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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **446,** 3768–3775 (2015) doi:10.1093/mnras/stu2345

SN Ia host galaxy properties and the dust extinction distribution

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Accepted 2014 November 4. Received 2014 November 3; in original form 2014 March 3

ABSTRACT

Type Ia supernovae (SNeIa) display a complex relation with their host galaxies. An important prior to the fit of the supernovae's light curve is the distribution of host galaxy extinction values that can be encountered. The Sloan Digital Sky Survey SuperNova survey project has published light-curve fits using both MLCS2K2 and SALT2. We use the former fits extinction parameter (A_V) to map this distribution of extinction values. We explore the dependence of this distribution on four observables; the inclination of the host galaxy disc, radial position of the supernova, redshift of the supernova and host, and the level of star formation in the host galaxy. The distribution of A_V values encountered by supernovae is typically characterized by :$N_0 e^{-A_V/\tau}$, with $\tau = 0.4$ or 0.33. We find that the inclination correction using an infinitely thin disc for the SN Ia is sufficient, resulting in similar exponential A_V distributions for high- and low-inclination discs. The A_V distribution also depends on the radial position in the disc, consistent with previous results on the transparency of spiral discs. The distribution of A_V values narrows with increased star formation, possibly due to the destruction or dispersion of the dusty interstellar medium by stellar winds prior to the ignition of the supernova. In future supernova searches, certainly the inclination of the host galaxy disc, should be considered in the construction of the A_V prior with $\tau = 0.4/\cos(i)$ as the most likely prior in each individual host galaxy's case.

Key words: catalogues – dust, extinction – ISM: structure – galaxies: ISM – distance scale.

1 INTRODUCTION

Interest in Type Ia supernovae (SNe Ia) has greatly increased since their use as standard candles led to the discovery of the accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). The latest generation of SN Ia surveys, e.g. the Supernova Legacy Survey (SNLS; Astier et al. 2006), Equation of State: SupErNovae trace Cosmic Expansion (ESSENCE; Wood-Vasey et al. 2007), and the Sloan Digital Sky Survey SuperNova survey (SDSS-SN; Kessler et al. 2009) however are limited by the possibility of systematic uncertainties in their calibration of SN Ia luminosities. In order for SN Ia light curves to evolve into a next generation cosmological tool, we will need to understand the various physical properties that could affect the relation between peak luminosity and light-curve width (Phillips 1993) that is used to calibrate SNe Ia.

Many studies focus on the stellar population which produces the supernova (SN). For example, Gallagher et al. (2005), Mannucci et al. (2006), Sullivan et al. (2006), Kistler et al. (2013), and Pan et al. (2014) derive host galaxy stellar population and metallicity from general photometry to compare these to the SN Ia rates and luminosity profiles. In general, a two subpopulation model is emerging: blue, star-forming galaxies host higher rates of fast declining SN and red, passive galaxies host predominantly more slowly declining SNe Ia (Hamuy et al. 1996; Howell 2001; van den Bergh, Li & Filippenko 2005; Mannucci, Della Valle & Panagia 2006; Schawinski 2009; Lampeitl et al. 2010; Wang et al. 2013). This model suggests the difference in light-curve characteristics to the different progenitor stellar populations.

However, simultaneously, the issue of host galaxy extinction has come to the fore, either the applicability of the appropriate extinction law (Riess, Press & Kirshner 1996; Phillips et al. 1999; Altavilla et al. 2004; Reindl et al. 2005; Conley et al. 2007; Jha, Riess & Kirshner 2007), the validity of the prior of extinction values (Jha et al. 2007; Wood-Vasey et al. 2007), or the possibility that the geometry of the dusty interstellar medium (ISM) (and hence the extinction distribution) may change with galaxy evolution (Holwerda et al. 2008). The source of extinction in SNe is thought to be the surrounding host galaxy (Phillips et al. 2013). The uncertainty in host galaxy extinction has been identified in the Dark Energy Task

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Group Report (Albrecht et al. 2006) as the dominant remaining systematic that stands in the way of SN Ia measurements attaining the next step in cosmological precision. Current attention is on the photometric calibration of the various surveys into a single system (e.g. Conley et al. 2011; Betoule et al. 2014; Scolnic et al. 2014) but after this technical issue is dealt with the host extinction still stands in the way of the final goal of 1 per cent precision for SN I (e.g. Riess et al. 2011; Kelly et al. 2014).

The distribution of host galaxy extinction values is an important Baysian prior to the MLCS2K2 light-curve fit program (Jha et al. 2007; Kessler et al. 2009). The benefits of the use of a Baysian prior are (1) full use of the information on the host galaxy to reduce the uncertainty, and (2) mitigation of the effect of colour measurement error (see the appendix in Jha et al. 2007). A distinct disadvantage is that an incorrect prior will result in biases in the distance measurement and some light-curve fitting programs therefore have opted to not include a host galaxy extinction prior. To date, the extinction model is primarily based on Monte Carlo simulations of spiral discs (Hatano, Branch & Deaton 1998; Commins 2004; Riello & Patat 2005) that also predicted SN Ia rates but check against the data (Jha et al. 2007 and their fig. 6). The dusty disc in these model host galaxies was assumed to be extremely flat, relatively transparent with some approximation for the spiral arms. These models may now be in need of revision as observations of nearby spirals show a much more complex dust geometry of spiral galaxies: part of the dust is distributed in a vertical component with a similar height to the stellar disc (e.g. Howk & Savage 1997, 1999; Howk 1999; Thompson, Howk & Savage 2004; Seth, Dalcanton & de Jong 2005; Kamphuis et al. 2007), and the radial distribution is increasingly better characterized with a disc and radially declining spiral arm component (see Domingue et al. 1999; Domingue, Keel & White 2000; White, Keel & Conselice 2000; Keel & White 2001a,b; Holwerda et al. 2005a,d, 2007b,a, 2009, 2013; Holwerda, González, Allen & van der Kruit 2005b,c,e; Holwerda, Keel & Bolton 2007c; Holwerda & Keel 2013; Keel et al. 2013).

Luckily, there is an opportunity to use the SN Ia themselves to probe the host galaxy dust disc characteristics, as large samples of SN in the nearby Universe, complete with host galaxy properties, are becoming available, notably the SDSS-SN search. In this paper, we compare the distribution of dust extinction values (A_V) for the SN in this sample (Frieman et al. 2008; Sako et al. 2008, 2014, hereafter S14) for which uniform host galaxy properties (inclination, positions, typical radii, a classification of star formation and redshift are available.

Our goal here is not to present a precise measurement of the underlying A_V distribution, but rather to explore how the observed distribution relates to host galaxy observables to ascertain which host galaxy property should have priority in future SN Ia surveys. The SDSS-SN fits used in this analysis made use of a particular extinction distribution as a prior, and we are arguing that this prior was at best the average of the priors of different host galaxy populations. However, as long as the different host galaxy populations have A_V distribution derived using the same prior, the use of an incorrect prior should only decrease our sensitivity to detect a relationship with a host galaxy characteristic rather than introduce a spurious relation, and hence does not invalidate our results. Future, more detailed studies aiming to precisely measure the underlying A_V distribution will have to properly take the effects of the S14 prior into account.

This paper is organized as follows: Section 2 describes the SDSS-SN data we used for this paper, Section 3 describes our analysis in detail, Section 4 lists our conclusions.

2 DATA

SN Ia are the mainstay of cosmological distance measurements. The photometric properties of their light curves are very stable but appear to depend slightly on host galaxy properties (e.g. star formation rate or stellar mass). With this mind, the third incarnation of the Sloan Digital Sky Survey (SDSS-3) included a SN search with spectroscopic follow-up. This SDSS-SN search (SDSS-SN)[1] has yielded a wealth of galaxy and SN properties.

SDSS-SN is described in Frieman et al. (2008) and in more detail in Sako et al. (2008) and S14. Observing for three months of the year from 2005 to 2007, SDSS-SN identified hundreds spectroscopically confirmed SNe Ia in the redshift range $0.05 < z < 0.35$.

S14 present the final data-product of the tremendous observational effort. They include an assessment of SN type based on the light curve (PSNID output) and light-curve fits using the two most commonly used packages, SALT2 (Guy et al. 2007) and MLCS2K2 (Jha et al. 2007). The shape of the MLCS2K2 A_V prior used for the light-curve fits was: $P(A_V) \sim e^{-A_V/\tau_0}$, with $\tau_0 = 0.4$. Because it has host galaxy extinction as an explicit prior and a model relation between A_V distribution width (τ_0) and A_V bias, we use the MLCS2K2 values for our further analysis here. For example, Wood-Vasey et al. (2007) use this tool to explore the dependence of the extinction law used on redshift. We focus only on those objects that have a reasonable chance of being bona fide SN Ia (S/N > 5 and P(SN Ia) > 90 per cent, according to PSNID) to ensure the conclusions for the improved prior are based on these only (3585 SN in the total sample).

Host galaxy properties are those available from the SDSS-DR9 data base and stellar mass and star formation are modelled with two different packages, FSPS (Conroy & Gunn 2010) and PEGASE (Bruzual A. 2009). For the purpose of this paper, the star formation is of interest and we choose the FSPS value for the further analysis.

In addition to the values thoughtfully provided by the SDSS-SN project in S14, we retrieve the axes ratio, position angle, and Petrosian radius from the SDSS server. Using these values, we compute the galactocentric radial distance from the centre of the host galaxy in Petrosian radii.

3 ANALYSIS

The analysis focuses on four observables of the host galaxy and their effect on the A_V distribution: disc inclination (i), radial distance from the centre of the galaxy disc (r), redshift (z), and the level of star formation (type); of these the last has been mostly the focus of the SDSS-SN collaboration (Lampeitl et al. 2010). The SN sample has a complex selection function, part of which is the extinction A_V that we are interested in. Hence, we compare subsamples of the SDSS-SN sample; in this case the selection is at least uniform, if not always complete. We compare subsamples of SNe Ia based on these four host galaxy characteristics and plot the distribution of A_V values, typically with 25 bins. We fit an exponential to each A_V distribution to quantify the drop-off rate:

$$N = N_0 e^{-A_V/\tau}, \qquad (1)$$

for positive values of A_V. The typical SN Ia prior value for τ is 0.33 (Kessler et al. 2009), 0.4 (Jha et al. 2007; Sako et al. 2008) or 0.38 ± 0.06 (Bernstein et al. 2012). The mean extinction law is found to be $R_V = 2.3$, which is lower than the canonical Milky

[1] http://www.sdss.org/supernova/aboutsupernova.html

Way extinction law ($R_V = 3.1$; Cardelli, Clayton & Mathis 1989). In their appendix, Lampeitl et al. (2010) try to constrain this R_V value using this SN sample.

The central assumptions for our analysis is that (a) the shape of the A_V distribution is similar to the prior shape (equation 1), i.e. the convolution with data does not result in a dramatic change, and (b) the A_V distribution for subsamples selected based on host characteristics that do not matter to the A_V distribution should be the same.

In the following sections, we fit an exponentially modified Gaussian distribution to the full A_V distributions using a maximum likelihood method, normalizing it arbitrarily for visualization purposes. In each panel, we list the exponential drop-off, its uncertainty and the number of A_V values in the distribution.

Our second assumption is that above $A_V= 1$, the sample is not complete enough to contribute to a meaningful fit. The optimal number of bins (15) in the histograms was chosen by eye.

We should point out that both this paper and all the SN Ia work has assumed so far that the probability function for A_V follows equation (1). However, spectral energy distribution fits of stars in M31 (Dalcanton et al., in preparation), column density distributions of star-forming regions and our own *Hubble Space Telescope* (*HST*) mapping of extinction values all hint that a lognormal distribution may well be a better description of the data.

3.1 Inclination

Inclination of a spiral disc can be found from the major (a) and minor (b) axis according to

$$\cos^2(i) = \frac{(b/a)^2 - (b/a)^2_{\rm min}}{(b/a)^2_{\rm min}} \quad (2)$$

from Hubble (1926). The value for $(b/a)_{\rm min}$ is the typical oblateness of an edge-on galaxy ($b/a_{\rm min} = 0.1$). The axes are those observed for the Petrosian aperture in the SDSS-r filter. Hence, the oblateness of the dusty ISM disc may well be different from the $(b/a)_{\rm min}$ used here. Typically, it is assumed that this dusty ISM disc is in fact much thinner than the stellar disc ($(b/a)_{\rm min} \sim 0.1$). We apply this correction regardless whether the galaxy is an early or late type because (a) the majority of host galaxies is late type, and (b) the ISM will still be in a disc in the case of early types.

In Figs 1–3, we compare the A_V distribution of high- and low-inclination discs, before and after correction of the A_V values for inclination, assuming a thin disc model ($b/a_{\rm min} = 0.1$). We note that the majority of our host galaxies are moderately inclined ($30° < i < 60°$, Fig. 4), as can be expected from a random draw. The correction using this simple relation with inclination ($\cos(i) = b/a$) is sufficient to align the two distributions (similar τ values). Hence, nothing fancier is needed. We did vary the $(b/a)_{\rm min}$ value, but did not obtain a significantly better result.

An extremely thin dusty ISM disc is all that is needed to model the dusty ISM distribution. This is somewhat unexpected at intermediate redshift because of the evidence for a secondary vertical dusty ISM component (e.g. Kamphuis et al. 2007; Bianchi & Xilouris 2011; Holwerda et al. 2012a,b; Schechtman-Rook & Bershady 2013; Seon et al. 2014). It may be even less applicable at higher redshift; for instance, with an order of magnitude more star formation at $z \sim 1$, the resulting turbulence could result in a much thicker distribution at higher redshifts (Holwerda et al. 2008). For the remainder of this letter, we use the inclination-corrected A_V values.

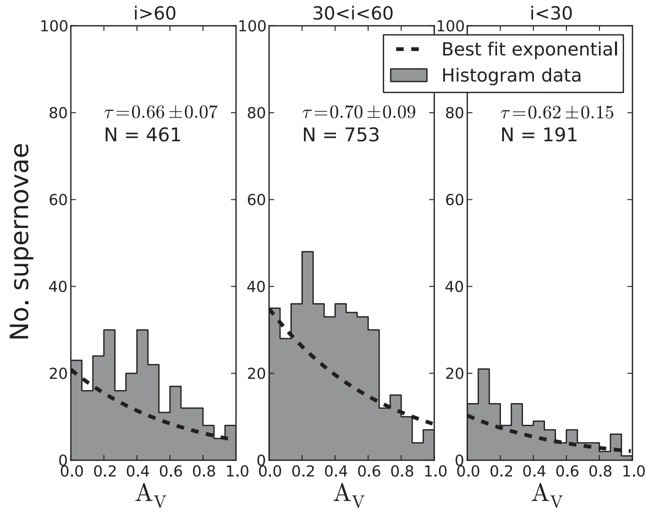

Figure 1. The distribution of observed A_V values for the high- ($i > 60°$), mid- ($30° < i < 60°$), and low-inclination ($i < 30°$) galaxies, before correction for inclination. In each panel, we list the exponential drop-off, its uncertainty and the number of A_V values in the distribution.

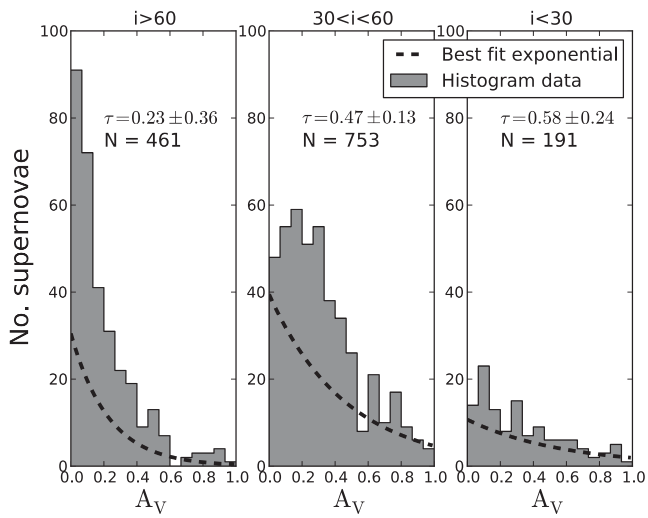

Figure 2. The distribution of corrected A_V values for the high- ($i > 60°$), mid- ($30° < i < 60°$), and low-inclination ($i < 30°$) galaxies. Drop-off values are more similar now for the moderately and face-on inclined.

Figs 3 and 5 shows the distribution of A_V values before and after correction for inclination. While the MLCS2K2 package can start with a *flat* prior for the dust attenuation, the distribution is wider than typically assumed for the prior however after correction to face-on, it is practically identical to the values ($\tau = 0.33, 0.4$) typically in use. We advocate therefore for the use of an extinction prior tailored using the known host galaxy inclination: $\tau \sim 0.4/\cos(i)$, where i is the disc's inclination.

3.2 Radius

Secondly, we test the dependence of the A_V distribution on the radial distance from the centre of the host galaxy. The radial distance can be obtained from the position of the galaxy (α_0, δ_0), the position of the SN (α_1, δ_1), the inclination (i), the position angle on the sky (ψ), and the angle between the two positions (ϕ): Fig. 6 shows the

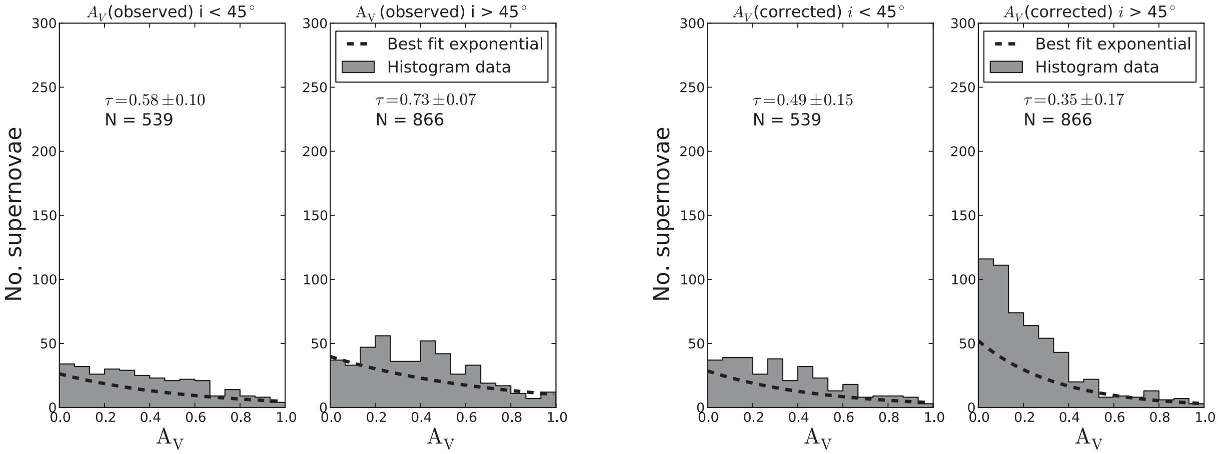

Figure 3. The distribution of corrected A_V values for the high- ($i > 60°$), mid- ($30° < i < 60°$), and low-inclination ($i < 30°$) galaxies. Drop-off values are more similar now for the moderately and face-on inclined.

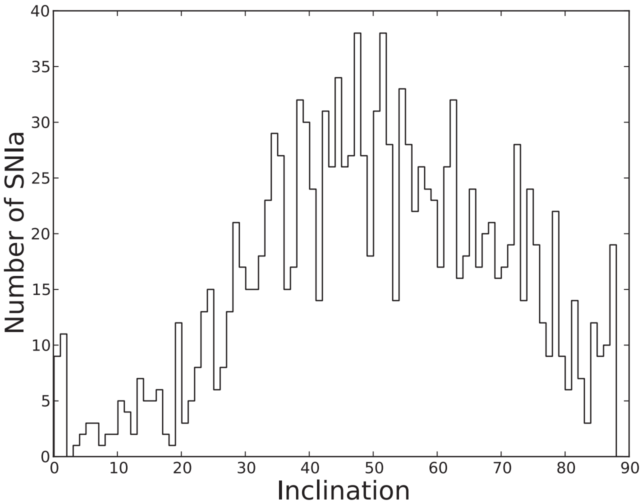

Figure 4. The distribution of disc inclination of the host galaxies based on the axis ratio (B/A).

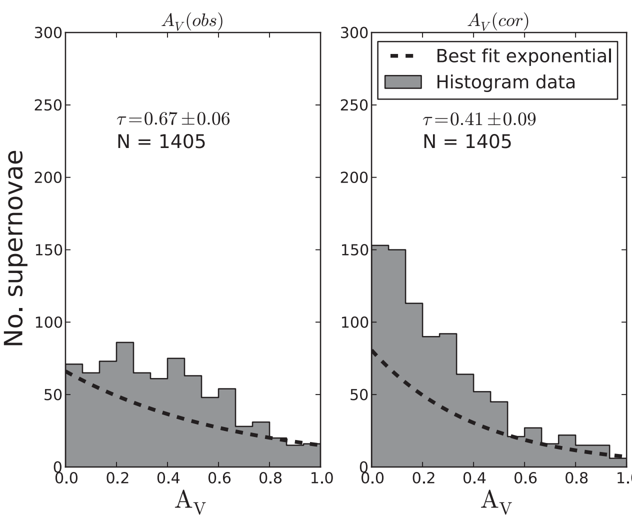

Figure 5. The observed A_V distribution and the A_V distribution after correction for disc inclination.

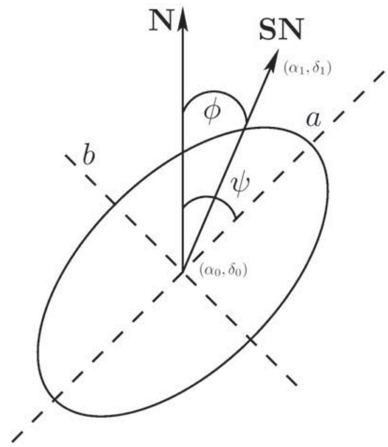

Figure 6. Geometry of the host galaxy and SN on the plane of the sky. The centre of the host galaxy (α_0, δ_0), and the SN (α_1, δ_1),

projected position of the SN on the inclined disc of the spiral host galaxy.

Using the expressions for proper motion, one can find the deprojected radial distance from the centre of the galaxy:

$$R = \mu\sqrt{\left[\frac{\sin(\phi - \psi)}{\cos i}\right]^2 + \cos^2(\phi - \psi)} \tag{3}$$

which, combined with the Petrosian radius (Petrosian 1976), can be used to divide the SN Ia up into samples inside and outside the stellar disc of the host galaxy. We use the Petrosian radius to scale the radial positions of the SNe Ia in all the galaxies.

Fig. 7 shows three A_V distributions within one, between one and two times the Petrosian radius and outside two Petrosian radii. SNe inside two Petrosian radii encounter a variety of extinction values ($\tau \sim 1.48$–0.38), as can be expected and those outside two Petrosian radii encounter a more extended distribution ($\tau \sim 0.5$). Hence, where the SN Ia is in the plane of the galaxy is critical for determining the A_V distribution to be used. Fig. 8 shows the radial distribution of A_V values, normalized to the Petrosian radius and it shows a consistent picture of an extended disc of A_V= 0.5 out to greater radii and a steeper falling off spiral arm component (consistent with the disc transparency measures presented in Domingue et al. 1999; 2000; Keel & White 2001a,b; Holwerda, González,

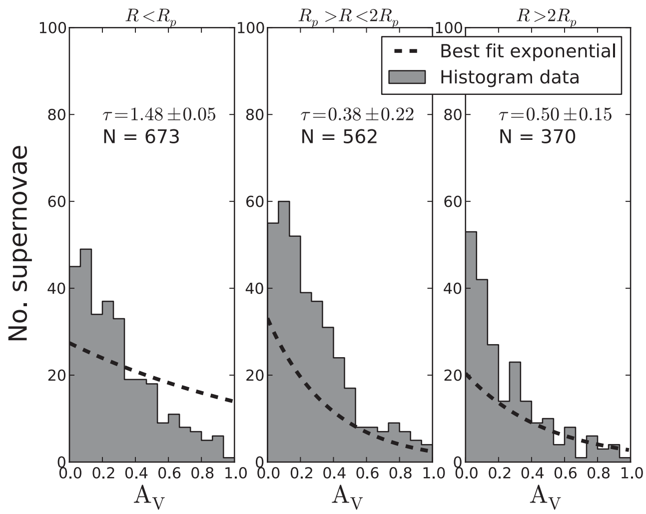

Figure 7. The distribution of inclination-corrected A_V values for three divisions according to radius, expressed as a fraction of the Petrosian radius of the host galaxies.

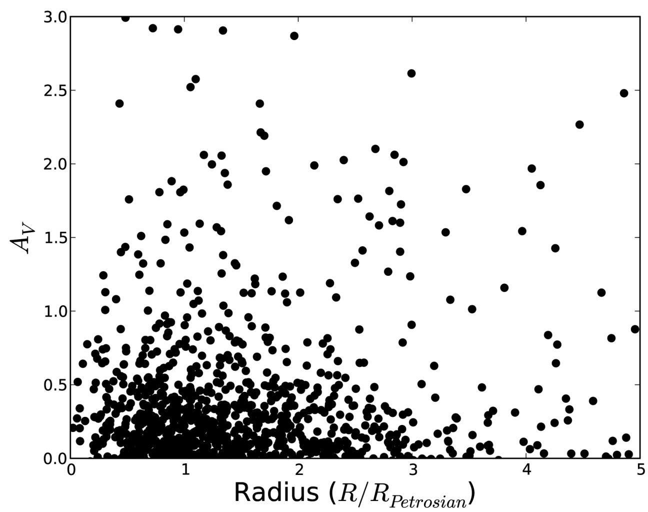

Figure 8. The inclination-corrected A_V values, as a function of radius of the host galaxies, expressed as a fraction of the Petrosian radius. Three of the SNe Ia are beyond five Petrosian radii and could have due to misidentified host galaxies. These were excluded for further analysis.

Allen & van der Kruit 2005b; Holwerda, Keel & Bolton 2007c; Holwerda et al. 2009, 2013; Holwerda & Keel 2013; Keel et al. 2013, 2014).

3.3 Redshift

The third characteristic of the host galaxy that may influence the A_V distribution is evolution of the host galaxy's dust geometry (see Holwerda et al. 2008). The selection effects as a function of redshift was exhaustively explored in Wood-Vasey et al. (2007) and Kessler et al. (2009). Fig. 9 shows the A_V distributions as a function of redshift. There is only a gradual decrease in τ with redshift. This decline is consistent with a scenario where the A_V distribution is progressively less complete at higher redshift (Malmquist bias for the SNe suffering from more extinction), very consistent with what previous authors have found.

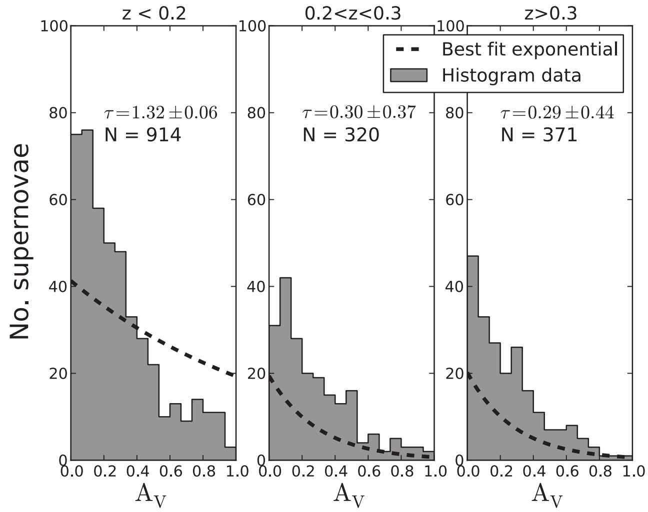

Figure 9. The distribution of inclination-corrected A_V values for different redshift ranges.

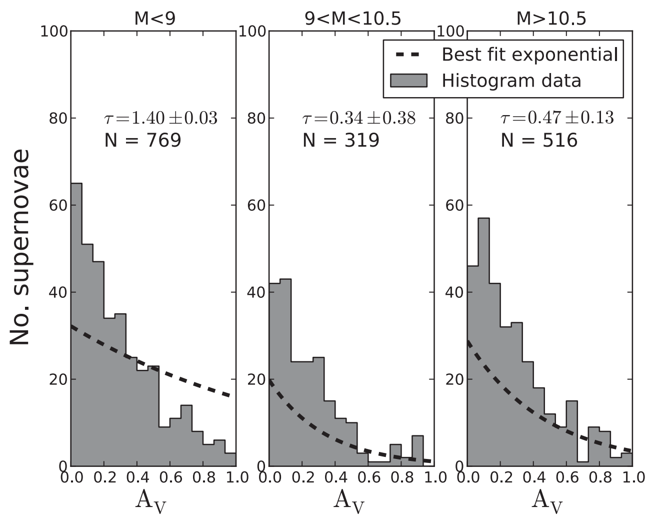

Figure 10. The distribution of inclination-corrected A_V values for different host galaxy stellar mass (FSPS fit).

3.4 Stellar mass and star formation rate

S14 and other authors have already explored the relationship between SN Ia colour and host galaxy properties such as stellar mass and star formation rate. The catalogue released by S14 includes stellar mass estimates using the FSPS (Conroy & Gunn 2010) and PEGASE (Bruzual A. 2009) packages and a star formation estimate from the FSPS fit. We use the FSPS fit values. Fig. 10 shows the distribution of A_V values for different stellar masses, and Fig. 11 the distribution for different specific star formation levels. One would expect the distribution to be different as a function of either. For example, Dalcanton, Yoachim & Bernstein (2004) show that the ISM and stellar discs of spiral galaxies are flatter in more massive systems. In smaller galaxies, the ISM (and dusty) discs extends more into the stellar disc, changing the probability that the light from an SN would encounter significant ISM. Binning the sample into three stellar mass bins however we note that there is no clear trend (perhaps a slight increase with mass) in the probability an

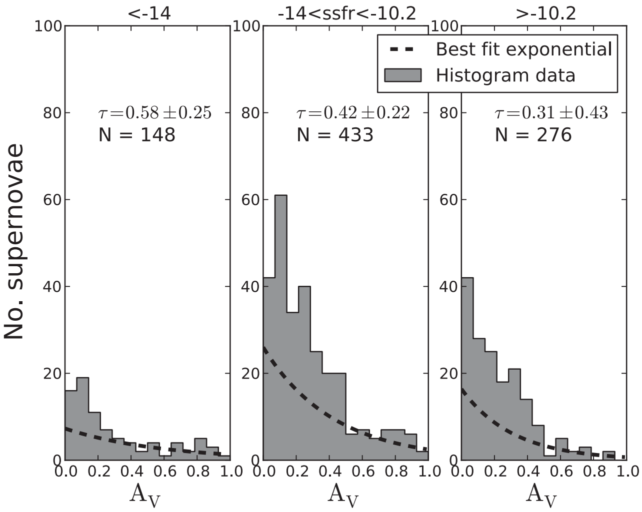

Figure 11. The distribution of inclination-corrected A_V values for different host galaxy specific star formation rate (FSPS fit). Bins are in $\log_{10}$(SSFR) in $1 \mathrm{yr}^{-1}$.

SN Ia encountered more or less dust in different mass galaxies in Fig. 10. This is either because the effect Dalcanton et al. (2004) notes happens in much smaller systems or the final A_V distribution does not depend critically on the vertical distribution of the ISM.

Another product of the S14 catalogue is the specific star formation (SSFR) rate of each host galaxy. The distribution of inclination-corrected A_V values in Fig. 11 shows a decline of τ with increased SSFR. Most of the SDSS galaxies are around $\log_{10}(\mathrm{SSFR}) \sim 10.2 \ 1\mathrm{yr}^{-1}$ which is why the first (quiescent) bin has so few galaxies in it. Contrary to what could be expected from higher star formation (a wider range of A_V values due to turbulence in the ISM), the value of τ *declines* with increased star formation. This is contrary to the distribution observed in the interacting galaxy UGC 3995 (Holwerda & Keel 2013), where the interaction and accompanying star formation has removed much of the diffuse component. One explanation of any behaviour of decreasing τ may be that in star-forming galaxies, the dust grains are destroyed or blown out of the line of sight by the star formation prior to SN ignition (e.g. Baumgartner & Breitschwerdt 2013).

4 CONCLUSIONS

Using SDSS-II SNe Ia as our plumbing lines into the dusty ISM of the host galaxies we can conclude the following.

(i) The inclination correction we applied to the distribution of extinction values was the simple $A_V(\mathrm{corrected}) = A_V(\mathrm{observed}) \times \cos(i)$, i.e. $\tau(\mathrm{corrected}) = \tau(\mathrm{observed}) \times \cos(i)$ for the whole distribution. The distributions of A_V values become more similar for the highly and lowly inclined host galaxies after this correction (Figs 1 and 2). Hence, we conclude that this correction is sufficient *for the whole distribution*, i.e. the differences in τ between the subsamples after inclination correction are consistent with purely the measurement error.
To first order SNe mostly encounter a thin dusty component of the host galaxy.

(ii) The distribution of A_V depends on the radial position within the host galaxy disc. SNe in the inner disc exhibit a wider range of A_V values (Fig. 7). This change with radius is highly consistent with the picture of disc opacity that has been developed over the last two decades (Fig. 8). Therefore, the position of the SN in the disc should be considered in future A_V priors for light-cuve fits.

(iii) There is a mild decline in the width of the A_V distribution with redshift (Fig. 9). This is consistent with a selection bias against higher A_V values at greater distances.

(iv) The host galaxy's star formation level influences the A_V distribution contrary to our expectations; values of τ decrease with the level of star formation (Fig. 11). The high star formation seems to remove higher values of A_V experienced by SNe. One possibility is that the star formation clears the ISM prior to the SN ignition.

We explored the dependence of the A_V distribution for SN Ia light-curve fits on host galaxy characteristics. Important factors determining the A_V distribution appear to be the inclination and – to a lesser extent – the radial position in the disc. In future searches for much greater numbers of SNe Ia, specific priors depending on the position in the host's disc could be of use to decrease the extinction systematic. The occulting galaxy programme with *HST* (Holwerda 2014) is specifically motivated to provide template A_V distributions of different galaxy masses and types for their use – among others – as priors for SN Ia light-curve fits.

ACKNOWLEDGEMENTS

We would like to thank the anonymous referee for his or her excellent commentary on the earlier drafts of this manuscript, which helped to improve it. We acknowledge support from the National Research Foundation of South Africa, specifically the 'Human Capacity Development for Multi-wavelength Astronomy' grant to the Astronomy Department at UCT (P.I. R. Kraan-Korteweg). The work of BWH is supported by Leiden Observatory. We thank Captain Reynolds for inspiration and useful monologues. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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APPENDIX A: CHECK WITH SPECTROSCOPICALLY CONFIRMED SN Ia

The choice of P(SN Ia) > 90 per cent as the inclusion cut for the SN Ia sample is a stringent but ultimately arbitrarily one. We therefore repeat the analysis on those SNe that have been spectroscopically confirmed as SN Ia (classifications either 'SNIa', 'pSNIa' or 'zS-NIa'). The resulting sample is only 981 objects and thus we can slice it only in courser bins for the comparison. Figs A1–A3 are the equivalent figures of Figs 1, 2, and 7 for the spectroscopically confirmed sample of SN Ia.

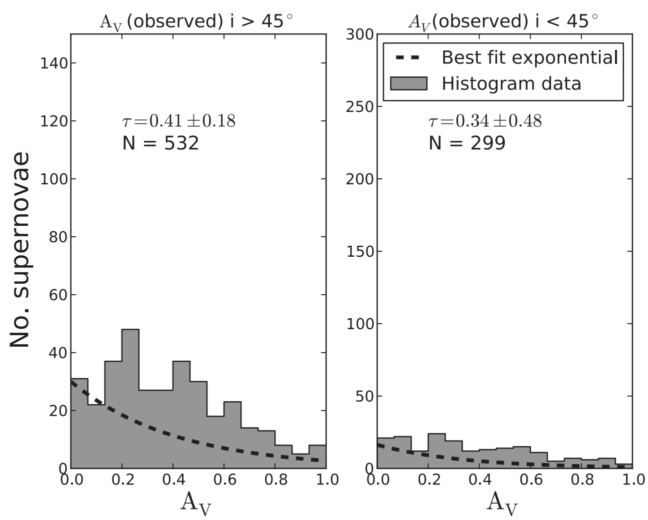

Figure A1. Spectroscopically confirmed SN Ia: the distribution of observed A_V values for the high- ($i > 45°$) and low-inclination ($i < 45°$) galaxies, before correction for inclination.

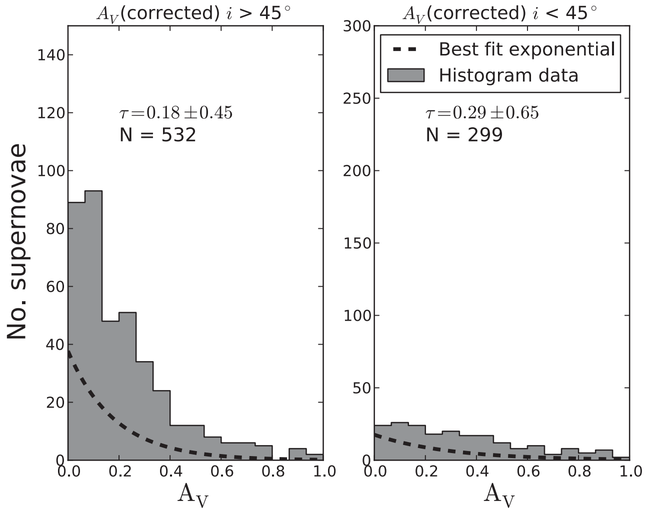

Figure A2. Spectroscopically confirmed SN Ia: the distribution of observed A_V values for the high- ($i > 45°$) and low-inclination ($i < 45°$) galaxies, before correction for inclination.

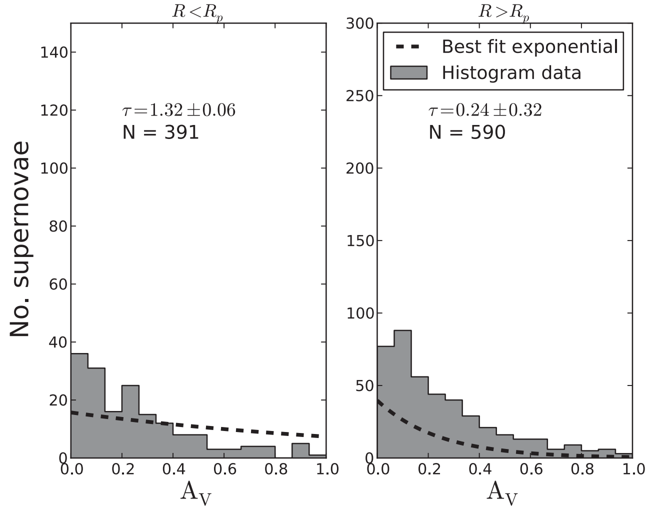

Figure A3. The distribution of inclination-corrected A_V values for three divisions according to radius, expressed as a fraction of the Petrosian radius of the host galaxies. Values for τ decline with radius.

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