Probing Systematic Bias in Low-redshift Type Ia Supernova Measurements by Cross Analyzing Surface Brightness and Hubble Residuals

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Abstract

For low-redshift ($z < 0.1$) SN Ia samples used in several cosmological analyses over the past decade, we probe for systematic bias by looking for correlations between surface brightness (SB) measurements and Hubble residuals (HR). For 292 SNe Ia, we measure SB at the location of the SN Ia from publicly available Pan-STARRS (PS1) images. The Hubble residuals are from two recent measurements with low-$z$ SNe Ia that overlap the PS1 footprint: (1) the DES 3 yr cosmology analysis, with 120 overlapping low-$z$ SNe Ia from the Harvard-Smithsonian Center for Astrophysics surveys and Carnegie Supernova Project, and (2) the PS1 single-telescope analysis, with 172 overlapping low-$z$ SNe Ia from the Foundation Supernova Survey. This study is motivated by previous reports of anomalous inefficiencies and flux scatter for transients on bright galaxies. We compare HR distributions of the bright and faint halves of the SB distribution: the mean HR values differ by $\Delta HR = 0.031 \pm 0.018$, consistent with no difference at the $2\sigma$ level. We also perform a Kolmogorov–Smirnov (KS) test for the bright and faint half HR distributions, and conclude that the two distributions are statistically consistent with a KS $p$-value of 0.07. However, if future studies with larger data sets find $\Delta HR \sim 0.03$ with high significance, this difference would be a leading systematic uncertainty in measurements of the dark energy equation of state, $w$.

Key words: Supernovae

1. Introduction

Since the discovery of cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999), SN Ia distance measurements continue to be a critical analysis tool for measuring cosmic distances and the properties of dark energy. To measure the dark energy equation of state, $w$, with high precision, accurate SN Ia photometry and calibration is crucial. Efforts to improve these measurements have been made by large-area surveys such as the Sloan Digital Sky Survey (SDSS; Kessler et al. 2009), Supernova Legacy Survey, (SNLS; Astier et al. 2006; Guy et al. 2010), Pan-STARRS (PS1; Scolnic et al. 2018; Jones et al. 2019), Dark Energy Survey (DES; DES Collaboration et al. 2019), and Joint Light-curve Analysis (JLA; Betoule et al. 2014). These analyses find that cosmic acceleration is consistent with a cosmological constant ($w = -1$), and the combined statistical and systematic uncertainty on $w$ is $\sim 0.05$. As part of these measurements, it is important to quantify systematic uncertainties from many effects including zero-points, filter transmissions, and spectral energy distribution (SED) dependencies. Here we explore a new systematic effect related to the local surface brightness (SB) of the underlying galaxy.

This search is motivated by recent reports of anomalous detection inefficiencies and flux scatter of transients on bright galaxies, where anomalous refers to effects that are much larger than expectations from increased Poisson noise. For the DES transient detection pipeline, Kessler et al. (2015) used fake SN Ia light curves overlaid on images to show that flux uncertainties are underestimated in proportion to local galaxy SB (see Figure 10 of Kessler et al. 2015). For the brightest sources, which generally correspond to lower redshifts ($z \sim 0.1$), the SN Ia flux uncertainty is under-estimated by about a factor of 5. For a kilonova search using data from DES, Doctor et al. (2017) also examined fake transients and found decreasing detection efficiency for faint objects with higher underlying SB (see Figure 7 of Doctor et al. 2017). The explanation for this effect is not known but hypotheses include errors in point-spread function (PSF) modeling, atmospheric refraction, and effects from pixel correlation.

These issues raise concerns about the existence of data reduction artifacts in the photometry of low-redshift SNe Ia. Artifacts such as SB-related biases have not been explored in
The low-redshift SN Ia sample used in this analysis includes: 72 from CfA3, 38 from CfA4, 10 from CSP, 172 from Foundation. The DES-SN3YR analysis includes 2 additional low-redshift SNe Ia (122 total) that are outside the PS1 footprint. CfA1 and CfA2 are not included because DES-SN3YR only uses events with measured telescope-filter transmissions.

2.2. PS1 Imaging Data

PS1 is a 1.8 m telescope with a 1.4 gigapixel camera (GPC1; Waters et al. 2016). PS1 utilizes a wide-field astronomical imaging and data processing facility developed and operated by the Institute for Astronomy at the University of Hawaii (Kaiser et al. 2010). GPC1 has a pixel size of 10 $\mu$m which subtends 0.258 and is well below the FWHM size of the PSF of $\sim 1.3''$ (Chambers et al. 2016).

All PS1 images are processed through the Image Processing Pipeline at the Maui High Performance Computer Center. The pipeline processes the images through a series of stages, including de-trending or removing the instrumental signature, a flux-conserving warping to a sky-based image plane, masking and artifact removal, object detection and photometry, and sky-subtraction (Chambers et al. 2016).

The data we use to make SB measurements is from PS1 3π Steradian Survey, publicly available from the PS1 data release 2 (DR2). DR2 covers the entire sky above decl. $-30^\circ$. The data set contains stacked, sky subtracted images, and has uniform calibration to within 0.005 mag (Schlafly et al. 2012). For the $griz$ filters used in our SB analysis, the mean 5σ point source limiting sensitivities are 23.3, 23.2, 23.1 mag, respectively.

3. Analysis

3.1. Low-redshift Hubble Residuals

The luminosity distance ($d_L$) dependence on cosmological parameters is

$$d_L = (1 + z)c \int_0^z \frac{dz'}{H(z')} ,$$

(1)

where

$$H(z) = H_0[\Omega_m(1 + z)^3 + \Omega_\Lambda(1 + z)^3(1+w)]^{1/2} ,$$

(2)

and the Hubble constant ($H_0$), matter density ($\Omega_m$), and dark energy density ($\Omega_\Lambda$) are defined at redshift 0. The dark energy equation of state parameter is $w$, and $w = -1$ for a cosmological constant. The $\Lambda$CDM model distance modulus is defined as $\mu_{\text{model}} = 5 \log(d_L/10pc)$.

As part of measuring $\mu$ in the DES-SN3YR and Foundation analyses, the standardization of SNe Ia is based on color and stretch parameters determined from a light curve fit. For each SN Ia they used the SALT2 model from Betoule et al. (2014) to

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6. https://github.com/djones1040/PS1_surface_brightness
7. https://panstarrs.stsci.edu
determine the amplitude ($x_0$), light curve width ($x_1$), and color ($C$). These SALT2 parameters were used to measure the distance modulus using a modified Tripp equation (Tripp 1998):

$$
\mu = m_B + \alpha x_1 - \beta C + M_0 + \gamma G_{\text{host}} + \Delta \mu_{\text{bias}},
$$

(3)

where $m_B = -2.5 \log(x_0)$, $\alpha$ and $\beta$ are the nuisance parameters describing the brightness-stretch and brightness-color relations, $M_0$ is the absolute SN Ia magnitude with $C = x_1 = 0$ ($H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$), $\gamma G_{\text{host}}$ is the dependence of the shape- and color-corrected SN magnitude on host galaxy stellar mass (Conley et al. 2011), and $\Delta \mu_{\text{bias}}$ is a bias correction determined from simulations (Jones et al. 2019; Kessler et al. 2019). See DES Collaboration et al. (2019) Equation (4) for more details. For this sample, the nuisance parameters ($\alpha$, $\beta$, $\gamma$, $M_0$) were determined using the methodology from “BEAMS with Bias Corrections” (BBC; Kessler & Scolnic 2017).

The best fit cosmological model was obtained using CosmoMC (Lewis & Bridle 2002) which uses SN Ia distances (Equation (3)) and a prior from the cosmic microwave background (Planck Collaboration et al. 2016). From the CosmoMC fit the Hubble residuals are defined as

$$
HR = \mu - \mu_{\text{model}}.
$$

We do not repeat this analysis but instead we take the HR values from the public data releases for DES-SN3YR and Foundation.9

3.2. SB Measurements Using PS1 Images

To make SB measurements at SN Ia locations, we use a circular aperture with a radius of 1″ on PS1 images from DR2 and extract calibrated flux measurements in the gri filters as well as uncertainty values. The choice of radius comes from the ~1″ FWHM of the PS1 PSF. The pixel flux contributing to the SB flux is calculated using $f = F \cdot F_A$, where $f$ is the contributing pixel flux, $F$ is the total pixel flux, and $F_A$ is the fraction of each pixel contained inside the circle. The SB flux is defined as $F_{\text{SB}} = [\sum f_i] / \pi R^2$, where $i$, $R = 1″$, and PS1 fluxes are scaled to match the DES zero-point.

Figure 1 shows PS1 image stamps of three low-$z$ SN Ia host galaxies with varying surface brightness magnitudes ($m_{SB}$) and their circular apertures.

3.3. Cross-check with DES

Before using SB measurements of the low-redshift sample, we perform a cross-check using the DES subset of the DES-SN3YR sample that includes the gri SB measurements in their data release. The DES-SN sample was collected over three 5 months long seasons, from 2013 August to 2016 February, using the Dark Energy Camera (DECam, Flaugher et al. 2015) at the Cerro Tololo Inter-American Observatory. New transients were discovered using a difference-imaging pipeline (Kessler et al. 2015). These SB measurements are made on deep coadded templates using images with the best seeing.

Out of 207 DES SN Ia events, images were retrieved for 64, 100, and 111 SNe Ia that overlap with the PS1 footprint and have $F_{SB(PS1)}$, $F_{SB(DES)} > 10$ ($m < 25$) for the gri filters, respectively. Here we compare independent SB measurements from DES and PS1.

We converted the PS1 SB measurements to the same zero-point as DES. The gri filters for DES and PS1 are similar; the difference between the mean wavelengths ($\lambda_{PS1} - \lambda_{DES}$) of the gri filter responses are 39 Å, −220 Å, and −284 Å, respectively. For this cross-check, we do not K-correct SB measurements to account for filter differences. To estimate the error in the ratio of measured SB flux values ($F_{SB(PS1)} / F_{SB(DES)}$) we use six galaxy spectra from Coleman

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8 https://des.ncsa.illinois.edu/releases/sn
9 https://github.com/djones1040/Foundation_DR1
et al. (1980) and Kinney et al. (1996) and apply the PS1 and DES filter transmissions to the galaxy SEDs. The mean differences for the gri filters are 2.4%, 6.9%, and 11.6%, respectively. These PS1-DES differences are approximate uncertainties because we did not use spectra from the SN Ia host galaxies. To estimate the effect of different PSF sizes, we compare SB measurements between DES DR1 data (DES Collaboration et al. 2018) and PS1 DR2 data using the same algorithm and found systematic SB differences of up to 30%.

We make a linear fit to $F_{SB(PS1)}$ versus $F_{SB(DES)}$ for each band: the slopes are $1.219 \pm 0.024$, $1.063 \pm 0.018$, and $1.130 \pm 0.016$ for the gri bands, respectively. Figure 2 shows $F_{SB(PS1)}$ versus $F_{SB(DES)}$ for the r band. Including the filter transmission and PSF uncertainties, the observed slopes are consistent with 1.0. Considering the filter and PSF size differences between PS1 and DES, the cross-check validates our SB measurement method.

### 4. Results

In total we measured surface brightness values for 292 low-redshift SNe Ia for which we have Hubble residuals from the DES-SN3YR and PS1 cosmology analyses. Figure 3 shows SB magnitude ($m_{SB}$) distributions in the gri filters. The vertical line indicates median $m_{SB}$. The left and right sides of the vertical line are defined as the bright half and faint half, respectively. Table 1 shows the number of events in the bright and faint halves for each low-redshift sub-sample and for each band. While the total number of bright and faint $m_{SB}$ events is the same by definition, all bright and faint sub-sample sizes are consistent as well. Figure 4 shows inverse-variance weighted HR versus r-band $m_{SB}$. The residuals are consistent with zero (reduced $\chi^2 = 1.7$), although there is a hint of a bias in the brightest $m_{SB}$ bins. Using the g and r bands, we find similar results with reduced $\chi^2 = 2.0$ and 1.6, respectively.

Next, we compare the bright and faint half HR distributions with a two-sampled Kolmogorov–Smirnov (KS) test. Figure 5 shows overlaid HR distributions of the bright and faint sub-samples and the results of the comparison. Table 2 shows the difference between the mean HR values ($\Delta_{HR}$) and rms ratios of the bright and faint half distributions, along with KS $p$-values. For each band, $\Delta_{HR}$ are consistent with zero at the $2\sigma$ level and the rms ratios are consistent with 1 at the $1\sigma$ level. The KS $p$-values are 0.08, 0.04, 0.10 for the gri bands,
respectively. For our final result we take the average among the gri bands: $\Delta HR = 0.031 \pm 0.018$, rms ratio $= 1.055 \pm 0.087$, and KS $p$-value is 0.07.

Here we perform several cross-checks. First, we repeat our analysis with apertures of different radii ranging from 0\".75 to 2\", which yields results that agree with these values. Averaging over 6 different radii, $\Delta HR$ increases by 0.004 corresponding to $\sim 25\%$ of the uncertainty. The largest $\Delta HR$ shift is 0.008.

As an additional test, we divide the sample of 292 SNe Ia into two sub-samples: (1) Legacy sample of 120 SNe Ia from the Harvard-Smithsonian Center for Astrophysics surveys and the Carnegie Supernova Project, and (2) Foundation sample of 172 SNe Ia from Pan-STARRS. The Legacy sample is older (2001–2010), heterogeneous, and includes galaxy-targeted surveys. The Foundation sample is more recent (2015–2017), homogeneous, better-characterized, and primarily follows SNe from surveys that do not target pre-selected galaxies. In principle, sample selection biases should not impact photometric measurements and here we test this assumption.
Table 3 shows the results of our correlation study for the Legacy and Foundation sub-samples. Both sub-samples show consistency between the bright and faint halves. We conclude that there is no statistically significant difference between the bright and faint half distributions, and therefore we find no evidence for SB-related bias in the low-redshift SN Ia sample.

5. Discussion and Conclusion

We undertook an analysis of HR versus SB with 292 low-z SN Ia from Foundation, the Harvard-Smithsonian Center for Astrophysics Surveys (CfA3, CfA4), and the Carnegie Supernova Project. We found no significant evidence for SB-related bias in this sample; the HR difference between the bright and faint subsets is $\Delta HR = 0.031 \pm 0.018$. If such an HR difference turns out to be real, and it is not corrected in the analysis, this effect would cause a significant $w$-bias that is comparable in size to the largest systematic uncertainties in current analyses.

It is also worth noting that SB-related biases could add unphysical correlations between SN luminosity and host galaxy properties. To illustrate this potential effect, Figure 6 shows the correlation between our SB and the local mass measurements from Jones et al. (2018), and shows that a non-zero $\Delta HR$ could change the observed relationship between HR and local galaxy properties. The faint and bright subsets have a difference in median local mass of 0.8 dex. Note that there is a similar correlation between SB and local specific star formation rate.

With sufficiently large samples, we can gain further insight by studying $\Delta HR$ as a function of galaxy morphology and color. Finally, the Vera C. Rubin Observatory is expected to produce at least an order of magnitude larger sample at low-redshift, which will reduce the $\Delta HR$ uncertainty to well below the 1% level in future cosmological analyses.

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