the host mass step, we did not apply the host mass step in deriving this value.

We limited the Betoule et al. (2014) JLA to $z < 0.1$ because the large GALEX PSF makes the star formation measurement non-local with FHWM $\sim 8$ kpc. This low-$z$ sample includes data from low-redshift surveys such as CfA1-3 (Riess et al. 1999; Jha et al. 2006; Hicken et al. 2009a), the Carnegie Supernova Project (Hamuy et al. 2006; Stritzinger et al. 2011) and Calan/Tololo (Hamuy et al. 1996), and surveys extending to higher $z$ such as SDSS (Kessler et al. 2009a, 25 SNe after sample cuts) and SNLS (Conley et al. 2011, no SNe after sample cuts). We added low-$z$ CfA4 SNe from (Hicken et al. 2012, used in the PS1 analysis), PS1 SNe from Rest et al. (2014), and the upcoming 4-year PS1 cosmological analysis (12 SNe after sample cuts; D. M. Scolnic et al. 2015, in preparation). For both JLA and PS1, peculiar velocities are corrected following Neill et al. (2007) based on the Hudson et al. (2004) model.

The cuts applied to these data are listed in Betoule et al. (2014, their Table 6 and Appendix A). They make light curve shape, color, and SALT2-fit probability cuts (requiring a fit probability >0.01). We applied these same cuts to PS1 SNe, and removed 3.5$\sigma$ outliers from the full sample, including the 4 $> 3\sigma$ outliers removed by Betoule et al. (2014).

The JLA and PS1 samples with $0.01 < z < 0.1$ contain a total of 249 SNe. Of these, 207 were found in GALEX with an FOV radius $< 0.55$ and 179 remained after the sample cuts described in Section 3. We found no significant difference ($< 0.01$ mag) between the mean Hubble residual of the GALEX-detected sample and the full sample.

| No. SNe Ia | JLA+PS1 | R11 |
|----------|--------|-----|
| Initial sample | 249 | 240 | 239 | 237 |
| GALEX FUV data exist | 212 | 189 | 188 | 187 |
| FOV radius $<0.55$ | 207 | 181 | 180 | 179 |
| Global SFR known | 207 | 178 | 177 | 176 |
| Inclined SNe removed | 179 | 157 | 156 | 155 |

### 3. MEASURING THE STAR FORMATION DENSITY

R15 used the following procedure to measure the local star formation density, $\Sigma_{\text{SFR}}$, and its relation to SN distance estimates. We summarize the principal steps below and describe the differences in our analysis in Section 3.1. Section 3.2 discusses our systematic error treatment. Table 2 gives a summary of the quality cuts applied to our SN Ia sample and the number of SNe remaining after each cut.

1. **R15** measured GALEX FUV aperture photometry at the location of the SN using a 4 kpc aperture diameter. They applied Milky Way dust corrections from Schlegel et al. (1998), where the FUV extinction $A_{\text{FUV}} = 7.9 \times E(B-V)$ (Cardelli et al. 1989; R15).

2. The photometry was corrected for host galaxy extinction in the FUV based on the measured FUV–NUV colors, which were converted to extinction using the relation from Salim et al. (2007). A Bayesian prior for $A_{\text{FUV}} = 2.0 \pm 0.6$ for star-forming galaxies was also applied (the final $A_{\text{FUV}}$ was a weighted mean of the prior and the measured $A_{\text{FUV}}$). R15 made no dust correction for passive galaxies.

To determine whether each galaxy was globally star-forming or passive, they used $\Sigma_{\text{SFR}}$ measurements from Neill et al. (2009, $\Sigma_{\text{SFR}} > -10.5$ is star-forming), who fit synthetic templates to the SN host UV–optical spectral energy distributions (SEDs). Because Neill et al. (2009) SED fits were unavailable for ~40% of their hosts, R15 used morphology for these, treating galaxy types Sa and later as star-forming (a less accurate method).

3. To minimize the effects of locally passive regions projected on top of locally star-forming regions (see R15, Appendix B.2), R15 removed SNe with host inclination angles $> 80^\circ$ from their sample.

4. Based on their photometric and dust-correction uncertainties, R15 calculated the probability of a SN Ia being above $(P(\text{Ia}))$ or below $(P(\text{Ia})) \log(\Sigma_{\text{SFR}}) = -2.9$.

5. R15 used a maximum likelihood approach (outlined in the Appendix) to determine the difference in corrected magnitude and dispersion between SNe Ia1 and Iae.
3.1. Our Analysis

We largely used the same methodology as R15, but improved the following aspects of the analysis.

1. We used the Schlafly & Finkbeiner (2011) dust corrections instead of the Schlegel et al. (1998) corrections used by R15, resulting in a ~14% reduction in our extinction values.
2. We used SDSS NUV–r color instead of morphology as a diagnostic of global SFR when UV+optical SED fits were unavailable.
3. For SNe outside the isophotal radii of their host, we did not make a dust correction as we expect these SNe to be minimally affected by extinction.
4. We made a slightly more conservative inclination cut, removing galaxies with inclinations >70°.
5. Using our maximum likelihood model, we fit for both SN Ia and SN Ic dispersion when determining the LSF step to allow for the possibility that these two quantities are significantly different and affect the magnitude of the step.

We discuss our changes and methodology in further detail below. However, these changes have only minor significance on our results (see Section 4.6). Our method of maximum likelihood estimation for calculating the LSF step is described in detail in the Appendix.

3.1.1. FUV Aperture Photometry

We used the same baseline 4 kpc aperture diameter as R15 for our photometry but corrected for Milky Way FUV extinction using the Schlafly & Finkbeiner (2011) dust corrections5 instead of the Schlegel et al. (1998) corrections used by R15. Schlafly & Finkbeiner (2011) derive a ~14% correction for the Schlegel et al. (1998) dust maps based on the expected versus measured colors of SDSS stars.

Using GALEX to estimate local star formation, as in Rigault et al. (2015) and Kelly et al. (2015), is complicated by the large GALEX PSF, 5′/4 FWHM in the NUV and 4′/5 in the FUV, which serves as a lower limit to the size of the local region that we can measure. Kelly et al. (2015) used a 10 kpc aperture diameter to measure local star formation, while Rigault et al. (2015) used a 4 kpc diameter. We adopt the R15 4 kpc diameter in this work.

Figure 2 shows representative hosts from our sample with FUV-based log(C_{SFR}) > ~2.9 contours to demonstrate the size of these apertures relative to their star-forming regions. A 4 kpc aperture appears to be a reasonable approximation to the local SN Ia environment in these cases, while a 10 kpc aperture radius encompasses the majority of the SN 2006en host. In the case of SN 2002ha, it is unclear whether either aperture is small enough to capture the star formation environment at the SN location.

3.1.2. Host Galaxy Extinction Correction

There are three principal differences between our local dust correction and that of R15. First, for galaxies without SFRs from Neill et al. (2009; 45% of our sample), R15 used morphological information to determine whether or not a galaxy was globally star-forming. However, GALEX NUV–SDSS r magnitude is a more reliable discriminator between passive and star-forming galaxies (e.g., Salim et al. 2007, their Figure 1). Passive galaxies have NUV-r ≳ 5, while star-forming galaxies have NUV-r ≲ 4. For the 45% of our sample with SDSS images, we corrected for dust in galaxies that had NUV-r < 4.5 based on SExtractor photometry (Bertin & Arnouts 1996). For the final 19% of our sample without Neill et al. (2009) SFR or SDSS images, we used morphology as an estimate of global star formation and performed a local dust correction for Sa and later-type galaxies. We removed three morphologically ambiguous hosts from our sample (SN 2005eu, SN 2006ah, and SN 2006is).

Second, SNe Ia near the edges of galaxies should have negligible local dust. We used SDSS and, when necessary, Digitized Sky Survey images6 to estimate the Sullivan et al. (2006) SExtractor-based R parameter, which gives the SN separation from the host normalized by the size of the host galaxy. For the 28% of SNe approximately outside the isophotal radius of their host galaxy (R > 3; Sullivan et al. 2006), we did not correct for local dust regardless of the Salim et al. (2007) extinction estimate, which does not apply for passive, low-dust regions. R15 dust-corrected all SNe in globally star-forming hosts, regardless of the location of the SN. Figure 3 shows two examples of spiral host galaxies and their approximate isophotal radii.

In total, our decision to apply or not to apply a dust correction was different from that of R15 for 14% of H09 SNe (13/92 SNe). For 7 of these 13 SNe, we did not apply a dust correction because the SN was outside the isophotal radius of its host. The other 6 SNe had morphology-based SF classifications that disagreed with our NUV-r data.

Finally, we adopted a slightly more conservative inclination cut, removing galaxies with inclinations >70° based on the Tully & Fisher (1977) axial ratio method. This removes an additional 16 SNe from the JLA+PS1 sample and 11 from the R11 sample. In total, the inclination cut removes ~13% of our sample.

3.2. Varying the Baseline Analysis

For a robust result, we performed several plausible variants of our baseline analysis (R15 used a similar method to evaluate the robustness of the LSF step). We used the standard deviation of the measured LSF step from all variations to estimate our systematic error.

Our FUV–NUV color measurements have a median signal-to-noise ratio of 3.02. Due to such large photometric uncertainties, the dust correction and resulting Σ_{SFR} is heavily affected by the 2 mag A_{FUV} prior (e.g., SN 2003ic in Figure 2). Because using this prior to correct for dust local to the SN Ia can have up to a ~1 dex effect on the measured Σ_{SFR}, we examined the effect of changing the Bayesian dust prior to A_{FUV} = 1.0 ± 0.6 and A_{FUV} = 3.0 ± 0.6. These values span the full range of A_{FUV} in blue galaxies measured by Salim et al. (2007, see their Figure 13). Changing this prior serves as a way to alleviate some of the uncertainty associated with our global SFR determination; lowering this prior by 1 mag changes ~10 SNe in our sample from Iaα to Ia.

Following R15, we tried an additional three local aperture diameters between 2 kpc and 6 kpc because the choice of a 4 kpc aperture is somewhat arbitrary and other reasonable...

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5 http://irsa.ipac.caltech.edu/applications/DUST/
6 http://archive.eso.org/dss/dss
choices exist. In part, the FWHM of the FUV PSF determines the minimum spatial scale we can probe with GALEX, which is approximately 2 kpc at our median redshift. However, Figure 2 shows that it is still possible that a local aperture will encompass components of a galaxy with different star-forming environments. The higher resolution star formation maps of M33 in Boquien et al. (2015) show large SFR variation on much smaller, sub-kiloparsec scales. Nevertheless, we might hope that star formation within a few kiloparsec aperture is still much better correlated with the SN progenitor environment than a global measurement due to the significant fraction of prompt progenitors and low velocity dispersions of young stars (de Zeeuw et al. 1999).

The boundary between SNe Iaα and Iaκ is also somewhat arbitrary. We used values of log(SFR) between −3.1 and −2.7.
For direct comparison to Kelly et al. (2015), we also examined the boundary between star-forming and passive of log(SFR) = \(-1.7\) and \(-1.85\) (accounting for a \(-0.4\) dex offset between our SFR measurements and Kelly et al. 2015) when discussing Hubble residual dispersion.

Finally, we tried using global rather than local star formation (global star formation is a less noisy measurement), and with or without 2.5\(\sigma\) clipping. Our list of analysis variations is given in Section 4, Table 4.

4. RESULTS

We used 179 GALEX-detected SNe from JLA+PS1 and 157 SNe from R11 to measure the LSF step and distance dispersion. Although for certain variants of the analysis we see differences between SNe Ia and Ia at a level of \(\sim 1\)–3\(\sigma\), the evidence for the LSF step is generally weak.

Although certain peculiar SNe (e.g., SN 1991bg-like and SN 1991 T-like) are not explicitly identified and removed from these samples, the shape and color cuts applied by JLA and R11 are sufficient to remove many of them. However, we make no effort to exclude peculiar SNe that JLA/R11 have determined to be cosmologically useful so that we can directly assess the affect of local SF on the JLA/R11 cosmological analyses. In contrast, Rigault et al. (2013) and R15 explicitly remove identified SN 1991T (\(\sim 3\%) of their sample).

In this section, we do not examine the effect of correcting for the relationship between host mass and SN distance (Sullivan et al. 2010) on the LSF step as only \(\sim 15\%) of our SNe are low-mass hosts (log(M*) < 10; R15 similarly found that few H09 SNe are in low-mass hosts). However, we briefly consider its effect on \(H_0\) in Section 5.2. A complete table with our GALEX measurements and Hubble residuals is available,\(^7\) with the first 25 rows given in Table 3 and the rest in a machine-readable format.

4.1. The Local Star Formation Step

We find a greatly reduced LSF step compared to R15 for all light curve fitters and values of \(R_V\). Using SALT2, we find an LSF step of 0.000 \(\pm\) 0.018 mag. With MLCS \(R_V = 2.5\) (the value used in the R11 baseline analysis), we find 0.029 \(\pm\) 0.027 mag. However, we do find mild evidence for an offset of 0.059 \(\pm\) 0.025 mag with \(R_V = 2.0\) (2.4\(\sigma\) significance). For \(R_V = 3.1\), we found a value of 0.013 \(\pm\) 0.030 mag. Our error budget includes systematic errors, which we estimated by measuring the standard deviation of several variants of our analysis.

Figure 4 presents our baseline measurement of the LSF step and Hubble residual dispersion for SNe Ia in locally passive and locally star-forming environments (SNe Ia and SNe Ia, respectively), with colors indicating the probability incorporated in our likelihood model that a given SN Ia has a locally passive environment, \(P(\text{Ia})\). We find that 47.2\% of R11 SNe in our sample are Ia and 46.0\% of JLA+PS1 SNe in our sample are Ia. The overall intrinsic dispersion for our full MLCS sample (\(~0.13–0.17\) mag; 0.14 for \(R_V = 2.5\)) is higher than for SALT2 (0.12 mag), likely due to the lack of recent calibration of MLCS2k2. Intrinsic dispersion can also be affected by the distribution of light curve parameters in the sample and the robustness of the photometric measurements.

\(^7\) http://www.pha.jhu.edu/djones/lsfstep.html

We find no significant difference in dispersion between SNe Ia and SNe Ia in SALT2. In the R11 MLCS sample, however, we find some evidence that SNe Ia have lower dispersion (\(\sigma_{\text{Ia}}\)) than SNe Ia. For \(R_V = 3.1\), the LSF step is the lowest and \(\sigma_{\text{Ia}}\) is the highest (0.09 mag > \(\sigma_{\text{Ia}}\): 2.6\(\sigma\) with sys. error). These results disagree with R15 at the 3\(\sigma\) level. For MLCS with \(R_V = 2.5\), \(\sigma_{\text{Ia}}\) is \(\sim 0.05\) mag less than \(\sigma_{\text{Ia}}\) (1.9\(\sigma\) significance). For \(R_V = 2.0\) we detected only a \(\sim 0.03\) mag difference in dispersion (1.3\(\sigma\)).

We found that if we restrict to \(z > 0.023\) (the R15 minimum \(z\)), we see more evidence for the LSF step. After this cut, there are 135 SALT2 SNe Ia and 104 MLCS SNe Ia. The increased significance of these results is expected because \(\sim 3/4\) of our MLCS sample is from R15 when we apply this redshift cut. For MLCS \(R_V = 2.0\), 2.5, and 3.1 we find LSF steps of 0.086 \(\pm\) 0.028 (3\(\sigma\)), 0.076 \(\pm\) 0.030 (\(~0.5\%) of R15; 2.5\(\sigma\)), and 0.064 \(\pm\) 0.037 (35\% of R15; 1.8\(\sigma\)). For SALT2, we only find a very small offset, 0.017 \(\pm\) 0.019 (18\% of the R15 result) at 0.9\(\sigma\) significance. The MLCS LSF steps are \(~50\%) of those found by R15. Except in the case of MLCS with \(R_V = 2.0\), the low-\(z\) data alone (0.01 < \(z < 0.023\)) show slightly brighter SNe Ia at \(\sim 0.02\)–0.03 mag but with only 0.5\(\sigma\) significance for MLCS (0.06 mag with 1.4\(\sigma\) for SALT2). This effect is mostly due to \(\sim 5\) bright low-\(z\) SNe, which do not have a large effect on the final result (see the 2.5\(\sigma\) clipping in Table 4). If the peculiar velocity corrections and uncertainties for low-\(z\) SNe were in error, we would expect, but do not observe, a significant increase in uncertainty-weighted \(M^\text{cont}_B\) dispersion below \(z = 0.023\) (we see \(< 0.015\) mag difference). We did not find evidence that our highest \(z\) data (\(z > 0.07\)) had a significant effect on our results.

4.2. Systematic Uncertainties

Several different variants of our analysis are consistent with the baseline result. The JLA+PS1 variants are shown visually in Figure 5, and the R11 variants are shown in Figure 6. For the LSF step, the full results from both data sets are presented in Table 4 and our dispersion results are presented in Table 6. We have added the standard deviation of the LSF step from all variants in quadrature to our measured values (giving each type of variant, e.g., aperture size, SFR boundary, etc., an equal weight). Because using the global SFR is not truly a local measurement, we have excluded it from our error computation but include it in our list of variants for comparison.

For nearly all samples, our most significant detections of the LSF step were at a log(SFR) boundary of \(-3.1\) and a 3 kpc aperture radius. For a log(SFR) boundary of \(-3.1\), with SALT2 and MLCS \(R_V = 2.5\) (the most relevant versions for cosmology), we detected steps of 0.023 \(\pm\) 0.019 and 0.044 \(\pm\) 0.029, respectively. These are \(~25\%) of the R15 values and insignificant.

For MLCS with \(R_V = 2.5\) and 3.1, our most significant detections came from the variant with 2.5\(\sigma\) clipping. They had values of 0.060 \(\pm\) 0.026 mag (2.3\(\sigma\)) for \(R_V = 2.5\) and 0.046 \(\pm\) 0.028 (1.6\(\sigma\)) for \(R_V = 3.1\). This may mean that outliers are affecting our measurement. However, we also expect that they affect the R11 \(H_0\) measurement in the same way, and note that \(R_V = 2.0\) 2.5\(\sigma\) clipping has no significant effect.

The variant with the smallest LSF step was the one based only upon global SFR instead of local. However, the
### Table 3
The LSF Step Sample

| Name     | Survey | $z$     | JLA+PS1 | SALT2 $\Delta M^\text{lim}_{B}$ | R11 MLCS2k2 $\Delta M^\text{lim}_{B}$ | GALEX Data | Global | $R^2$ | Dust Corr. | $\log(C_{\text{SF}})$ | $P(\text{Ia})$ | Cuts |
|----------|--------|---------|---------|----------------------------------|----------------------------------------|------------|--------|-------|-----------|------------------------|-------------|------|
|          |        |         |         | $R_V = 2.0$                       | $R_V = 2.5$                            |            |        |       |           |                        |             |      |
| 010010   | PS1    | 0.100   | 0.270 ± 0.113 | ...                     | ...                                        | 10629      | 24.90 ± 0.21 | SF    | 5.37  | N         | −3.072 ± 0.083 | 98         | Incl |
| 010026   | PS1    | 0.032   | 0.092 ± 0.159 | ...                     | ...                                        | 16222      | 21.75 ± 0.04 | SF    | 1.28  | Y         | −2.239 ± 0.054 | 0          |      |
| 070242   | PS1    | 0.064   | 0.167 ± 0.129 | ...                     | ...                                        | 92341      | 28.82 ± 1.09 | SF    | 35.00 | N         | −4.895 ± 0.259 | 100        |      |
| 10028    | SDSS   | 0.064   | −0.102 ± 0.117 | ...                     | ...                                        | 3272       | 25.68 ± 0.60 | Pa    | 0.46  | N         | −3.712 ± 0.194 | 100        |      |
| 10805    | SDSS   | 0.044   | −0.198 ± 0.128 | ...                     | ...                                        | 8006       | 21.02 ± 0.04 | SF    | 0.88  | Y         | −1.501 ± 0.552 | 0          |      |
| 1241     | SDSS   | 0.088   | −0.092 ± 0.108 | ...                     | ...                                        | 1670       | 26.04 ± 1.50 | SF    | 4.84  | N         | −3.321 ± 0.422 | 97         |      |
| 12779    | SDSS   | 0.079   | 0.055 ± 0.122 | ...                     | ...                                        | 206        | 24.47 ± 2.07 | SF    | 1.91  | Y         | −1.983 ± 0.592 | 15         |      |
| 12781    | SDSS   | 0.083   | 0.191 ± 0.119 | ...                     | ...                                        | 3354       | >26.43       | Pa    | 3.34  | N         | <−3.670 ± 0.071 | 100        |      |
| 12898    | SDSS   | 0.083   | 0.002 ± 0.107 | ...                     | ...                                        | 1627       | 23.38 ± 0.24 | SF    | 0.94  | Y         | −2.160 ± 0.295 | 4          |      |
| 12950    | SDSS   | 0.081   | 0.078 ± 0.102 | ...                     | ...                                        | 4954       | 22.01 ± 0.08 | SF    | 0.55  | Y         | −1.817 ± 0.105 | 0          |      |
| 130308   | PS1    | 0.082   | 0.037 ± 0.123 | ...                     | ...                                        | 4024       | 24.99 ± 0.32 | ~SF   | 0.90  | Y         | −2.451 ± 0.329 | 12         |      |
| 17240    | SDSS   | 0.071   | −0.159 ± 0.143 | ...                     | ...                                        | 3053       | >27.31       | Pa    | 4.15  | N         | <−3.970 ± 0.159 | 100        |      |
| 17258    | SDSS   | 0.088   | −0.188 ± 0.118 | ...                     | ...                                        | 4130       | 23.73 ± 0.20 | SF    | 0.88  | Y         | −1.900 ± 0.251 | 1          |      |
| 17745    | SDSS   | 0.062   | −0.000 ± 0.117 | ...                     | ...                                        | 1643       | 23.34 ± 0.26 | SF    | 0.89  | Y         | −1.973 ± 0.176 | 2          |      |
| 18241    | SDSS   | 0.094   | 0.176 ± 0.165 | ...                     | ...                                        | 544        | 24.19 ± 0.95 | SF    | 1.07  | Y         | −1.885 ± 0.292 | 5          |      |
| 19899    | SDSS   | 0.090   | −0.048 ± 0.107 | ...                     | ...                                        | 2147       | 25.57 ± 0.92 | SF    | 5.88  | N         | −3.220 ± 0.334 | 96         |      |
| 1990af   | JRK07  | 0.050   | −0.063 ± 0.160 | −0.213 ± 0.170         | −0.204 ± 0.178                         | 336        | >24.09       | Pa    | 1.77  | N         | <−3.230 ± 0.071 | 100        |      |
| 1990b    | JRK07  | 0.031   | −0.107 ± 0.150 | −0.071 ± 0.140         | −0.050 ± 0.144                         | 145        | 22.13 ± 0.67 | SF    | 2.95  | Y         | −2.156 ± 0.422 | 9          |      |
| 1990t    | JRK07  | 0.040   | −0.048 ± 0.136 | 0.029 ± 0.194          | 0.019 ± 0.203                         | 208        | 23.45 ± 1.05 | SF    | 3.92  | N         | −3.070 ± 0.583 | 85         |      |
| 1990y    | JRK07  | 0.039   | −0.314 ± 0.155 | −0.139 ± 0.259         | ...                                    | 4063       | 21.41 ± 0.06 | SF    | 1.77  | N         | −2.524 ± 0.027 | 0          |      |
| 1991ag   | JRK07  | 0.014   | −0.150 ± 0.237 | −0.107 ± 0.199         | −0.085 ± 0.200                         | 2301       | 20.10 ± 0.05 | SF    | 1.84  | Y         | −2.134 ± 0.072 | 0          |      |
| 1991is   | JRK07  | 0.056   | 0.025 ± 0.129 | 0.050 ± 0.156          | 0.064 ± 0.164                         | 108        | 23.53 ± 1.31 | SF    | 3.36  | Y         | −2.072 ± 0.375 | 11         |      |
| 1991u    | JRK07  | 0.033   | −0.342 ± 0.143 | −0.346 ± 0.174         | −0.367 ± 0.190                         | 107        | 20.67 ± 0.33 | ~SF   | 0.35  | Y         | −1.593 ± 0.309 | 2          |      |
| 1992ae   | JRK07  | 0.075   | −0.182 ± 0.171 | −0.147 ± 0.172         | −0.086 ± 0.197                         | 224        | 23.70 ± 0.89 | Pa    | 1.84  | N         | −2.730 ± 0.316 | 30         |      |

**Notes.**

a JRK refers to the Jha et al. (2007) sample, which includes SNe from the CfA1, CfA2, and Calan/Tololo SN surveys (Hamuy et al. 1996; Riess et al. 1999; Jha et al. 2006).

b SN separation from the host galaxy, normalized by the SExtractor-measured host galaxy size (Sullivan et al. 2006). We did not apply a local dust correction for SNe with $R > 3$, as these are outside the isophotal radius of the host.

c Visual inspection found that this SN Ia was within the isophotal radius of its host. A dust correction was applied.

(This table is available in its entirety in machine-readable form.)
significance of the difference is only $\lesssim 1\sigma$ except in the case of $R_V = 2.0$. The difference may stem from the fact that 25% of SNe with globally star-forming environments in our samples had locally passive environments ($P(\text{Ia}) > 50\%$). Only 5% of SNe with globally passive environments had a $>50\%$ probability of being locally SF. Qualitatively, this agrees with $H_0$ data from Rigault et al. (2013, their Figure 5), who found that globally star-forming hosts often had locally passive regions.

Even after adding the systematic error in quadrature, the MLCS $R_V = 2.0$ LSF step is detected at 2.4$\sigma$ ($0.059 \pm 0.025$ mag). Future cosmology analyses using MLCS with low $R_V$. 

Figure 4. Our baseline analysis for the JLA+PS1 sample (SALT2; upper left), and the R11 sample with different values of $R_V$ (MLCS2k2 fitter). The color of each SN indicates the probability that it has a locally passive environment, $P(\text{Ia})$. Shaded bars indicate the uncertainty on the mean (dark shading; statistical error only) and the standard deviation of the maximum likelihood Gaussian (the weighted dispersion; light shading). The LSF step is much smaller and has a lower significance than the step found by R15, although we detect it at 2.6$\sigma$ for the $R_V = 2.0$ case (2.4$\sigma$ with systematic errors). For $R_V = 3.1$ and 2.5, we find lower dispersion among SNe in locally passive environments than those in locally star-forming environments at 3.3$\sigma$ and 2.2$\sigma$, respectively. For consistency with R15, SNe with only $\Sigma_{\text{SFR}}$ upper limits are placed at $\log(\Sigma_{\text{SFR}}) = -5.3$. Systematic uncertainties are estimated from several variants of our analysis (Table 4).
should measure the LSF step in their samples to evaluate its effect on cosmology.

The difference in the dispersion between the two SN populations in MLCS is greatest in those same analysis variants discussed above, but as with our baseline analysis, we see an effect opposite to that found by R15. We do not detect any difference in dispersion for SALT2 with the exception of using global instead of local SFR, for which we find a $0.05 \pm 0.018$ mag ($2.8\sigma$) reduction in dispersion for passive hosts. For MLCS $R_V = 2.5$ and 3.1, we find a reduction in dispersion for locally passive SNe of $\sim0.05-0.1$ mag ($\sim1-3\sigma$) for a log ($\Sigma_{SFR}$) boundary of $-3.1$ and a 3 kpc aperture radius.

### 4.3. Consistency with R15

R15 measured a much larger LSF step of 0.094 ± 0.037 mag with SALT2, 0.155 ± 0.041 mag with MLCS2k2 $R_V = 2.5$ and 0.171 ± 0.040 mag with MLCS2k2 $R_V = 3.1$. We did not directly compare to their $R_V = 1.7$ data, but our $R_V = 2.0$ offset is 50% smaller than theirs. Our measured SALT2 LSF step has a $2.3\sigma$ discrepancy with the R15 measurement, our MLCS2k2 $R_V = 2.5$ LSF step has a $2.6\sigma$ discrepancy, and our MLCS2k2 $R_V = 3.1$ LSF step has a $3.2\sigma$ discrepancy.

Table 4 demonstrates the step-by-step impact of changes in e.g., aperture size variants, SFR boundary variants, etc. The global SFR variant is excluded.

Table 5 demonstrates the step-by-step impact of changes in e.g., aperture size variants, SFR boundary variants, etc. The global SFR variant is excluded.

Note. Bold values indicate that a negative difference in dispersion was measured for these analysis variants.

$^a$ The systematic error is computed from the standard deviation of each type of variant (e.g., aperture size variants, SFR boundary variants, etc.). The global SFR variant is excluded.
there is significant scatter in probability for $10^\% < P(\text{Ia}) < 90^\%$, in large part due to our modest changes in dust correction methodology. However, we find only 3\% median offset in $P(\text{Ia})$ between our data and R15 and in Section 4.6 we find that our method of $\Sigma_{\text{SFR}}$ measurement has little impact on the final results. Our full set of $\Sigma_{\text{SFR}}$ measurements can be compared to R15 using the data we provide online and in Table 3.}

There are four SNe in R11 and four SNe in JLA that pass the R11/JLA light curve cuts but do not pass the H09 cuts (SNe 1992d, 1993h, 1999aw, 2001ic, 2006bd, 2006gt, 2007ba, and 2007cq). We found that including them reduces the SALT2 LSF step by a significant 37\% (0.9\$\sigma$) and reduces the MLCS LSF step by ~15\% (0.9\$\sigma$). When applying any LSF-dependent effect to cosmology, it is appropriate to match the cuts used in the cosmological analysis to those used in the measurement.

For both the LSF step and the dispersion in MLCS, there is a $>1\sigma$ change when we use the full SN Ia sample. Although the total statistical change from 3.6\$\sigma$ to 1.2\$\sigma$ is large, we do not expect this to be a result of peculiar velocity bias from our low-z data. Some of the change may result from a greater sample dispersion, which reduces the significance of small offsets. A dispersion term is typically added in quadrature to distance modulus uncertainties in cosmological analyses, including R11 and Betoule et al. (2014), and has the same effect. In addition, Table 5 does not incorporate systematic error, which may have an impact; high-z data effectively have a larger aperture size due to a PSF width that is a greater fraction of the 4 kpc aperture diameter. Figure 6 shows that aperture variations may have up to a $\sigma$ effect on the measured LSF step, and to expand our sample size we have preferentially added low-z data with smaller effective apertures (0.01 < z < 0.023).

Table 5 shows that the MLCS increase in Iao dispersion is mostly caused by the addition of new SNe rather than to our $\Sigma_{\text{SFR}}$ measurements or new distance moduli. The surveys that comprise our sample typically have larger dispersion than H09, which reduces the significance of the H09 sample. There are a number of possible sources for increased dispersion of a SN Ia sample, including underestimating photometric difference image uncertainties near bright hosts and nightly or absolute photometric calibration uncertainties (Scolnic et al. 2014a). For MLCS, R11 may also have higher sample dispersion because they make no cut on the $\chi^2$ of the MLCS light curve fits, while H09 remove SNe with reduced $\chi^2 > 1.5$.

4.4. The Effect of MLCS Sample Cuts

In MLCS, the total difference of ~0.14 mag between our analysis and R15 may appear surprising, but in addition to the possible reasons discussed above, much of the change between the R15 measurement and ours appears to arise from the different demographies of the two samples and the peculiarities of the MLCS light curve fitter. H09 find that for both high $\Delta_S$ SNe and high $\Delta$ SNe, MLCS tends to overcorrect leading to negative residuals, and these negative residuals are not subtle. In our $R_S = 2.5$ sample, SNe with $\Delta_S > 0.5$ have a mean residual of ~0.22 mag, which has been seen elsewhere as evidence for a lower $R_S$ in high-extinction environments. Likewise, SNe with $\Delta > 0.7$, where the relation between light curve shape and luminosity becomes non-linear and is poorly sampled especially when MLCS2k2 was trained, have a mean residual of ~0.23 mag. Accordingly, the balance of rare high $\Delta$ SNe to rare high $\Delta$ SNe can affect an apparent LSF step as the frequency of these objects correlates with host properties.

Passive hosts have preferentially higher $\Delta$ than SF hosts (H09, their Figure 19), while SF hosts have preferentially higher $\Delta_S$. In R15, the H09 data that have GALEX imaging and pass their cuts contain several SNe with large $\Delta$ but only two SNe with $\Delta_S > 0.45$ for $R_S = 1.7$ (for $R_S = 3.1$, only two SNe with $\Delta_S > 0.7$). Therefore, a sample like R15 without high $\Delta_S$ hosts but with high $\Delta$ hosts will have brighter passive SNe Ia on average, producing a larger apparent LSF step.

One approach to decrease sensitivity to the MLCS Hubble residual trends is to first remove the trends, and then determine the LSF step. In Figure 7, we fit a simple linear model to MLCS Hubble residuals as a function of $\Delta$ and $\Delta_S$, using the R11 SNe in H09 (with $\Delta_S > 1.5$ and $\Delta < 1.5$ to match H09). When we correct for these slopes, we see that the measured LSF step using the R11 SNe in H09 shrinks by a factor of 2.5 and is reduced from 4.5\$\sigma$ to 1.6\$\sigma$ significance.

SALT2 does not have the strong residual trends with $X_1$ and $C$ that MLCS does with $\Delta_S$ and $\Delta$, and we also find that restricting our sample to the H09 “best” SALT2 cuts (−0.1 < C < 0.2) does not introduce an LSF step (but changing $\beta$ may; see Section 5.1). However, it is likely that recent substantial improvements to the SALT2 model have removed some of the biases in its derived distances. Due to the lower dispersion of the SALT2-fit SNe, the lack of these residual trends, and because MLCS fits assume an extinction law, it is likely that SALT2 is more effective at standardizing SNe Ia.

In a future update of MLCS using a larger training sample, it would be important to verify that these trends with host, $\Delta_S$ and $\Delta$ are diminished.

4.5. Kelly et al. (2015) Scatter

Using MLCS, Kelly et al. (2015) see reduced Hubble residual scatter of only 3.5\% in distance in highly star-forming regions (log($\Sigma_{\text{SFR}}$) > −2.1 and log($\Sigma_{\text{SFR}}$) > −2.25). Due to differences in methodology, there is a ~0.4 dex offset in $\Sigma_{\text{SFR}}$ measurements between our data and those of Kelly et al. (2015). Because of this, we adopt log($\Sigma_{\text{SFR}}$) > −1.7 and log($\Sigma_{\text{SFR}}$) > −1.85 as our $\Sigma_{\text{SFR}}$ boundaries for comparison.

In part, the low scatter seen by Kelly et al. (2015) is because they explicitly remove SNe with Hubble diagram residuals >0.3 mag (>15\% in distance). Because of this and because the R11 sample does not cut SNe with high extinction or large $\Delta$, our unweighted standard deviation is a significantly larger, ~0.25 (12\% in distance), for the R11 sample at log($\Sigma_{\text{SFR}}$) > −1.7 and log($\Sigma_{\text{SFR}}$) > −1.85. For SALT2, the standard deviation is a slightly lower, 0.20 mag, or 10\% in distance, with no difference between SNe in locally passive/locally star-forming environments.

We also see no difference in uncertainty-weighted dispersion for these $\Sigma_{\text{SFR}}$ boundaries in SALT2, and we find that the dispersion for SNe in both passive and star-forming environments in SALT2 data is smaller than the lowest dispersions we observe with MLCS. The scatter in our sample is much higher than in Kelly et al. (2015), and we find a ~0.02 mag (~14\%; ~0.1–0.5\$\sigma$) reduction in dispersion for MLCS with $R_S = 2.0$. SNe in star-forming environments have higher dispersion with low significance for MLCS $R_S = 2.5$. For $R_S = 3.1$, SNe in star-forming environments have ~0.07 mag higher dispersion at ~$\sigma$ significance. A summary of our intrinsic dispersion measurements are in Table 7.
2.5, 2.0, 2.0. This is not a local measurement.

The global SFR variant is excluded from the systematic error calculation, as our measured systematic errors are only a small fraction of our statistical errors. SALT2. The results from different variants of our analysis are very consistent; SNe, but shrinks to shows our full SN Ia data set. The step we detect is quadrature to the uncertainties from each individual variant. The top panel bars represent the standard deviation of all variants of our analysis added in different variants of our analysis on the measurement of the LSF step. Red error Figure 5.

Systematic error of the SALT2 LSF step estimated by the effect of different variants of our analysis for $R_v = 2.0, 2.5,$ and $3.1$ in the R11 SN Ia sample. The LSF step has $2.4\sigma$ significance for $R_v = 2.0$. The baseline analysis used to determine $H_0$ uses $R_v = 2.5$, for which we see a small LSF step at $1.1\sigma$ significance. We see $<1\sigma$ significance for $R_v = 3.1$. The blue dashed lines and shaded regions show the R15 LSF step and $1\sigma$ uncertainties for MLCS2k2. The global SFR variant is excluded from the systematic error calculation, as this is not a local measurement.

If we apply the H09 $\Delta$ and $A_V$ cuts to our data, we still see an effect opposite to that found by Kelly et al. (2015). We can only reproduce the Kelly et al. (2015) results using their strict $\Delta$ and $A_V$ cuts, which have not been used in any cosmological analysis to date. However, these cuts may prove useful in the future if this low-scatter population persists when additional SNe are added to the data.

4.6. Additional Consistency Checks

We performed several consistency checks to verify that individual SN data sets and differences between our analysis and R15 did not bias our results. First, we removed SNe discovered prior to the year 2000, leaving 130 SNe from JLA/PS1 and 116 SNe from R11. Our results were consistent with our baseline analysis; we measured a SALT2 LSF step of $0.010 \pm 0.025$ mag and an MLCS $R_V = 2.5$ step of $0.040 \pm 0.031$ mag. The $R_V = 2.0$ step was a slightly higher, but consistent, $0.079 \pm 0.030$ mag ($2.7\sigma$). The dispersion of SNe in highly SF regions was not significantly reduced.

Second, the photometry and calibration from low-$z$ surveys is not as robust as recent data from SDSS and PS1. The JLA/PS1 sample has 37 SNe with redshifts less than 0.1 that have GALEX data and pass our cuts, while the R11 sample includes no SDSS/PS1 SNe as it predates them. For comparison, we fit SDSS and PS1 SNe with MLCS to see if the LSF step derived from these surveys alone are consistent with the R11 results. With SALT2, we find an LSF step of $0.034 \pm 0.028$ mag with lower SF dispersion by $0.049 \pm 0.024$ mag ($2.0\sigma$). With MLCS, we find a large LSF step with 35 SNe of $\sim 0.14 \pm 0.055$ mag with $1.7-2.9\sigma$ significance. As the sample consists of only $\sim 10-15$ locally passive SNe, this step could still be caused by low statistics or a limited range of light curve parameters comprising the sample. As discussed in Section 4.4, the trends MLCS residuals have with different light curve parameters may be a factor, as the size and significance of the LSF step is somewhat reduced when this sample is restricted to low $\Delta$ and $A_V$. This step is also unlikely to affect recent cosmological analyses, which are based on SALT2 or comprised mainly of low-$z$ data (e.g., H09; R11). However, it is an interesting result that should be explored further with photometric PS1 SNe and future Dark Energy Survey (DES) data. This sample is too small at log($\Sigma_{SFR}$) $> -1.85$ for a reliable check on our Kelly et al. (2015) comparison.

If we make a host galaxy inclination cut at $> 80^\circ$ following R15 (instead of our more conservative cut of $> 70^\circ$), the results are consistent with our baseline result, with MLCS LSF steps ranging from $0.00$ mag ($R_V = 3.1$) to $0.045$ mag ($R_V = 2.0$) with uncertainties $\sim 0.025$ mag. The SALT2 LSF step is $-0.016$ mag ($<1\sigma$ significance).

Finally, we apply a dust correction to the FUV flux from all SN regions in star-forming hosts when determining $\Sigma_{SFR}$, now including the 20 R11 SNe and 25 JLA/PS1 SNe with $R > 3$ (see Section 3.1.2). We again find a comparable result; the SALT2 LSF step is $0.012 \pm 0.019$ mag, and the MLCS $R_V = 2.5$ LSF step is $0.040 \pm 0.028$ mag.
Table 6

The Effect of Step-by-Step Changes in R15 Data, Distances, SFR Measurements, and Sample Cuts

| Measurements | SALT2 | MLCS $R_V = 2.5$ |
|--------------|-------|------------------|
| SN Sample    | $\mu_{\text{resid}}$ | $\Sigma_{\text{SFR}}$ | SN Cuts | SNe | $\delta(M_b^{\text{core}})_{3\sigma}$ | Sig. | $\delta_{\text{LCS}} - \delta_{\text{R15}}$ | SNe | $\delta(M_b^{\text{core}})_{3\sigma}$ | Sig. | $\delta_{\text{LCS}} - \delta_{\text{R15}}$ |
| H09          | H09   | R15              | H09     | 77  | 0.093 ± 0.026 | 3.5$\sigma$ | −0.034 ± 0.073 | −0.5$\sigma$ | 81  | 0.169 ± 0.026 | 6.5$\sigma$ | 0.057 ± 0.033 | 1.7$\sigma$ |
| H09          | H09   | R15              | JPR$^c$, H09 | 59  | 0.129 ± 0.030 | 4.3$\sigma$ | 0.012 ± 0.047 | 0.2$\sigma$ | 74  | 0.144 ± 0.025 | 5.6$\sigma$ | 0.038 ± 0.034 | 1.1$\sigma$ |
| H09          | JPR   | R15              | JPR, H09 | 59  | 0.062 ± 0.032 | 1.9$\sigma$ | 0.030 ± 0.031 | 1.0$\sigma$ | 74  | 0.149 ± 0.025 | 5.9$\sigma$ | 0.023 ± 0.031 | 0.7$\sigma$ |
| H09          | JPR   | Here$^d$          | JPR, H09 | 59  | 0.071 ± 0.033 | 2.2$\sigma$ | 0.009 ± 0.031 | 0.3$\sigma$ | 74  | 0.119 ± 0.026 | 4.5$\sigma$ | −0.010 ± 0.030 | −0.3$\sigma$ |
| H09          | JPR   | Here$^e$          | JPR$^e$ | 63  | 0.045 ± 0.033 | 1.3$\sigma$ | 0.015 ± 0.030 | 0.5$\sigma$ | 78  | 0.097 ± 0.027 | 3.6$\sigma$ | −0.029 ± 0.030 | −1.0$\sigma$ |
| JPR$^c$      | JPR   | Here$^e$          | JPR, $z > 0.023$ | 135 | 0.017 ± 0.019 | 0.9$\sigma$ | −0.020 ± 0.019 | −1.1$\sigma$ | 103 | 0.076 ± 0.029 | 2.6$\sigma$ | −0.041 ± 0.029 | −1.4$\sigma$ |
| JPR$^e$      | JPR   | Here$^e$          | JPR$^e$ | 179 | 0.000 ± 0.018 | 0.0$\sigma$ | −0.013 ± 0.018 | −0.7$\sigma$ | 156 | 0.029 ± 0.025 | 1.2$\sigma$ | −0.053 ± 0.024 | −2.2$\sigma$ |

Notes. We show the difference between our analysis and R15 by improving one element of the analysis at a time. We start with the R15 results and sequentially show the effect of adding light curve cuts from JLA+/PS1/ R11, using JLA/ R11 distance moduli, using JLA/ R11 light curve cuts, and finally adding in the full SN samples with and without the R15 redshift cut of $z > 0.023$. The biggest differences come from adding the full sample for both SALT2 and MLCS and using the improved SALT2 distance moduli. The R11 SN light curve cuts also make a 1$\sigma$ difference in the MLCS results. For consistency, we have used the likelihood minimizer used in the rest of this study to reproduce the R15 results (The SciPy Optimize package). This minimizer returns smaller uncertainties than Minuit, which was used in R15, but we find negligible differences in the maximum likelihood values themselves. The difference in LSF step we find for the R15 data with MLCS (our value is 0.014 mag higher) is because we adopt two separate dispersions for SNe Ia and SNe Ia whereas R15 use a single value for the full sample. Bold values demarcate the element of the analysis that has changed relative to the previous line in the table. The biggest differences come from adding the full sample for both SALT2 and MLCS and using the improved SALT2 distance moduli.

$^a$ $\delta(M_b^{\text{core}})_{3\sigma}$ denotes the magnitude of the LSF step.

$^b$ The difference in uncertainty-weighted dispersion between SNe Ia and Ia (using the standard deviation of the maximum likelihood gaussians; $\delta_{\text{LCS}}$ and $\delta_{\text{R15}}$ in Equation (3)).

$^c$ JLA+/PS1 $M_b^{\text{core}}$ for SALT2, R11 $M_b^{\text{core}}$ for $R_V = 2.5$.

$^d$ Measurements of $\Sigma_{\text{SFR}}$ from this work (see Section 3).

$^e$ The full JLA+/PS1 (SALT2) and R11 (MLCS) SN samples.
5. DISCUSSION

We find that local star formation has little to no effect on SN Ia distances in the R11 and JLA+PS1 samples. Our results have several important implications for cosmological analyses, $H_0$, and future measurements of relationships between SNe Ia and their host galaxy properties.

5.1. The Effect of $\beta$ and $R_V$ on SN Ia Distances

Although the modest differences we observe in mean magnitude and dispersion for MLCS with certain values of $R_V$ could be due to the relation between SN Ia progenitor properties and derived distances, we consider it much more likely that host galaxy extinction, which is highly correlated with star formation, is causing any observed bias. We propose that some of the effects seen in R15, Kelly et al. (2015), and our data may be due to dust rather than to a secondary effect such as the progenitor age (e.g., Childress et al. 2014).

With MLCS, the LSF step we found is $0.046 \pm 0.039$ mag higher assuming $R_V = 2.0$ than assuming $R_V = 3.1$ (systematic errors added). The $R_V = 2.0$ LSF dispersion is $0.053 \pm 0.044$ (stat+sys) mag lower than $R_V = 3.1$. It has been observed by several groups (e.g., Burns et al. 2014) that SNe Ia in high-extinction environments have lower values of $R_V$. Because of this, it seems likely that the $R_V = 3.1$ extinction law is failing to properly correct for the dust in some star-forming regions.

For SALT2, our value of $\beta$ has a value $\sim 0.6$ higher in the latest cosmological analyses than the value found in H09. This can have an important effect on the measured LSF step. For example, a SNe Ia in a locally star-forming environment with $\sim 0.17$ mag of $A_V$, would have its corrected magnitude shifted by 0.1 mag with this new value of $\beta$. For comparison, R15 SNe with locally star-forming environments have a mean fitted $A_V = 0.25$ for $R_V = 3.1$ and $A_V = 0.22$ for $R_V = 1.7$. We do not see such a large effect in our data, and would not expect $\beta$ to have the exact effect of $R_V$, but we do find that using a lowered $\beta$ of 2.5 (the value used in H09) in our analysis raises the SALT2 LSF step to $0.024 \pm 0.018$ (1.3$\sigma$ significance).

In future cosmological analyses, it may be possible to separate star-forming and passive hosts and fit for two different values of $\beta$ or $R_V$. This could reduce scatter and provide more precise SN Ia distances for subsets of the population, provided the systematic uncertainties in such an analysis are well understood.

The SALT2 light curve fitter shows the least difference between SNe Ia in and SNe Ia $M^\text{SALT2}_{B}$ and also has the lowest dispersion in both star-forming and passive regions. The lowest dispersion we find using MLCS is still higher than the SALT2 dispersion for both SNe Ia and Iao. For this reason, SALT2 may be a more reliable light curve fitter for cosmological analyses. In its current version, MLCS fails to standardize SNe Ia to the extent that SALT2 does and has fitter biases that correlate with host properties (such as Hubble residual nonlinearities with $\Delta$ and an assumed value for $R_V$). Perhaps a re-trained version of MLCS that incorporates terms such as random SN color scatter (Scolnic et al. 2014b) would reduce the MLCS outlier fraction and provide more precise distances.

5.2. The Effect on Measuring $H_0$

Because our final measurement of the LSF step with $R_V = 2.5$ is only a 1.2$\sigma$ detection, there are no grounds in the Bayesian sense to correct $H_0$ for the LSF step. However, a useful test of systematic uncertainties in the future will be to use only star-forming hosts in the Hubble flow sample, which have similar physical properties to the nearby Cepheid-calibrated sample and will better control for unknown biases in metallicity, dust, or progenitor age.

Adopting the 47.2% SN Ia fraction we find for R11 and the 7.0% SN Ia fraction found by R15 for the Cepheid sample with Equation (1), we find no evidence for a reduced value of $H_0$. Following R15, if we were to replace the host mass step with the LSF step, our measurement suggests a 0.1% increase in $H_0$ because the size of the LSF correction is slightly less than the size of the host mass correction.

One caveat is that R11 added the MLCS intrinsic SN Ia dispersion but not the full apparent intrinsic dispersion in quadrature to the distance modulus uncertainties in their
Hubble flow SNe. We find that forcing our maximum likelihood Gaussian model to use only the MLCS intrinsic dispersion of 0.08 mag raises the magnitude of the $R_V = 2.5$ LSF step we derive to 0.045 ± 0.019 (a 2.4σ detection, but 2.1σ with systematic uncertainty added). This could be because it allows outliers to have a greater effect on the measurement. However, applying this correction after removing the host mass step still only results in a reduction in $H_0$ of 0.11 km s$^{-1}$ Mpc$^{-1}$. The R11 value for $H_0$ is within the 1σ uncertainty of the LSF step. The highest LSF step we are able to find using all our analysis variants with 0.08 mag dispersion is 0.066 ± 0.022 mag (the 2.5σ clipped variant), and even this extreme measurement lowers $H_0$ by only 0.4 km s$^{-1}$ Mpc$^{-1}$.

Finally, if we measure the LSF step after host mass correction using masses fromNeill et al. (2009, 53% of the R11 sample) and again using a dispersion of 0.08 mag, we find a LSF step of 0.023 ± 0.027 (stat+sys) mag for $R_V = 2.5$. This results in a small reduction of 0.3 km s$^{-1}$ Mpc$^{-1}$. Because we detect this effect at <1σ (with systematic error added in quadrature), we do not believe a correction is justified.

5.3. Future Measurement of the LSF Step

Although we have only detected the LSF step at low significance with GALEX FUV data, GALEX alone is not the best tool for studying local regions due to its large PSF width and the uncertain UV extinction correction. The LSF step would be best identified in local Ho (e.g., Rigault et al. 2013), high-resolution UV data from the Hubble Space Telescope (HST), or local SED fitting.

Table 5 shows that sample selection has a significant effect on our results. We suggest that studies examining host galaxy effects use the same SN Ia samples and selection criteria as the latest cosmology analyses when possible. It may be possible to detect the LSF step or differences in dispersion at higher significance using different light curve or distance modulus cuts, but the results of such analyses would not necessarily apply to typical measurements of cosmological parameters.

Local SED fitting may be the optimal approach for studying the relation between host galaxy properties and SN Ia distances, as it can put simultaneous (albeit sometimes degenerate) constraints on a number of parameters that may correlate with SN Ia distances such as stellar age, extinction, star formation history, and mass contained in a local region. Approaches that do not depend entirely on GALEX data will also be able to measure local regions at higher redshifts and put better constraints on possible redshift-dependent biases.

The size of the samples with which we can examine the effects of host galaxy properties on SN Ia corrected magnitudes will increase dramatically in the next few years. The PS1 photometric sample alone will consist of up to ~2000 SNe Ia with cosmologically useful light curves. The DES will contribute thousands more up to redshifts of ~1. Although measurements of local regions become more difficult at high-$z$, a ground-based optical survey with PSF FWHM ~ 1 arcsec will be able to use a much larger SN sample provided the absence of UV data is not prohibitive. Surveys such as PS1 or DES are able to examine local regions of 5 kpc diameter, similar in size to the apertures used in this study, up to $z \approx 0.35$.

6. CONCLUSIONS

Analyzing the same SNe Ia used to determine the most recent values of $w$ and $H_0$, we find little evidence for a LSF step, which suggests that correcting cosmological parameters for this effect is not necessary. There is only 1.1σ evidence for the LSF step in R11 MLCS data assuming $R_V = 2.5$ (the $R_V$ R11 used in their baseline analysis) and 0.0σ evidence for the LSF step in the JLA+PS1 SALT2 data. Our most significant detection uses MLCS data assuming $R_V = 2.0$, for which we find 2.4σ evidence for a step. The sizes of both of these steps are greatly reduced compared to the measurement of R15. Lower values of $\beta$ in SALT2 and $R_V$ in MLCS may increase the size and the significance of the LSF step.

Compared to R15, differences in our $\Sigma_{\text{SFR}}$ measurement and dust-correction technique reduced the size of the MLCS LSF step by ~20% and increased the SALT2 LSF step by ~15%. Using MLCS sample cuts from R11 reduced the offset by an additional ~20% and adding the full R11 sample reduced the offset to 0.029 ± 0.027 mag, likely due to the higher dispersion and better statistics of the full sample. Using new distance moduli and sample cuts from only Betoule et al. (2014) and not H09, reduced the SALT2 LSF step by 60% and using the full JLA+PS1 sample reduced the SALT2 step to a value of 0.000 ± 0.018 mag.

MLCS sample cuts have a significant impact on the results. The MLCS Hubble diagram residuals are more negative at greater $A_V$ and $\Delta$, which must be carefully taken into account in cosmological analyses. In particular, passive hosts are known to have preferentially higher $\Delta$ but lower $A_V$ (H09). We suspect that because the R15 sample had few high $A_V$ SNe but a wide range of $\Delta$, their locally star-forming SNe had preferentially fainter Hubble residuals.

We found that the JLA+PS1 SNe fit with SALT2 had lower dispersion than the MLCS-fit R11 SNe in star-forming or passive environments. We also found that locally star-forming SNe in our sample did not have lower dispersion at log($\Sigma_{\text{SFR}}$) > −2.9. In MLCS with $R_V = 3.1$, SNe Ia in locally passive environments have lower dispersion than those in locally star-forming environments by ~0.09 mag, a 2.5σ result. Using MLCS with $R_V = 2.5$, we see a 0.053 ± 0.029 mag difference.

The lowest SN Ia dispersions come from using SALT2 distance moduli. In contrast to Kelly et al. (2015), with MLCS we found no evidence that SNe in highly star-forming environments have lower dispersion than locally passive SNe using $R_V = 2.0$. With $R_V = 3.1$ we found that SNe in star-forming environments had greater dispersion (~1–2σ significance), but note that we did not make the Kelly et al. (2015) sample cuts. We can only reproduce the Kelly et al. (2015) results by using their strict cuts on the SN light curve parameters $\Delta$ and $A_V$ and removing SNe with Hubble residuals >0.3 mag, which restricts our sample to largely the same data as Kelly et al. (2015).

The LSF step may also be difficult to detect because of the large PSF width of GALEX and it may also be that the LSF step is only apparent in analyses with certain types of light curve selection or outlier rejection. Future studies with local H0, SED fitting, or HST UV observations will have an improved ability to detect local effects. Our results also show that certain SN sample cuts may inadvertently increase biases in cosmology. We expect that with the large SN Ia samples from PS1 and DES that will be published in the next few years, the systematic
Table 7
Star Formation Dispersion with the Kelly et al. (2015) SFR Boundaries

| SFR Boundary | SNe  | $\sigma_{\text{passive}}$ | $\sigma_{\text{SF}}$ | Sig | SNe  | $\sigma_{\text{passive}}$ | $\sigma_{\text{SF}}$ | Sig | SNe  | $\sigma_{\text{passive}}$ | $\sigma_{\text{SF}}$ | Sig |
|--------------|------|-------------------------|-----------------|-----|------|-------------------------|-----------------|-----|------|-------------------------|-----------------|-----|
| $-1.7$ dex   | 179  | $0.127 \pm 0.010$       | $0.118 \pm 0.034$ | $0.3\sigma$ | 157  | $0.145 \pm 0.013$       | $0.141 \pm 0.046$ | $0.1\sigma$ | 156  | $0.193 \pm 0.014$       | $0.138 \pm 0.065$ | $0.9\sigma$ |
| $-1.85$ dex  | 179  | $0.114 \pm 0.010$       | $0.118 \pm 0.026$ | $-0.1\sigma$ | 157  | $0.146 \pm 0.013$       | $0.129 \pm 0.035$ | $0.5\sigma$ | 156  | $0.169 \pm 0.014$       | $0.171 \pm 0.040$ | $-0.0\sigma$ |

Note.
Bold values indicate that a negative dispersion was measured for these analysis variants.
uncertainties on $H_0$ and the dark energy equation of state will come into clearer focus.

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**APPENDIX**

**CALCULATION OF PROBABILITIES AND MAXIMUM LIKELIHOOD ESTIMATION**

The only significant difference between our method of measuring the maximum likelihood LSF step and Hubble residual dispersions and the R15 method is that we allowed the intrinsic dispersion of both SN Ia populations (Iac and $Iac_t$) to be fit by our maximum likelihood model. We describe our full procedure below.

We first converted the dust-corrected FUV flux into $\Sigma_{SFR}$ following R15 (their Equation (1)). We set the boundary between the locally star-forming and locally passive population at $\log(\Sigma_{SFR}) = -2.9$ as in R15, and measured the probability that the SN Ia exploded in a locally passive environment based on the full probability distribution from our dust-corrected photometric measurements.

We used these probabilities to construct a maximum likelihood model assuming two Gaussian populations of SNe with different mean Hubble residuals and dispersions. The likelihood is determined by the equation:

$$L_i = P(Iac) \times \frac{1}{\sqrt{2\pi(\sigma_i^2 + \sigma^2_\alpha)}} \exp\left(-\frac{(M_{i,i}^{corr} - \mu_\alpha)^2}{2(\sigma_i^2 + \sigma^2_\alpha)}\right)$$

$$+ P(Iac_t) \times \frac{1}{\sqrt{2\pi(\sigma_i^2 + \sigma^2_\alpha)}} \exp\left(-\frac{(M_{i,i}^{corr} - \mu_\alpha)^2}{2(\sigma_i^2 + \sigma^2_\alpha)}\right)$$

(3)

where $M_{i,i}^{corr}$ is the corrected magnitude and $\sigma_i$ is the corrected magnitude uncertainty of a given SN Ia. $P(Iac)$ and $P(Iac_t)$ are the probabilities that the SN environment is locally star-forming or locally passive, respectively. $\mu_\alpha$, $\sigma_\alpha$, and $\sigma$ are free parameters equal to the means and standard deviations of the normal distributions of SNe Ia $\alpha$ and Iac. To determine these parameters, we found the maximum likelihood model by minimizing:

$$\log(L) = -2 \sum_{i=1}^{N} \log(L_i)$$

(4)

where $N$ is the number of SNe Ia in the sample.

Instead of adding an intrinsic dispersion term in quadrature to the Hubble residuals such that the reduced $\chi^2$ of the sample is 1, as is commonly done in cosmological analyses (and in R15), we fit to the standard deviations of our Gaussian maximum likelihood model for SNe Ia $\alpha$ and Iac. We verified that allowing the dispersion to be fit by our model instead of specifying it beforehand does not affect our results.

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