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The reddening law of type Ia Supernovae

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Type Ia supernovae (SNe Ia) are valuable standard candles because of their intrinsic brightness and the relative homogeneity of their light curves. Their luminosity distances are measured via the standardization of their light curves using brightness-width (stretch, x_1, Δm_{15}) and color corrections [6, 8]. Whereas earlier work used the total-to-selective extinction ratio of the Milky Way, R_V=3.1, for the color determination, direct estimates from supernovae (SNe) Hubble diagram fits lead to lower values. While the derivation of this value is subject to assumptions about the natural color dispersion of SNe [5, 7], the reason for a difference between SNe data and the Milky Way average result had remained unknown as it may be affected by additional yet unidentified intrinsic dispersion

Equivalent widths are good spectral indicators for addressing this issue as they probe the intrinsic variability of SNe Ia and by construction they have little dependence on extinction due to their narrow wavelength baseline. In particular, there is a strong correlation between the equivalent width of the Si II λ4131 feature and the SALT2 x_1 width parameter and with M_B, which can thus be used to standardize the Hubble diagram.

We employ 76 type Ia supernovae with optical spectrophotometry within 2.5 days of B-band maximum light obtained by the Nearby Supernova Factory to derive the impact of Si and Ca features on supernovae intrinsic luminosity and determine a dust reddening law. After applying a correction based on the Si II λ4131 and the Ca II H&K equivalent widths, and introducing an empirical correlation between colors, we find a reddening law consistent with a Cardelli extinction law, and a value of the total-to-selective extinction ratio, $R_V = 2.8 \pm 0.3$. This result suggests that the long-standing controversy in interpreting SN Ia colors and their compatibility with a classical extinction law, critical to their use as cosmological probes, can be explained by the treatment of the dispersion in colors, and by the variability of features apparent in SN Ia spectra.

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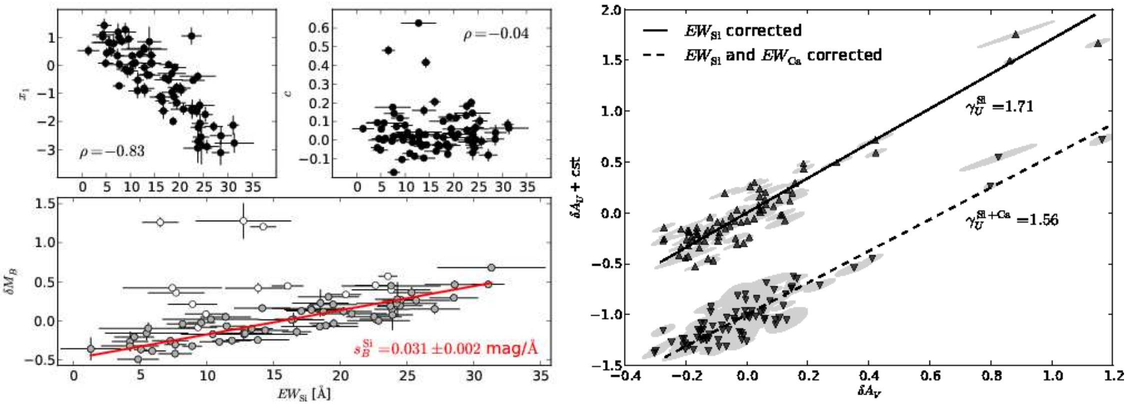

(a) (b)

Figure 1: (a): Correlations of $\mathrm{EW}^{\mathrm{Si}}$, SALT2 x_1 (*top left*) and c (*top right*) parameters and measured peak absolute magnitude up to a constant term, δM_B (*bottom*). $s_B^{\vec{\mathrm{Si}}}$ is equivalent for the B band to the red curve shown in Fig. 2a. (b): Relation between δA_U and δA_V after $\mathrm{EW}^{\mathrm{Si}}$ correction (*triangles up*) and after $\mathrm{EW}^{\mathrm{Si}}$ and $\mathrm{EW}^{\mathrm{Ca}}$ corrections (*triangles down*). The δA_U are displayed with an added arbitrary constant.

1. Data-set and derived quantities

This analysis uses flux calibrated spectra of 76 SNe Ia obtained by the Nearby Supernova Factory (SNfactory) collaboration with its SNIFS instrument [1] on the University of Hawaii 2.2-meter telescope on Mauna Kea. The subset used is composed by SNe having a measured spectrum within 2.5 days of B-band maximum, for which the uncorrected Hubble residuals $\delta M(\lambda) = M(\lambda) - \langle M(\lambda)\rangle$ are independently computed in spectral bins and in five top-hat UBVRI-like filters. The equivalent widths $\mathrm{EW}^{\mathrm{Si}}$ and $\mathrm{EW}^{\mathrm{Ca}}$ corresponding to the Si II λ4131 and the Ca II H&K features are also computed on these spectra close to the maximum light. This sample and the way to derived all the used quantities are fully described in [3].

2. Intrinsic corrections and empirical reddening law derivation

The Hubble residuals dependence on $\mathrm{EW}^{\mathrm{Si}}$ exhibit a linear behaviour, with an asymmetrical magnitude dispersion attributed to extinction and remaining intrinsic variability, as shown in Fig. 1(a) as an example with δM_B. We may thus model the Hubble residuals for a given SN, i, as a sum of intrinsic and dust components, making various assumptions about the number of spectral energy distribution (SED) correction vectors, $\vec{s_\lambda}$, from none (Eq.2.1a) to two (Eq.2.1c), to get the absorption part in each wavelength bin, δA_λ, of the SNe Ia variability:

$$\delta M_{\lambda,i} = \begin{cases} \delta A^0_{\lambda,i} & (2.1a) \\ \mathrm{EW}_i^{\mathrm{Si}} s_\lambda^{\vec{\mathrm{Si}}} + \delta A^{\mathrm{Si}}_{\lambda,i} & (2.1b) \\ \mathrm{EW}_i^{\mathrm{Si}} s_\lambda^{\vec{\mathrm{Si}}} + \mathrm{EW}_i^{\mathrm{Ca}} s_\lambda^{\vec{\mathrm{Ca}}} + \delta A^{\mathrm{Si+Ca}}_{\lambda,i} & (2.1c) \end{cases}$$

As we expect the relation between the δA_λ to be linear for dust extinction, as shown in Fig. 1(b) for the U and V bands, we model the empirical reddening law as $\delta A_{\lambda,i} = \gamma_\lambda\, \delta A^*_{V,i} + \eta_\lambda$ where $\delta A_{\lambda,i}$ are the measured values, the slopes γ_λ $(= \partial A_\lambda / \partial A^*_V)$ the reddening law coefficients, $\delta A^*_{V,i}$ the fitted

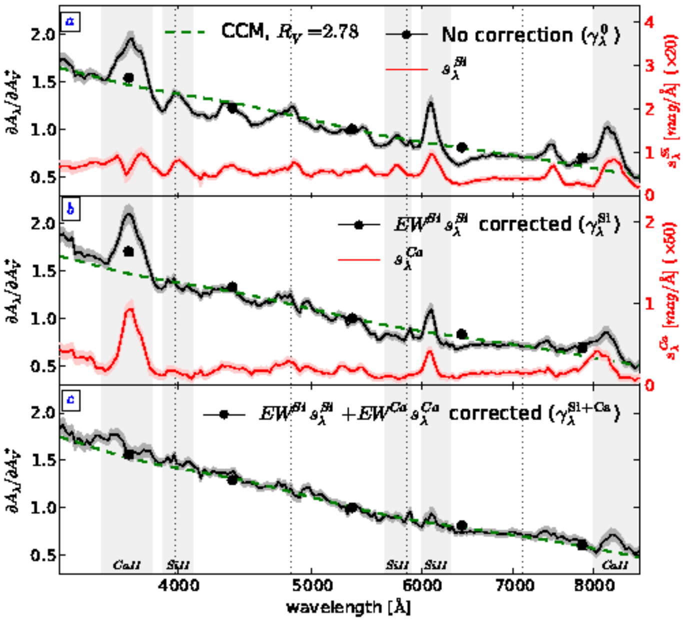

Figure 2: *Black:* Reddening law presented as $\gamma_\lambda \equiv \partial A_\lambda/\partial A^*_V$ as a function of wavelength. Filled circles correspond to the results obtained using the UBVRI-like bands, curves are for the spectral analysis. *Red:* Linear slope $\vec{s_\lambda}$ (mag/Å) of equivalent widths versus δM_λ. *Dotted lines*: CCM law fit corresponding to the broad bands analysis. *Panel a:* δM_λ corrected only for the phase dependence (eq. 2.1a). *Panel b:* δM_λ corrected for phase and EW$^{\mathrm{Si}}$ (eq. 2.1b). *Panel c:* δM_λ corrected for phase, EW$^{\mathrm{Si}}$ and EW$^{\mathrm{Ca}}$ (eq. 2.1c).

relative extinction for the SN i, and η_λ a free zero point. $\delta A^*_{V,i}$, γ_λ and η_λ are obtained by a χ^2 fit using the full wavelength covariance matrix of the $\delta A_{\lambda,i}$ measurements. However, the data are more dispersed than their measurement error (Fig. 1(b)), and another source of dispersion must be introduced, as described in [3].

3. Results

Results for the SED correction vector, $\vec{s_\lambda}$, and the reddening law, γ_λ, are presented in Fig. 2 for the different assumptions about the number of intrinsic components. If SNe were perfect standard candles affected only by dust as assumed by Eq. 2.1a and Fig. 2a, the empirical reddening law γ^0_λ would be a CCM-like law with an average R_V for our galaxy sample. However, γ^0_λ clearly exhibits small-scale SN-like features. These features correlate strongly with some of the features in the EW$^{\mathrm{Si}}$ correction spectrum, $\vec{s}^{\mathrm{Si}}_\lambda$, derived via Eq. 2.1b and illustrated in red in Fig. 2a.

The reddening law obtained after EW$^{\mathrm{Si}}$ correction (Fig. 2b) is closer to a CCM law, except in the Ca II H&K and IR triplet, and the Si II λ6355 region. This indicates the presence of a second source of intrinsic variability. The mean reddening law, γ^{Si+Ca}_λ, obtained after the additional correction by EW$^{\mathrm{Ca}}$ (Fig. 2c) is a much smoother curve with small residual features, and agrees well with a CCM extinction law. Thus it appears that these two components can account for SN Ia spectral variations at optical wavelengths. Any intrinsic component that might remain would have to be largely uncorrelated with SN spectral features fixed in wavelength, as well as being coincidentally compatible with a CCM law.

We apply the same treatment as above to our UBVRI-like synthetic photometric bands, and find agreement with the spectral analysis, as shown by the black points in the three panels in Fig. 2. The empirical fit presented previously can be forced to follow a CCM extinction law by substituting $\delta A_{\lambda,i} = (a_\lambda + b_\lambda/R_V)\,\delta A^*_{V,i} + \eta_\lambda$, where a_λ and b_λ are the wavelength dependent parameters given in [2], and a single R_V is fit over all bands. This fit applied to δA^{Si+Ca}_λ leads to an average $R_V = 2.78 \pm 0.34$ for the SN host galaxies in our sample. This value is compatible with the Milky Way average of $R_V = 3.1$, and has been discussed in [3].

4. Discussion and conclusions

Computing the Hubble residuals with $(\textsc{ew}^{\mathrm{Si}}, \textsc{ew}^{\mathrm{Ca}}, c)$ to standardize supernovae leads to a dispersion of 0.15 mag, which is a small improvement. Indeed, we do observe a correlation of $\textsc{ew}^{\mathrm{Ca}}$ and c, with $\rho = 0.34 \pm 0.10$, showing that c contains an intrinsic component, and that the SALT2 analysis is already accounting for some of this Ca effect. The presence of a second intrinsic parameter induces an increased variability in the UV.

Much lower effective R_V values have been found previously, from $R_V = 1.1$ to $R_V = 2.2$ [10, 9, 7, 4]. These values were derived accounting only for one intrinsic parameter beyond color. This difference is explained by the assumption on the dispersion matrix, and has little to do with the number of intrinsic parameters entering the correction. Indeed, if we instead use the one of [7], corresponding to an RMS between 0.09 and 0.11 mag on the diagonal, and all off-diagonal terms with an identical RMS of 0.09 mag, we obtain $R_V = 1.86$. This value is representative of previous analyses, but the matrix used is incompatible with our best fit matrix, for which an anti-correlation growing to -1 when the wavelength difference increases is observed, which implies a large color dispersion. This long-range anti-correlation implies that uncorrected variability in the SN spectra and/or the reddening law remains.

Equivalent widths are essentially independent of host reddening and provide a handle on the intrinsic properties of the SNe Ia. Correcting Hubble residuals with $\textsc{ew}^{\mathrm{Si}}$ and $\textsc{ew}^{\mathrm{Ca}}$ leads to a reddening law consistent with a canonical CCM extinction law, while adding a dispersion in colors during the fit leads to a value of R_V close to the Milky Way value of 3.1.

References

[1] Aldering, G., Adam, G., Antilogus, P., et al. 2002, SPIE Conference, 4836, 61

[2] Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

[3] Chotard, N., Gangler, E., Aldering, G., et al. 2011, A&A, 529, L4+

[4] Folatelli, G., Phillips, M. M., Burns, C. R., et al. 2010, AJ, 139, 120

[5] Freedman, W. L., Burns, C. R., Phillips, M. M., et al. 2009, ApJ, 704, 1036

[6] Guy, J., Astier, P., Baumont, S., et al. 2007, A&A, 466, 11

[7] Guy, J., Sullivan, M., Conley, A., et al. 2010, A&A, 523, A7+

[8] Jha, S., Riess, A. G., & Kirshner, R. P. 2007, ApJ, 659, 122

[9] Kessler, R., Becker, A. C., Cinabro, D., et al. 2009, ApJS, 185, 32

[10] Tripp, R. 1998, A&A, 331, 815