Host-Galaxy Correlations with Type Ia Supernovae

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Outline

• Why is it interesting to study Type Ia supernovae host galaxies
• SDSS photometrically classified sample
• Correlations with hosts
• Host galaxy spectra at the location of the SNe Ia
• Improvements on cosmology
• Gaia SNe Ia sample
Recent Cosmology results

Betoule et al. 2014: Joint SDSS+SNLS analysis

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Betoule et al. 2014: Joint SDSS+SNLS analysis
Issues now: Systematics

- **Calibration:** $\Delta \mu \approx 0.1$ mags
- **Host relation:** $\Delta \mu \approx 0.07$ mags
- **Malmquist bias:** $\Delta \mu \approx 0.05$ mags
- **SN model:** $\Delta \mu \approx 0.02$-0.03 mags
- **Non-Ia contamination:** $\Delta \mu \approx 0.01$-0.02 mags
- **Peculiar velocities, MW extinction correction, SN evolution, SN lensing**
Previous studies: Host Galaxy correlations

Sullivan et al. 2010 SuperNova Legacy Survey (SNLS)

Johansson et al. 2013 - Sloan Digital Sky Survey (SDSS) SuperNovae (SN) survey

Using two different values of M (in the distance modulus calculation) improves the cosmology fit by 3.8 – 4.5σ.
Previous studies: Host Galaxy correlations

Supernovae Factory: Childress et al. 2014  
Palomar Transient Factory: Pan et al. 2013

Figure 11. SALT2 Hubble residuals for SNfactory SNe Ia as a function of host galaxy mass. The solid line represents the best fit linear trend, the green points represent binned averages, and the thick red lines represent the averages for high- and low-mass bins. The histograms on the right show the distribution of residuals in high- and low-mass bins. The red filled circles represent the weighted-mean of the residuals in bins of host galaxy mass.

Figure 12. As Fig. 11, but considering gas-phase metallicity instead of $M_{\text{stellar}}$.

Figure 13. As Fig. 11, but considering stellar metallicity instead of $M_{\text{stellar}}$.

As Fig. 11, but considering $\log(\text{O/H})$ instead of $M_{\text{stellar}}$. Trends in SN Ia Hubble residuals as a function of host galaxy properties in Table 1. Note that three SN Ia hosts did not satisfy the criteria used to split the data.

We now discuss briefly why the observed trend of the step in SN Ia Hubble residuals persists when using K-corrections for galaxy magnitudes and colors.

We note that these quantities are in the observer frame and have not been K-corrected for the host galaxy redshift. Since this is a supernova-selected sample with host galaxy redshifts uncorrelated with galaxy absolute magnitudes, the step in SN Ia Hubble residuals is unlikely to be due to selection bias.
## Host Galaxy correlations

<table>
<thead>
<tr>
<th>Family 1</th>
<th>Family 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>More luminous</td>
<td>Less luminous</td>
</tr>
<tr>
<td>Broad light curve</td>
<td>Narrow light curve</td>
</tr>
<tr>
<td>Low Si ii 4130 pEW</td>
<td>High Si ii 4130 pEW</td>
</tr>
<tr>
<td>Stronger high-velocity features</td>
<td>Weaker high-velocity features</td>
</tr>
<tr>
<td>Late-type host</td>
<td>Early-type host</td>
</tr>
<tr>
<td>Low M</td>
<td>High M</td>
</tr>
<tr>
<td>High sSFR host</td>
<td>Low sSFR host</td>
</tr>
<tr>
<td>Short delay-time</td>
<td>Long delay-time</td>
</tr>
<tr>
<td>Blueshifted Na i D absorption</td>
<td>No Na i D absorption</td>
</tr>
</tbody>
</table>
CHAPTER 1. INTRODUCTION

Figure 1.12: The left-hand panel shows the SDSS telescope at the Apache Point Observatory, New Mexico. This photo was taken while I visited the observatory for the BOSS collaboration meeting in March 2011. The right-hand panel shows a front view diagram of the SDSS camera. It shows the 30 photometric and 24 astrometric/focus CCDs, plus their associated dewars and kinematic supports.

The Sloan Digital Sky Survey (SDSS-I 1998-2005, II 2005-2008 and III 2008-2014; York et al., 2000) is the largest galaxy, quasar and star survey undertaken so far. SDSS has imaged more than a third of the sky, concentrated on the northern and southern Galactic caps (above and below the plane of the Galaxy) and has created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.

SDSS produces these sky maps using a dedicated 2.5m telescope at the Apache Point Observatory, New Mexico (Gunn et al., 2006). The SDSS telescope, shown in the left-hand panel of Figure 1.12 has a modified two-corrector Ritchey-Chretien design, which is a specialized Cassegrain telescope. This has 2.5m hyperbolic primary and 1.08m hyperbolic secondary mirrors, designed to eliminate optical errors. The telescope has a Gascoigne astigmatism corrector, and a pair of highly aspheric correctors near the focal plane (one for imaging and the other for spectroscopy). The final focal ratio of the SDSS II SN survey 504 (360 high enough quality for cosmology analysis) spectroscopically-confirmed Type Ia supernovae.

The Sloan Telescope

- Sept-Nov between 2005 and 2007
- Regularly scanned “Stripe 82”
- Database of 10,000s of transient objects
- SDSS-II SN survey 504 (360 high enough quality for cosmology analysis) spectroscopically-confirmed Type Ia
- Cosmological analysis of the first year SDSS-II data
BOSS Host Galaxy Follow-up
Olmstead et al. 2013

- 3323 galaxies with accurate redshifts
  1) Probability of being a SNe (2382)
  2) Random sample of transients (941)
- Plates drilled with 1000 holes
- Spectroscopic redshift
  - Anchors SNe Ia on Hubble diagram
  - Improves classification and light curve fit
- Large sample of Host galaxy spectra:
  investigate intrinsic scatter
Photometric Hubble Diagram

Campbell et al. 2013

752 SN Ia (SDSS-II SN light curves + BOSS host redshifts)

Fig. 21.— The Hubble diagram of the photometrically-classified SDSS-II SN Ia sample. We have corrected for the Malmquist bias as discussed in Section 4.1. We use the best-fit values of and (see Section 6) and assumed the same M as in the simulations (M = 29.8) when creating this Hubble diagram. The SN intrinsic dispersion has been included in the error bars shown. Blue points show the subsample of SNe Ia that have been spectroscopically-confirmed as part of the SDSS-II SN Survey, while the black points only possess a photometric classification. The bottom panel shows the Hubble residuals of the data from the best-fit cosmology model (Section 6).

We investigate why this trend appears in the full photometric sample, but not in the "spec Ia" subsample. We plot in Figure 23 the maximum r-band S/N (at any epoch) for each SN Ia in our observed (left panel) and simulated (right panel) photometrically-classified samples. It is clear from the left panel of Figure 23 that SNe in the "spec Ia" (blue) subsample, at a given redshift, possess systematically higher S/N light-curves than photometrically-classified SNe Ia that weren't spectroscopically observed (black). The average S/N for the "spec Ia" subsample is 27.4, whereas the SNe Ia with only photometric classification have an average S/N of 9.6. This is of course expected, as the SDSS-II SN spectroscopic follow-up observations preferentially selected SN candidates that were easier to observe, naturally leading to a bias in S/N for the spectroscopic sample. Thus the "spec Ia" subsample has a smaller scatter because it contains the brightest SNe Ia from the whole population, which are then easier to fit and thus produce tighter distance modulus constraints. At z > 0.3, we see in Figure 23 the emergence of an apparent detection limit at S/N > 4.5. We have determined that this limit is due to the X-color cut (Section 3.1.5), as the SALT2...
Example Host Galaxy Spectra

Data

Fit

Error

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Host-galaxy Distribution

- BOSS host galaxy follow-up had $m_{r \text{ fiber}} = 21.2$ limit

- Fainter galaxies preferentially host only luminous (high X1) SNe Ia
  - target selection of hosts seems to favor fainter SNe Ia

- Photometric sample includes intrinsically brighter hosts
  - increased volume sampled.
  - spectroscopic follow-up avoiding brightest

- No bias in the $g^{0.1} - r^{0.1}$ model colors

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CHAPTER 7. SUPPLEMENTARY SCIENCE

Host galaxy separated Hubble Diagram

One value of \( M_0 \) for all.

Two \( M_0 \) values depending on the host galaxy mass. \( M_0 \) is 0.1 higher for SNe Ia in high-mass hosts.

Redshift

Distance Modulus

DATA

Hubble Residuals (mag)

0.0 0.2 0.4 0.6

0.0 0.2 0.4 0.6

10/9/2014 5th Gaia Alerts Meeting, Warsaw
Host galaxy correlations

298  448  385  385  448

HR_Corr

1.5  1  0.5  0
-0.5 -1 -1.5 -2

HR_Uncorr

1.5  1  0.5  0
-0.5 -1 -1.5 -2

Stretch

1.5  1  0.5  0
-0.5 -1 -1.5 -2

Colour

1.5  1  0.5  0
-0.5 -1 -1.5 -2

12+log[O/H]

8  9  10  11  12

log Mass

-12 -10 -8 -6 -4 -2

log SFR

-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2

log sSFR

-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2

Age

505 14

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Cosmology constraints: metallically correction

The $\Omega_m$ vs $w$ for sample of 298 SNe Ia with host-galaxy metallically.

![Uncorrected](image1)

![Corrected](image2)

Correction = $-0.172 \times \text{metallicity} + 1.5$
SN discovery rates

GAIA-C5-TN-IOA-SHO-001-00 (update of simulations of Belokurov and Evans (2003))

http://www.cbat.eps.harvard.edu/lists/Supernovae.html

See also: Supernovae and Gaia, Altavilla et al. 2011, 2012Ap&SS.tmp...66A
SN discovery rates

Point on the rise

Point on the rise + 5 total
SNe Ia light curves
Simulating Gaia light curves

- SNANA is a package (Kessler) for simulating supernova surveys, with realistic observing conditions and times

- Added Gaia as a survey: Filter response functions, kcorrections for the Gaia filters, MJD of observations, psf, etc.

- At the moment just simulating SN in regions sampled >200 times

- Fit with SALT2

- Create a Hubble diagram

\[ \mu = (m - M) + \alpha \text{stretch} - \beta \text{color} \]
Dense Regions

~9248 positions observed >200 times
~121 sq degrees

~83466 positions observed >150 times
~1094 sq degrees

3145728 total positions on the sky each ~ 0.0131 sq degrees
Gaia SNANA simulated light curves

SNID 11 $z = 0.128 \pm 0.001$
SALT2: $X_0 = (2.02 \pm 0.181) \times 10^{-4}$
$X_1 = 0.248 \pm 0.152$
color = $0.104 \pm 0.04$

SNID 54 $z = 0.131 \pm 0.001$
SALT2: $X_0 = (3.473 \pm 0.437) \times 10^{-4}$
$X_1 = -1.468 \pm 0.398$
color = $-0.013 \pm 0.056$

SNID 157 $z = 0.143 \pm 0.001$
SALT2: $X_0 = (1.989 \pm 0.217) \times 10^{-4}$
$X_1 = -1.356 \pm 0.119$
color = $0.023 \pm 0.04$
Hubble diagram with simulated Gaia SNe Ia

181 SNe Ia fitted with SALT
Fig. 17.— Hubble diagram of the CfA3 (red) and OLD (black) nearby SN Ia. Distance moduli from H09 using MLCS2k2 (RV = 1.7). The dispersion is 0.20 mag and the solid line is the distance modulus for a (ΩM = 0.27, ΩΛ = 0.73) universe.

Hicken et al. 2009
187 low-z SNe Ia

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Hicken et al. 2009
187 low-z SNe Ia
Photometric procession from follow-up

\[ \mu = (m - M) + \alpha \text{stretch} - \beta \text{color} \]

Left:
Three SDSS bands, few % photometry errors
SALT2:
\[ X_0 = (2.2 \pm 0.625) \times 10^{-4} \]
\[ X_1 = 0.7296 \pm 0.0612 \]
\[ \text{color} = -0.051 \pm 0.029 \]
\[ \mu = 36.865 \pm 0.257 \]

Right:
Three SDSS bands, 5x photometry errors
SALT2:
\[ X_0 = (2.2 \pm 0.731) \times 10^{-4} \]
\[ X_1 = 0.710 \pm 0.155 \]
\[ \text{color} = -0.049 \pm 0.033 \]
\[ \mu = 36.859 \pm 0.260 \]
Photometric procession from follow-up

$$\mu = (m - M) + \alpha \text{stretch} - \beta \text{color}$$

Left:
Two SDSS bands, few % photometry errors
SALT2:
$$X_0 = (2.2 \pm 0.63) \times 10^{-4}$$
$$X_1 = 0.7296 \pm 0.0612$$
$$\text{color} = -0.051 \pm 0.029$$
$$\mu = 36.865 \pm 0.257$$

Right:
Two SDSS bands, 5x photometry errors
SALT2:
$$X_0 = (2.2 \pm 0.732) \times 10^{-4}$$
$$X_1 = 0.710 \pm 0.1549$$
$$\text{color} = -0.049 \pm 0.0328$$
$$\mu = 36.859 \pm 0.260$$
Summary

• Host-galaxies parameters show correlations with the SNe Ia Hubble residuals and fitted parameters (stretch and colour)

• Host-galaxy correlations are vital for improving cosmology constraints for the next generation

• Gaia will allow us to investigate these host correlations in near by homogenous, unbiased sample - but photometric follow up is essential!