

Properties of extragalactic dust inferred from linear polarimetry of Type Ia Supernovae[★]

F. Patat¹, S. Taubenberger², N. L. J. Cox³, D. Baade¹, A. Clocchiatti⁴, P. Höflich⁵, J. R. Maund⁶, E. Reilly⁶, J. Spyromilio¹, L. Wang⁷, J. C. Wheeler⁸, and P. Zelaya⁴

¹ European Organisation for Astronomical Research in the Southern Hemisphere (ESO), Karl-Schwarzschild-Str. 2, 85748 Garching b. München, Germany
e-mail: fpatat@eso.org

² Max Planck Institute for Astrophysics (MPA), Karl-Schwarzschild-Str. 1, 85748 Garching b. München, Germany

³ Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, bus 2401, 3001 Leuven, Belgium

⁴ Departamento de Astronomia y Astrofísica, PUC, Casilla 306, Santiago 22, Chile

⁵ Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA

⁶ Queen's University Belfast, Belfast, BT7 1NN, UK

⁷ Department of Physics, Texas A&M University, College Station, Texas 77843, USA

⁸ Department of Astronomy and McDonald Observatory, The University of Texas at Austin, Austin, TX 78712, USA

Received April, 2014; accepted ?? 2014

ABSTRACT

Aims. The aim of this paper is twofold: i. investigate the properties of extragalactic dust and compare them to what is seen in the Galaxy; ii. address in an independent way the problem of the anomalous extinction curves reported for reddened Type Ia Supernovae (SN) in connection to the environments in which they explode.

Methods. The properties of the dust are derived from the wavelength dependence of the continuum polarization observed in four reddened Type Ia SN: 1986G, 2006X, 2008fp and 2014J. The method is based on the observed fact that Type Ia SN have a negligible intrinsic continuum polarization. This and their large luminosity makes them ideal tools to probe the dust properties in extragalactic environments.

Results. All four objects are characterized by exceptionally low total-to-selective absorption ratios (R_V) and display an anomalous interstellar polarization law, characterized by very blue polarization peaks. In all cases the polarization position angle is well aligned with the local spiral structure. While SN 1986G is compatible with the most extreme cases of interstellar polarization known in the Galaxy, SN 2006X, 2008fp and 2014J show unprecedented behaviors. The observed deviations do not appear to be connected to selection effects related to the relatively large amounts of reddening characterising the objects in the sample.

Conclusions. The dust responsible for the polarization of these four SN is most likely of interstellar nature. The polarization properties can be interpreted in terms of a significantly enhanced abundance of small grains. The anomalous behavior is apparently associated with the properties of the galactic environment in which the SN explode, rather than with the progenitor system from which they originate. The question as to why lines-of-sight to Type Ia SN are so different from what is seen for stars in the Galaxy remains unanswered. Recent studies suggest that there is a link between the dust properties and the chemical/physical evolutionary stage of the host galaxy.

Key words. ISM: dust, extinction - supernovae: general - supernovae: individual: 1986G, 2006X, 2008fp, 2014J

1. Introduction

Studying cosmic dust has important consequences on our understanding of a number of astrophysical processes, ranging from galaxy evolution to stellar and planetary formation. The

characterization of dust in the diffuse interstellar medium relies heavily on the observed wavelength dependencies of extinction and polarization (see Voshchinnikov 2012 for a comprehensive review). While this study can be undertaken in the Galaxy using pair-matching of stars of the same spectral and luminosity classes (see Whittet 2003 for a review), its application to the extragalactic case is only possible for very few nearby systems, like the Magellanic clouds. At larger distances other methods are used: foreground extinction of distant quasars, differential extinction of multiply lensed quasars, gamma-ray-

Send offprint requests to: F. Patat

[★] Based on observations made with ESO Telescopes at the Paranal Observatory under Program IDs 076.D-0177 and 076.D-0178. Also based on observations collected at the German-Spanish Astronomical Center, Calar Alto (Spain) and on observations made with the Mercator Telescope, Roque de los Muchachos, La Palma (Spain) equipped with the HERMES spectrograph.

Table 1. Basic properties of the SN sample

SN	Host	Host type	Host notes	R_V	A_V	E_{B-V}	Ref.	P_{04} (%)	λ_{max} (μm)	P_{04}/E_{B-V} (% mag $^{-1}$)	θ (deg)
1986G	NGC5128	S0, pec	starburst	$2.57^{+0.23}_{-0.21}$	$2.03^{+0.09}_{-0.13}$	$0.79^{+0.08}_{-0.08}$	1	5.1 ± 0.1	0.43	6.5 ± 0.7	117.9 ± 0.8
2006X	NGC4321	SAB(s)bc		$1.31^{+0.08}_{-0.10}$	$1.88^{+0.09}_{-0.13}$	$1.44^{+0.11}_{-0.15}$	1	7.8 ± 0.2	<0.4	5.4 ± 0.5	139.5 ± 0.1
2008fp	ESO 428-G14	SAB(r)0	active	$1.20^{+0.26}_{-0.14}$	$0.71^{+0.10}_{-0.08}$	$0.59^{+0.15}_{-0.10}$	1	2.6 ± 0.1	<0.4	4.4 ± 1.0	148.4 ± 0.2
2014J	NGC3034	IO	starburst	1.40 ± 0.10	1.85 ± 0.11	1.37 ± 0.03	2	6.6 ± 0.1	<0.4	4.8 ± 0.1	42.2 ± 0.3

References: (1) Phillips et al. (2013); (2) Amanullah et al. (2014).

burst/supernova host extinction, extinction in star-burst galaxies.

In this article, we focus on the use of Type Ia Supernovae (SN). These bright ($M_V \sim -19$) objects were used several times as line-of-sight probes to infer the properties of the intervening material. The technique applied so far can be considered as an extension of the pair-matching method, in which the observed spectrophotometric properties are compared to a set of un-reddened templates. This has led to the striking result that the total-to-selective absorption ratio (R_V) is systematically and significantly lower than what is typical in the Galaxy ($R_V \sim 3$; Fitzpatrick & Massa 2007). From the analysis of 80 Type Ia SN with $E_{B-V} \leq 0.7$, Nobili & Goobar (2008) derived an average value $R_V = 1.75 \pm 0.27$. Although this result was revised towards more “normal” values ($R_V = 2.8 \pm 0.3$, Chotard et al. 2011), objects with relatively large reddening ($E_{B-V} > 0.4$) show unusually low R_V (Phillips et al. 2013). This has interesting implications both for our understanding of dust and the explosion environments of Type Ia SN.

Here we discuss an independent approach, which relies on the fact that SN Ia have a very low intrinsic continuum polarization (<0.3%, Wang & Wheeler 2008). This level of continuum polarization is negligible when the reddening is significant ($E_{B-V} > 0.1-0.2$) and the interstellar polarization prevails. Their luminosity, insignificant intrinsic continuum polarization and supposed absence of significant amounts of circumstellar material (at variance with core-collapse events) with possibly peculiar characteristics, make Type Ia SN suitable background illuminators to probe the dust properties in extragalactic environments.

The paper is structured as follows. In Section 2 we present the sample. Section 3 discusses the continuum polarization dependence and compares it to a sample of Galactic stars. The significance of the observed deviations from the Galactic behavior and their physical implications are analyzed in Section 4. Finally, our conclusions are summarized in Section 5.

2. Data

The number of reddened Type Ia SN ($E_{B-V} > 0.5$) with polarimetric data of sufficient quality (in terms of accuracy and wavelength coverage) is very small. To the best of our knowledge this includes only SN 1986G (NGC 5128; Cen A), 2006X (NGC 4321; M100), 2008fp (ESO 428-G14) and the recent 2014J (NGC 3034; M82). Other Type Ia SN have spectropolarimetric data: 1997dt, 2002bf, 2003du, 2004dt (Leonard et al. 2005); 2001el (Wang et al. 2003); 2007sr (Zelaya et al. 2013);

2005ke (Patat et al. 2012); 2011fe (Smith et al. 2012); 2012fr (Maund et al. 2013); however, the low reddening associated with these events makes the study of the interstellar polarization (ISP) wavelength dependence very uncertain, if not impossible (see also Zelaya et al. 2014).

The four selected objects show a pronounced continuum polarization at position angles remarkably aligned with the local spiral arms of their hosts, as expected for dust grain alignment along the galactic magnetic field (Scarrot, Ward-Thompson & Warren-Smith 1987). In all cases, the wavelength dependence of the polarization position angle is very mild or null, similarly to what is seen in Galactic stars (Dolan & Tapia 1986). All four SN Ia have high-quality, high-resolution spectroscopy data, with a number of separate interstellar absorption components indicating significant amounts of gas (atomic and molecular) at different velocities along the line-of-sight (D’Odorico et al. 1989; Cox & Patat 2008; Cox & Patat 2014a; Cox et al. 2014b; Goobar et al. 2014; Welty et al. 2014).

The relevant properties of the sample discussed in this paper are summarized in Table 1. In addition to the reddening characteristics, the table reports the basic polarization parameters, which will be introduced and discussed in Section 3.

2.1. SN 1986G, 2006X and 2008fp

SN 1986G is the first Type Ia SN that was used for studying the polarization properties of the intervening dust. For this object, UBVRJH broad-band polarimetry was obtained by Hough et al. (1987). SN 2006X and 2008fp were observed in the framework of our spectropolarimetric programme with the FOCal Reducer/low-dispersion Spectrograph (FORS1), mounted at the Cassegrain focus of the ESO–Kueyen 8.2m telescope (Appenzeller et al. 1998). The data and their reduction are discussed in Patat et al. (2009) and Cox & Patat (2014a).

2.2. SN 2014J

Spectropolarimetry of SN 2014J is reported here for the first time. A preliminary analysis was published by Patat et al. (2014). A full analysis of the spectropolarimetric data will be presented in a separate paper, while here we focus purely on the continuum polarization.

Linear spectropolarimetry of SN 2014J was obtained on three epochs (Jan 28, Feb 03 and Mar 08, 2014), using the Calar Alto Faint Object Spectrograph (CAFOS), mounted at the 2.2 m telescope in Calar Alto, Spain (Meisenheimer 1998; Patat & Taubenberger 2011, hereafter PT11). All spectra were

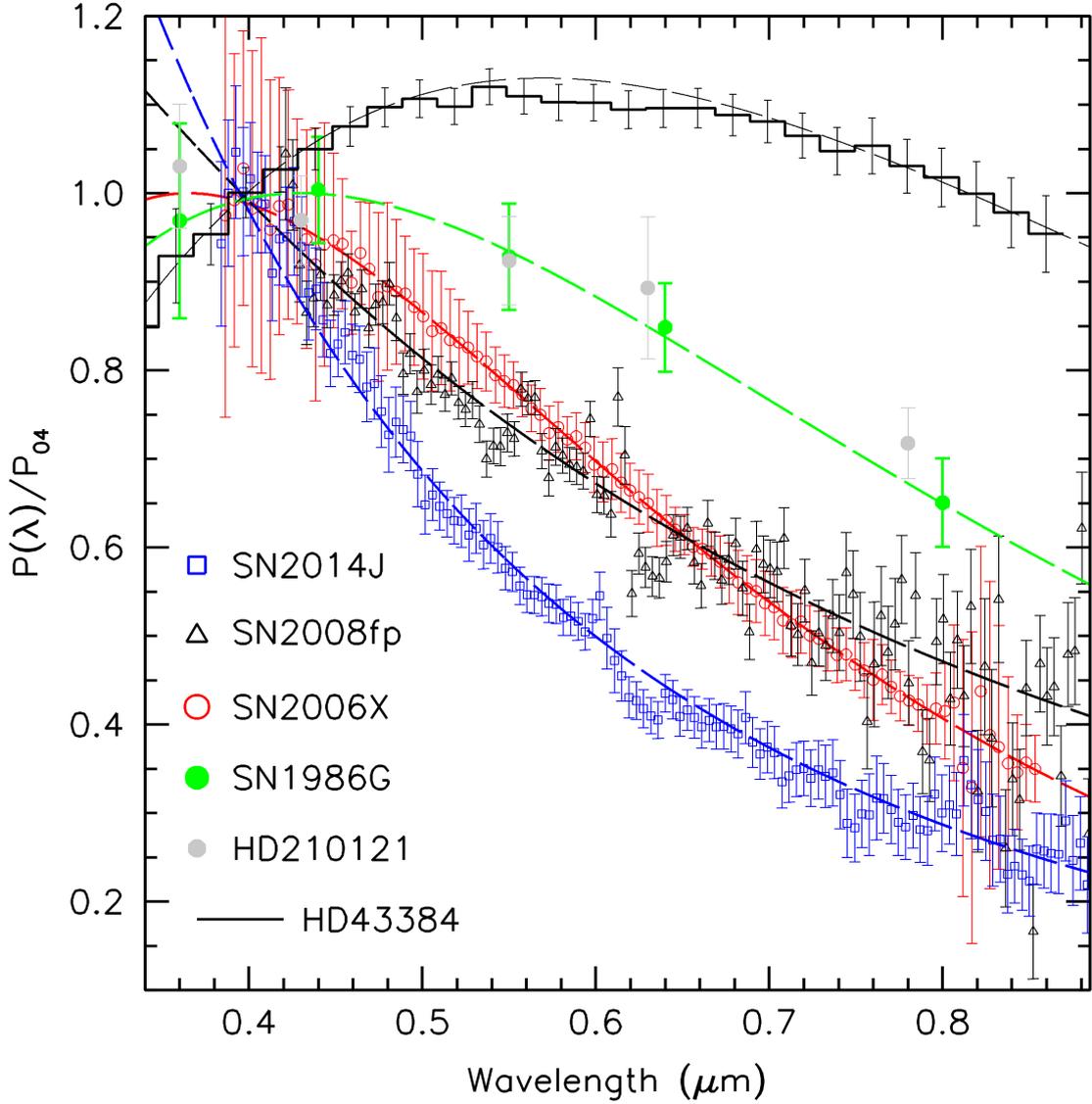


Fig. 1. Observed polarization wavelength dependence for SN 1986G (Hough et al. 1987), SN 2006X (Patat et al. 2009), SN 2008fp (Cox & Patat 2014a) and SN 2014J (this work). For comparison, the data of HD 43384 (this work) and HD 210121 (Larson et al. 1996) are also plotted. The dashed curves trace Serkowski law best fits. For presentation, the curves were normalized to P_{04} (see text). The error bars were kept at their original values. HD 43384 is a polarized standard; HD 210121 is a Galactic star with very low R_V .

obtained with the low-resolution B200 grism coupled with a 1.5 arcsec slit, giving a spectral range 3300–8900 Å, a dispersion of $\sim 4.7 \text{ \AA px}^{-1}$, and a FWHM resolution of 21.0 Å. For each retarder angle we obtained two exposures; integration times ranged from 10 to 25 minutes per exposure. Because of the low signal-to-noise ratio and the known instrumental limitations (PT11), the CAFOS spectropolarimetric data below 3800 Å cannot be used.

The Stokes parameters were derived with the same procedure as used for SN 2006X and 2008fp. Error estimates were performed following the prescriptions described by Patat & Romaniello (2006a), while the HWP zero-point angle chroma-

tism was corrected using tabulated data (PT11). To check and correct for instrumental polarization, the unpolarized standard HD 90508 (Serkowski 1974) was observed at each epoch. A spurious polarization of 0.3% is detected. Although the polarization level of HD 90508 is constant ($\sim 0.25\%$; see also PT11), different corrections were applied to the three data sets, as the polarization angle changed between the epochs. For this reason the correction is accurate to a few 0.1%. Given the high level of polarization displayed by SN 2014J (see below), this does not affect any of the conclusions presented in this paper. The overall performance of the system and the quality of the chromatic and instrumental polarization corrections were checked

using observations of the polarized standard star HD 43384 (Mathewson & Ford 1970). The maximum polarization is $P_{max}=3.10\pm 0.05\%$ at $\lambda_{max}=0.539\ \mu\text{m}$ and average position angle $\theta=170.3\pm 0.2$ degrees. These values are fully consistent with those reported by Serkowski, Mathewson & Ford (1975): $P_{max}=3.0\%$, $\lambda_{max}=0.53\ \mu\text{m}$, $\theta=170$ degrees. The marked wavelength dependence of the position angle ($d\theta/d\lambda=7.4\pm 0.6$ degrees μm^{-1}) is consistent with the findings of Doland & Tapia (1986).

For the purposes of this paper, we use the data of the second epoch that, being obtained closest to maximum light, have the best signal-to-noise ratio. The first and the last epoch show a very similar behavior, with the changes related to the evolution of the intrinsic SN properties, most prominently in the Si II 6355 Å and the Ca II near-IR triplet. The continuum polarization level is constant within the measurement errors.

The signal is dominated by a continuum polarization that grows steadily and rapidly from the red to the blue, reaching about 6.6% at 0.4 μm . The average polarization position angle for SN 2014J is 42.2 ± 0.3 degrees, which is well aligned with the local spiral structure and in good agreement with the value reported by Greaves et al. (2000) for the dust lane (40 degrees). In particular, it is fully consistent with the position angle distribution along the dust lane of M82 (Jones 2000; see his Figures 4 and 5) and identified as being generated by transmission (as opposed to scattering).

3. ISP wavelength dependence

In Figure 1 we present the wavelength dependence displayed by the four SN. The deviation from the typical behavior seen in the Milky Way (MW) is illustrated by the comparison with the Galactic star HD 43384 (solid histogram). While SN 1986G shows a polarization maximum at $\lambda_{max}=0.435\ \mu\text{m}$, SN 2006X, 2008fp and 2014J do not show evidences of a peak in the spectral range covered by the data. In the absence of a maximum, we quantify the polarization level with the value measured at 0.4 μm ($P_{0.4}$). This is then used to compute the polarization efficiency $P_{0.4}/E_{B-V}$, which ranges from 4.4 to 6.5 % mag⁻¹ (see Table 1). Since the polarization maximum is not observed, these are only lower limits for the true polarization efficiency. It is therefore not possible to firmly establish whether or not the SN conform to the Galactic limit $P_{max}/E_{B-V} < 9\ \text{mag}^{-1}$ (Serkowski et al. 1975). The weighted average $P_{0.4}/E_{B-V}$ is $4.9\pm 0.4\ \text{mag}^{-1}$. Given the relatively large values of E_{B-V} , this estimate is robust, by contrast to low-extinction cases (see the discussion in Leonard et al. 2002). For presentation, the polarization curves are normalized to $P_{0.4}$. The errorbars were kept at their original amplitudes to allow for a direct comparison of the different uncertainties characterising the various data-sets.

The exceptional behavior displayed by Type Ia SN compared Galactic stars is made more evident by considering the wavelength dependence of the most extreme known cases. To the best of our knowledge, HD 193682 has the bluest ISP peak reported in the literature, with $\lambda_{max} \leq 0.32\ \mu\text{m}$ (Anderson et al. 1996); however, a more recent study revised this finding, re-positioning the maximum at $0.445\pm 0.020\ \mu\text{m}$ (Weitenbeck 2008). Other interesting cases are those of Cyg OB2 No. 10

and 12, for which Whittet et al. (1992) report $\lambda_{max}=0.33\ \mu\text{m}$ and $0.35\ \mu\text{m}$, respectively. The polarization wavelength dependence seen in these two objects resembles that of SN 1986G, possibly with a larger slope (see also the best fit presented by Martin et al. 1992 for Cyg OB2 No. 12: $\lambda_{max}=0.35\pm 0.02\ \mu\text{m}$, $K=0.61\pm 0.04$). Another relevant case is that of HD 210121, for which independent estimates of polarization and total-to-selective extinction are available. This star was reported to have $\lambda_{max}=0.38\pm 0.02\ \mu\text{m}$ and an exceptionally low $R_V=2.1\pm 0.2$ (Larson, Whittet & Hough 1996). In general, the wavelength dependence is again similar to that of SN 1986G. In the optical and near-UV, the two data sets are consistent within the one-sigma errors (see Figure 1, gray filled circles), while the near-IR data indicate a slightly flatter curve for HD 210121.

As already discussed in Patat et al. (2009), SN 2006X shows a steadily growing polarization to the blue, reaching about 8% at the blue edge of the spectral coverage. The curve flattening observed in the blue suggests that the maximum polarization occurs shortly before 0.38 μm . A non-linear least squares fit using the Serkowski empirical expression ($P(\lambda)/P_{max} = \exp[-K \ln^2(\lambda_{max}/\lambda)]$) gives $K=1.47\pm 0.05$ and $\lambda_{max}=0.365\pm 0.02\ \mu\text{m}$. Although the derived value for K is completely different from what is predicted by the Whittet et al. (1992) relation (0.62 ± 0.07), the resulting curve gives an excellent match to the data (see Figure 1).

The case of SN 2008fp is similar to that of SN 2006X (see also Cox & Patat 2014a); however, the nature of the data and the increased noise in the red (partially due to a marked fringing) do not allow a well constrained fitting with a Serkowski law (the formal solution is rather degenerate, with very elongated contours in the χ^2 space). We note that probably one third of the reddening suffered by this object arises in the Milky Way (see also Cox & Patat 2014a), so that the red portion of the curve may be affected by the Galactic component. The slope observed in the blue favors a value of K smaller than that of 2006X, with a possible maximum below 0.4 μm . A formal least-squares fit using the Serkowski formulation yields $K=0.40\pm 0.05$ and $\lambda_{max}=0.148\pm 0.03\ \mu\text{m}$.

Finally, SN 2014J appears to be the most extreme case, with a very steep polarization increase in the blue. With the lack of UV data, it is impossible to extrapolate the position of the polarization peak. The Serkowski law was shown to approximately hold in the UV for Galactic stars with λ_{max} in the optical and UV coverage (see Anderson et al. 1996; Martin, Clayton & Wolff 1999). However, with only the possible exception of HD 193682, there are no published direct observations of Galactic objects with peaks in the UV. The best fit for SN 2014J has $K=0.40\pm 0.07$ and $\lambda_{max}=0.05\pm 0.02\ \mu\text{m}$. We remark that for both SN 2008fp and 2014J the derivation of the Serkowski parameters is based on the unjustified assumption that the expression can be extrapolated to extremely short wavelengths. The best fit curves are plotted in Figure 1 for pure illustrative purposes (see next section).

In summary, with the possible exception of SN 1986G, the wavelength dependence seen in our SN sample has never observed in the Galaxy.

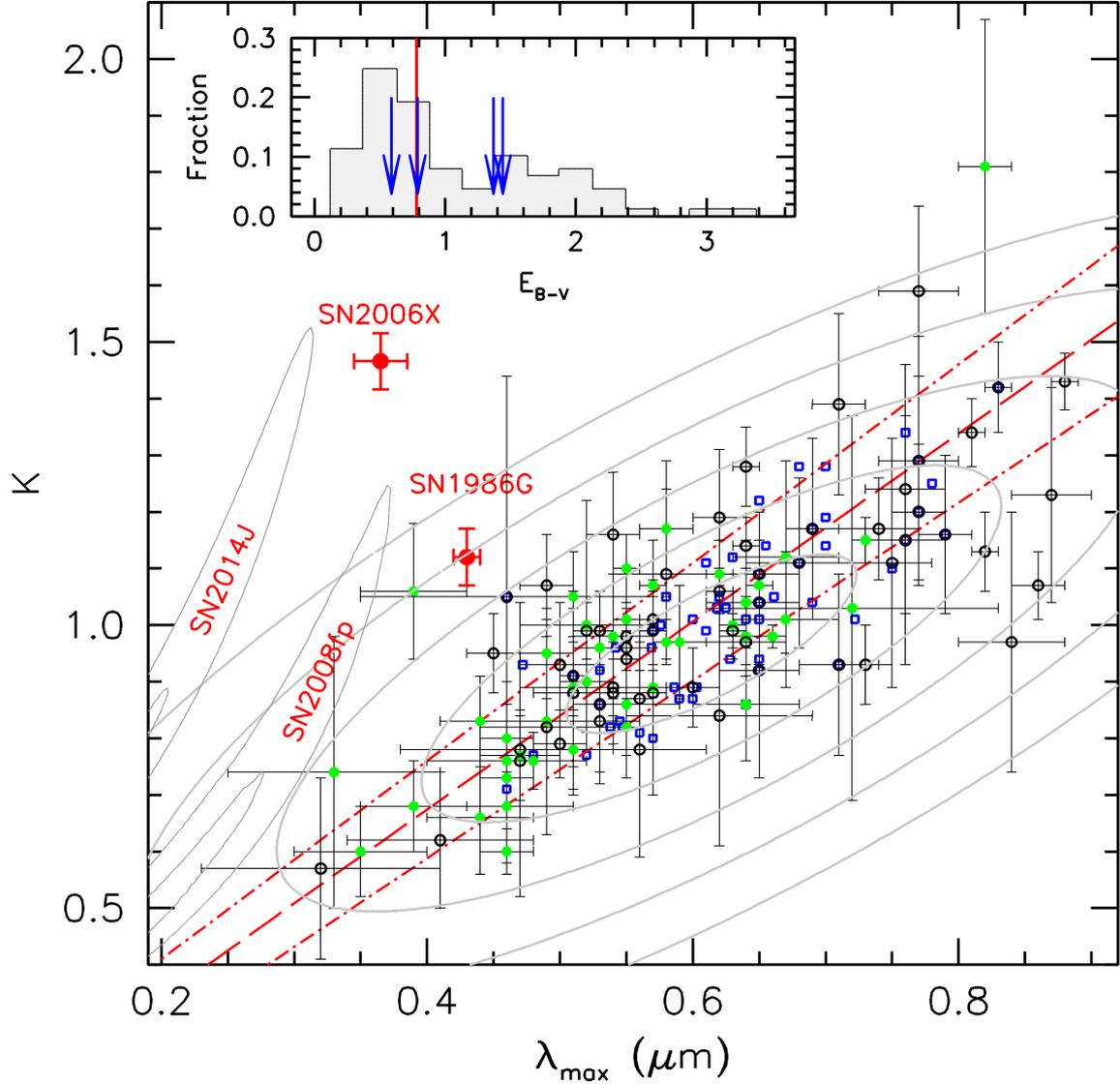


Fig. 2. Serkowski parameters λ_{max} and K for Galactic stars. The data are from Whittet et al. (1992, circles) and Voshchinnikov et al. (2013, squares). Filled symbols indicate objects with $E_{B-V} > 0.8$. The ellipses trace the 1- to 5-sigma confidence levels for the full Whittet et al. sample (for a bi-variate Gaussian distribution). For comparison, the parameters derived for SN 1986G and 2006X are plotted (large filled circles). The long dashed line traces the Whittet et al. relation (the dashed-dotted lines indicate the ± 1 -sigma levels). The contours in the lower left corner of the plot indicate the 10- and 20-sigma confidence levels for SN 2008fp and 2014J. The upper left insert plots the E_{B-V} distribution of the Whittet et al. (1992) sample of 105 stars. The vertical line marks the median value of E_{B-V} , while the arrows indicate the values of the four SN (see Table 1).

4. Discussion

4.1. Statistical significance

Although we have shown with some confidence that all four SN in our sample deviate from the average behavior seen in the Galaxy, it is important to quantify the significance of this deviation. For this purpose, in Figure 2 we present the Galactic samples by Whittet et al. (1992) and Voshchinnikov et al. (2013) on the $\lambda_{max} - K$ plane. The second sample has some intersection with the first and no error bars are given. It is therefore

included only for the sake of completeness and it is not used in the statistical analysis that follows.

As concluded by Whittet et al. (1992; see also Wilking, Lebofsky & Rieke 1982), the Galactic data cluster around a linear relation ($K = 0.01 \pm 0.05 + [1.66 \pm 0.09] \lambda_{max}$). This empirical law (see Figure 2, long-dashed line) was derived by Whittet et al. (1992) rejecting 27 objects from the original sample including 105 stars. For quantifying the bi-dimensional distribution, we have estimated the probability contours from the error-weighted covariance matrix computed on the full Whittet et al.

sample. These are traced as light-colored ellipses at 1-sigma intervals. The misalignment between the best fit Whittet et al. relation and the major axis of the ellipses is due to the inclusion of the 27 objects rejected by Whittet et al. (1992).

Out of the total sample, 1.9% of the Galactic objects fall outside of the 4-sigma level. Of the 5 stars with $\lambda_{max} < 0.4 \mu\text{m}$, 4 have K values that are consistent with the derived relation. The other, Cyg OB 2 A, is off by 4 sigma ($\lambda_{max}=0.39\pm0.04 \mu\text{m}$, $K=1.06\pm0.12$; $E_{B-V}=2.59$). Interestingly, for this star Whittet et al. (1992) report that it “has a polarization curve rising anomalously steeply to the blue, and lay furthest from the best straight line”. Although the wavelength dependence is very similar to that shown by SN 1986G, for this star there are no U-band data and the B point is characterized by a relatively large uncertainty ($P=6.6\pm0.7\%$). At face value, there are no signs of a maximum in the optical domain for this star.

Cy OB 2 A represents slightly less than 1% of the Whittet et al. (1992) sample. This fraction decreases to $\sim 0.7\%$ if one includes the Voshchinnikov et al. (2013) sample, giving a first quantitative estimate of the rarity of SN 1986G-like polarizations in our Galaxy. As first pointed out by Hough et al. (1987), this indicates that the dust along the line of sight to SN 1986G is significantly different from what has been studied and published so far for the Milky Way. SN 2006X constitutes an even more deviant case (Patat et al. 2009). The polarization law for this SN appears to be at more than 9 sigma from the MW sample (see Figure 2).

The cases of 2008fp (Cox & Patat 2014a) and 2014J are more difficult to place on the $\lambda_{max} - K$ plane, because of the degeneracy of the Serkowski law fitting caused by very weakly constrained peak positions (see previous section). Nevertheless, one can get an indication by running a brute-force χ^2 mapping as a function of λ_{max} and K . The resulting 10- to 20-sigma confidence levels are plotted in Figure 2 (left lower corner). As anticipated, they are very elongated, hence implying a wide range of suitable parameter combinations. Although this is strictly valid only for a Serkowski law (and there is no guarantee that this holds when the maximum is in this extremely blue regime), the contour plots indicate that both objects deviate in a very significant way from the Galactic behavior. Given the similarities between SN 2006X and 2008fp (see Figure 1), we argue that SN 2008fp deviates from the Galactic sample at a similar statistical significance level.

This analysis confirms the findings presented in the previous section: all four SN in our sample display exceptional properties. If they were all drawn from the Galactic distribution, then having four outlier events at the observed significance levels would be very unlikely. At face value this leads to the conclusion that they belong to a different underlying population.

4.2. Selection effects

The current sample of SN is small and possible selection effects may be playing an important role. By construction, the four SN discussed in this paper are all significantly reddened ($0.6 \lesssim E_{B-V} \lesssim 1.4$; see Table 1). One may therefore argue that this in-

roduces systematic biases with respect to the Galactic sample, hence favoring special λ_{max}, K combinations. The E_{B-V} distribution for the Whittet et al. sample is shown in the insert of Figure 2 and has a median $E_{B-V} \simeq 0.8$. The stars with a reddening larger than the median tend to show smaller values of λ_{max} and K (see the filled circles in Figure 2). However, the linear correlation coefficients of λ_{max} and K vs. E_{B-V} are -0.34 and -0.24 , respectively, indicating a weak dependence of these parameters on the reddening (see Figure 3). In addition, $\sim 30\%$ of the Whittet et al. stars have $E_{B-V} > 1.4$, i.e. larger than the highest value in the SN sample (see Table 1). These facts imply that, at least for the Galactic sample, selecting highly reddened objects does not lead to strong systematic effects on the final determination of the K vs. λ_{max} relation, or on the overall distribution of the selected events on the $\lambda_{max} - K$ plane.

We note that the ISP wavelength dependence observed in several supernovae, not only of Type Ia, clearly deviates from the Galactic Serkowski law (Leonard & Filippenko 2001; Maund et al. 2007a; Patat et al. 2010; Maund et al. 2010a). Notably, the Type II SN 1991gi shows a *normal* wavelength dependence ($K=1.15$ and $\lambda_{max}=0.51 \mu\text{m}$, Leonard et al. 2002). This SN suffered of a minimal reddening ($E_{B-V}=0.21\pm0.09$, with a robust upper limit of $E_{B-V} < 0.45$). Although in the light of the above findings this may be more an exception than the rule, the low reddening experienced by this object may again indicate that the strong deviations occur in highly obscured events.

Another possible source of bias resides in the host characteristics. Both NGC 5128 (S0, peculiar) and NGC 3034 (I0, edge on) are starburst galaxies, a fact which may have some relevance for the dust properties (see for instance Hutton et al. 2014). While SN 2014J in NGC 3034 is the most discordant object, SN 1986G in NGC 5128 is the least deviant one. The host of SN 2006X is a normal SAB(s)bc spiral, while 2008fp exploded in a peculiar SAB(r)0 galaxy, with radio jets and signs of activity (Veron & Veron 2006). Given the exiguous size of the sample, it is impossible to tell whether there is a systematic correlation between the host properties and the ISP behavior.

Finally, one can question whether the observed behaviors are due to the peculiar nature of isolated clouds along the line-of-sight. In both SN 2008fp and 2006X (that incidentally show a similar ISP wavelength dependence), the bulk of reddening is produced within molecular clouds signaled by exceptionally strong CN features (Cox & Patat 2008, 2014a; see also the discussion in Phillips et al. 2013). Molecular gas was also detected towards SN 1986G in the form of weak CH and CH⁺ absorptions, although no CN features were reported (D’Odorico et al. 1989). The situation is very similar for SN 2014J, towards which CN is very weak (Welty et al. 2014; Sternberg et al. 2014).

In the case of 2006X and 2008fp the bulk of reddening (and hence polarization) most probably originates within one single large thick cloud, this is not the case for SN 1986G and 2014J. For these two objects high-resolution spectroscopy reveals a number of Na I and Ca II features with comparable depth. This is illustrated for 2014J in Figure 4, which presents the absorption profiles of Na and K lines (see also Welty et al. 2014). In addition to the Galactic component at zero velocity, the profile

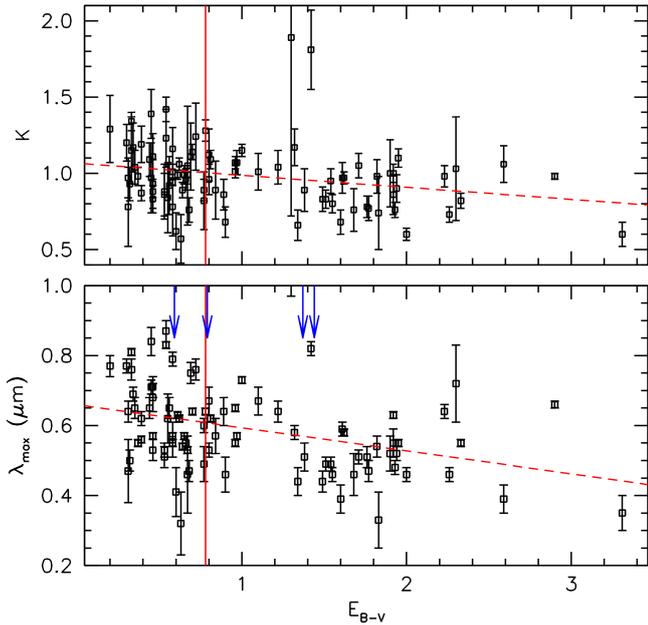


Fig. 3. Serkowski parameters K and λ_{max} as a function of E_{B-V} for the Whittet et al. (1992) sample. The dashed lines trace the best linear least squares fit to the data. The vertical solid line marks the median E_{B-V} , while the arrows are placed at the values of the four SN (see Table 1).

shows more than ten extragalactic absorptions. Even within the strongly saturated Na I D feature, the weaker K I line reveals more than five distinct components of comparable strength. This excludes that the bulk of reddening (and polarization) is generated within one single thick cloud with peculiar properties. The observed behavior results from the combined presence of numerous clouds along the line-of-sight, spanning a wide range of velocities (and most probably positions) within the host. For this reason we conclude that what is observed in SN 2014J reflects the average properties of the disk of M82, which is seen almost edge-on. This conclusion probably applies also to SN 1986G, which displays a similarly large number of components (D’Odorico et al. 1989).

4.3. Implications on dust properties and extinction law

Before addressing the implications of the findings presented in the previous sections, it is important to note that deviations from the empirical Serkowski law can be obtained by combining the effects of two or more clouds with different properties (see Coyne & Gehrels 1966. See also Patat et al. 2010; Appendix B). For instance, one can imagine a case in which the observed polarization results from the combination of two dust systems, individually described by different combinations of P_{max} , λ_{max} , K and position angle θ . Depending on the values of these parameters, the output polarization may show very deviant wavelength dependencies. Normally this is accompanied by a wavelength dependence of the position angle (like the one observed for HD 43384; see Section 2). For SN 2006X,

2008fp and 2014J $d\theta/d\lambda$ is consistent with zero; but Hough et al. (1987) reported a mild dependence ($d\theta/d\lambda=4.5\pm 1.9$ degrees μm^{-1}) for 1986G, which may signal that the polarization position angles of the various clouds along the line-of-sight are different. It is important to note that there is no way any combination of Serkowski laws with λ_{max} in the wavelength interval found in our Galaxy can produce polarization curves like those observed for SN 2006X, 2008fp and 2014J. This implies that the observed behavior must come from systematic differences in the dust properties.

The observed linear dependence of K on λ_{max} is qualitatively understood as a systematic increase in the number of small, aligned grains in regions displaying bluer polarization peaks (Martin et al. 1999; Whittet et al. 2001; Voshchinnikov 2012). This argument has been used, for instance, to infer that the size of dust grains along the line-of-sight to SN 1986G is significantly smaller than what is typical in the Milky Way (Hough et al. 1987). This is more quantitatively confirmed by recent modeling. Siebenmorgen, Voshchinnikov & Bagnulo (2014; their Figure 5) show that substantial changes in the polarization law take place in the optical and UV domain when the minimum grain size decreases from 200 nm to 50 nm, with the polarization peak moving from $\sim 1 \mu\text{m}$ to $0.25 \mu\text{m}$, respectively; however, the modeling also demonstrates that dust size is not the only ingredient (see below).

It has been suggested for a long time that the shape of the polarization law is related to the extinction law. Serkowski et al. (1975) found that the total-to-selective absorption ratio relates to the position of the polarization peak, following the empirical relation $R_V = 5.5\lambda_{max}$. This was slightly revised by Whittet & van Breda (1978; $R_V=[5.6\pm 0.3]\lambda_{max}$) and Clayton & Mathis (1988; $R_V=-0.29\pm 0.74 + [6.67\pm 1.17]\lambda_{max}$). Inserting $\lambda_{max} \leq 0.4 \mu\text{m}$ into these empirical relations gives the following upper limits on R_V : 2.2, 2.2 ± 0.1 and 2.3 ± 0.9 , respectively. All these values are consistent with the spectrophotometric derivations of R_V for SN 2006X, 2008fp and 2014J (although we note that the uncertainties in the Clayton & Mathis relation are quite large). For SN 1986G, the cited relations give $R_V=2.4$ - 2.6 , which fully agrees with the spectrophotometric estimate (Table 1. See also the discussion in Phillips et al. 2013).

The R_V vs. λ_{max} relation has been shown to behave differently in different regions of the Galaxy, to the extent that in some cases there is a poor (or even no) correlation between the two quantities (Whittet et al. 2001; Andersson & Potter 2007). This is interpreted as an indication of a dependence of the grain alignment on its nature, which brings the dust composition into the game. The models show that, at least in the Galaxy, silicates are most likely the only contributors to polarization (see Voshchinnikov 2012 and references therein). Therefore, while the extinction curve (and hence R_V) is determined by dust grains of all species (silicate, carbonaceous, iron-rich, etc.) the polarization law is not. Consequently, under particular conditions, the two can become weakly or even not correlated (Voshchinnikov 2012). For the sake of completeness, we mention that none of the cited works included stars with $\lambda_{max} < 0.39 \mu\text{m}$.

Despite these facts, the four SN presented in this paper consistently show values of both λ_{max} and R_V that are very un-

common (or even unprecedented) in our Galaxy. The Galactic sample presented by Valencic, Clayton & Gordon (2004) does not include any object with $R_V \leq 2$, while Fitzpatrick & Massa (2007) report only one such star ($\sim 0.3\%$ of their sample). This fraction increases to $\sim 6\%$ in the anomalous extinction sample by Mazzei & Barbaro (2011). The deviating objects are not associated with high reddening ($E_{B-V} < 0.5$), hence excluding the possibility that the exceptionally low values derived for our SN are necessarily the product of large extinction. Although R_V ratios that significantly deviate from the average are observed in our Galaxy, the distribution is significantly skewed towards large values. In the Fitzpatrick & Massa sample, the fractions of stars with $R_V \geq 3.5$ and $R_V \geq 4.0$ are 21.6% and 9.5%, respectively. Therefore, the exceptional behaviors observed for the Type Ia sample are very hard to interpret in terms of anomalous lines-of-sight if the host galaxy dust mixtures were similar to that of the Milky Way.

At face value, these findings lead to the striking, anti-Copernican conclusion that something is special about the dust of the Milky Way. Another possibility is that the magnetic field of the Galaxy is special. If the field lines are more ordered or the field strength is higher, then the alignment of grains and the resulting polarization would be different.

Although not very much is known about extragalactic dust, some information is available. For instance, Finkelman et al. (2014) derived $R_V = 2.8 \pm 0.4$ for a sample of nine early-type galaxies with dust lanes, and concluded that the extragalactic dust properties are similar to those typical for the Galaxy. This would suggest that there is something special with the lines-of-sight associated with some Type Ia SN. As shown by Wang (2005), Patat et al. (2006b) and Goobar (2008), unusually low values of R_V can be produced by scattering by circumstellar dust. Although, in principle, this scenario provides a viable explanation, it leaves a number of open issues.

Most importantly, the propagation of the light echo through the local dust is expected to produce rapid time variability, both in the resulting R_V and in the polarization (in case the dust has an asymmetric geometry). Secondly, in order to have a measurable effect on R_V , this requires conspicuous amounts of dust in the SN vicinity. This poses problems both in terms of dust survival and in the implied presence of significant amounts of gas which, with the possible exception of SN 2006X, were not detected (see Patat et al. 2006b for a detailed discussion on the subject). In the cases of 2006X and 2008fp, it is anyway difficult to believe that those thick molecular clouds, where the bulk of reddening and polarization are expected to arise (Cox & Patat 2008, 2014a), are directly associated with the SN. A similar argument applies to the numerous components detected along the lines-of-sight to 1986G and 2014J.

Other counter-arguments against a circumstellar origin for the bulk of dust in these events are related to the observed polarization angles and wavelength dependence. In the case in which the dust is mostly placed at very large distances from the SN, the polarization is acquired purely by transmission (i.e. through dust dichroism) and the polarization angle reflects the properties of the galactic magnetic field via the dust grain alignment. The picture becomes significantly different if a relevant fraction of the dust is confined to the immediate surroundings

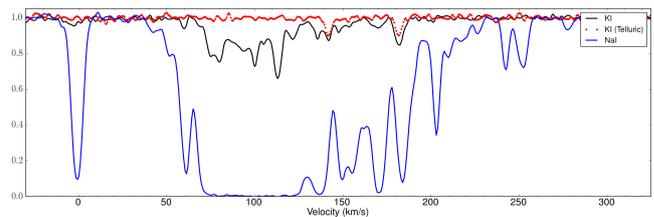


Fig. 4. Galactic and interstellar absorption components for Na I D (blue) and K I (black). The dotted curve traces a telluric absorption spectrum for the K I region. The data were obtained with the HERMES spectrograph (Sternberg et al. 2014.)

of the progenitor system. In these circumstances, a non negligible contribution to polarization would come from photons scattered into the line-of-sight, because scattering is a very efficient polarization mechanism (see Patat 2005 and references therein). In that scenario, the net polarization depends on the geometrical dust distribution (the polarization is perpendicular to the scattering plane) and it is null in the case this is spherically symmetric. In all other cases, the resulting net polarization would carry the geometrical imprints through the polarization angle, which for circumstellar material has no relation to the magnetic field of the host. The fact that the measured position angles are well aligned with the spiral structure of the hosts strongly favors an interstellar nature for the dust producing the polarization.

The peculiarities of the extinction law along the line-of-sight to SN 2014J are discussed by Amannullah et al. (2014). They conclude that these peculiarities are compatible with a power-law extinction with an index close to -2 , as expected from multiple scattering of light (Patat et al. 2006b; Goobar 2008). This conclusion is hard to reconcile with the above considerations, as it would require that most of the dust responsible for the observed extinction is confined to distances $\leq 10^{16}$ cm from the SN. In addition, the large optical depth implied by the measured extinction ($\tau_{dust} \approx 2$) would imply a considerable contribution by multiple scattering. In these circumstances, the linear polarization is expected to show a steady increase from $0.3 \mu\text{m}$ to $1.0 \mu\text{m}$ (see for instance White 1979; Voshchinnikov & Karjukin 1994; Kartje 1995; Zubko & Laor 2000), a behavior that is observed in reflection nebulae (Zellner 1974). This is incompatible with the wavelength dependencies discussed in this paper, which are compatible (at least qualitatively) with dichroic polarization by mixtures with an enhanced amount of small particles with respect to the typical MW distribution. In this respect we note that, to explain the extinction curve of NGC 3034 (M82), Hutton et al. (2014) suggest that the small grains are entrained in the supernovae-driven wind region, and that they would reflect the general properties of the galaxy ISM.

Based on multi-wavelength data including UV spectra, Foley et al. (2014) reached the conclusion that the peculiarities observed in the extinction curve of SN 2014J can be explained by a hybrid model. In this scenario, the reddening (which is found to vary with time) is produced by both circumstellar and interstellar dust, contributing in roughly similar fractions. While the interstellar component has rather normal

characteristics ($R_V \sim 2.6$), the circumstellar dust has LMC-like properties and is described by a power-law extinction with an index very close to -2 , as proposed by Amanullah et al. (2014).

While the case in which all the dust is circumstellar is very difficult to reconcile with the findings reported here and the large number of clouds along the line-of-sight (see above), the scenario proposed by Foley et al. (2014) may still be consistent with the continuum polarization properties. The lack of time variability in the polarization level and the orientation of the electric field indicate that, if there is a substantial amount of circumstellar dust, this has to be distributed in a spherically symmetric way, so that the net scattering-induced polarization is nulled. However, this is not sufficient, as local dust along the line-of-sight would still contribute via dichroism to the global polarization. There are two possibilities to produce a consistent picture: i) the local dust is special in terms of chemical composition and does not produce significant polarization by transmission; ii) the local dust grains do induce dichroic polarization, but they are aligned with the galactic magnetic field. Either way, the dust responsible for the observed polarization has to have very non-standard properties, no matter whether or not a substantial fraction of this is located in the circumstellar environment.

Therefore, although the presence of some dust in the vicinity of the SN cannot be excluded based on the data presented here, we conclude the anomalous behavior shown by the polarization reflects the intrinsic dust properties (i.e. size distribution and chemical composition) and not its geometrical distribution. The question as to why the galactic environments of these SN are systematically different from what is seen in similarly reddened stars in the Galaxy remains unanswered. Here we only emphasize that the MW dust properties are deduced from observations of the solar neighborhood. No line-of-sight through any external galaxy will geometrically ever be similar to any line-of-sight from the Earth through the MW.

One important aspect that will need to be considered in future studies of this kind, is that dust composition and size distribution are not fixed in time (Hutton et al. 2014). While large grains produced by stars initially dominate the size distribution, later on in the galaxy history this is controlled by ISM processes (Asano et al. 2013a, 2013b, 2014). As a consequence, the extinction curve is flatter in the earliest stages of galaxy evolution. The shape of the extinction curve may be related to the phenomena that lead to dust formation (SN II, AGB stars) and dust destruction (SN shocks, metal accretion onto dust grains, etc.). Asano et al. (2013b) find that the dust mass growth in the ISM becomes effective when the metallicity in a galaxy exceeds a critical value. This threshold is larger for a shorter star-formation time-scale. Therefore, it is possible that the anomalous behavior reported in this paper is telling us something about the chemical evolutionary state of the galaxy, or areas of the galaxy, in which the explosions occur.

Future studies will have to proceed on two different fronts: a) increase the sample of well studied Type Ia SN, in order to investigate in a statistically robust way possible correlations between dust properties, galaxy types and SN characteristics; b) obtain high quality spectropolarimetry of low R_V Galactic

objects to establish possible connections to what is seen in extragalactic environments.

5. Conclusions

The results presented in this paper can be summarized as follows:

1. All four Type Ia SN included in the sample display an anomalous interstellar polarization law.
2. While SN 1986G shows a behavior that is compatible with the most extreme cases known in the Galaxy, SN 2006X, 2008fp and 2014J display an unprecedented wavelength dependence, with $\lambda_{max} < 0.4 \mu\text{m}$.
3. The total-to-selective absorption ratio R_V derived from spectrophotometry is exceptionally low for all four events.
4. In SN 2006X and 2008fp, the bulk of the polarization most likely arises within thick molecular clouds. The anomalous polarimetric behavior may be associated with the peculiar properties of these clouds.
5. In SN 1986G and 2014J, the polarization is more probably generated within multiple components of similar optical depth along the line-of-sight. For these events, it is hard to argue in favor of peculiar properties of a single cloud. More plausibly, the observations reflect global characteristics of the hosts.
6. The very small size of the sample does not allow to establish a relation between the anomalous polarimetric properties and the morphological type of the hosts.
7. Although the objects in the sample are significantly reddened ($0.6 \leq E_{B-V} \leq 1.4$), this does not explain the observed behavior in terms of systematic effects related to high dust optical-depth lines-of-sight.
8. The dust responsible for the anomalous polarization properties is most probably of interstellar nature.
9. Although the presence of circumstellar dust cannot be excluded, the lack of time evolution and the alignment with the local spiral arm pattern pose rather stringent constraints on its composition and/or geometrical distribution.
10. The observed polarization properties can be understood in terms of an enhanced abundance of small grains with respect to the typical MW dust mixture.
11. The reasons why all SN in the sample show a behavior so different from what is seen in the Galaxy are unclear. The chemical/physical evolution of the hosts may be playing a relevant role.

Acknowledgements. This paper is dedicated to the memory of Prof. Guido Barbaro, who first introduced F. P. to the physics of the interstellar medium.

The German-Spanish Astronomical Center, Calar Alto (Spain) is jointly operated by the Max-Planck-Institut für Astronomie Heidelberg and the Instituto de Astrofísica de Andalucía (CSIC). The Mercator Telescope is operated on the island of La Palma by the Flemish Community, at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The HERMES spectrograph is supported by the Fund for Scientific Research of Flanders (FWO), Belgium, the Research Council of KU Leuven, Belgium, the Fonds National de la Recherche

Scientifique (F.R.S.-FNRS), Belgium, the Royal Observatory of Belgium, the Observatoire de Genève, Switzerland and the Thüringer Landessternwarte Tautenburg, Germany. The authors are grateful to the Calar Alto Observatory and its staff for carrying out the observations in a very efficient way.

S. T. acknowledges support by the Trans-regional Collaborative Research Centre TRR33 of the German Research Foundation (DFG). The research of J. C. W. is supported in part by NSF Grant AST-1109801.

References

- Amanullah, R., et al., 2014, ApJ, 788, 21
 Anderson, C. M., et al., 1996, AJ, 112, 2276
 Andersson, B.-G. & Potter, S. B., 2007, ApJ, 665, 369
 Appenzeller, I., et al., 1998, The Messenger, 94, 1
 Asano, R. S., Takeuchi, T. T., Hirashita, H. & Nozawa, T., 2013a, MNRAS, 432, 637
 Asano, R. S., Takeuchi, T. T., Hirashita, H. & Inoue, A. K., 2013b, EP&S, 65, 213
 Asano, R. S., Takeuchi, T. T., Hirashita, H. & Nozawa, T., 2014, MNRAS, in press, (arXiv:1401.7121)
 Coyne, G. V. & Gehrels, T., 1966, AJ, 71, 355
 Chotard, N., et al., 2011, A&A, 529, L4
 Clayton, G. C. & Mathis, J. S., 1988, ApJ, 327, 911
 Cox, N. L. J. & Patat, F., 2008, A&A, 485, 9
 Cox, N. L. J. & Patat, F., 2014a, A&A, 565, 61
 Cox, N. L. J., Davis, N., Patat, F., & Van Winckel, H., 2014b, ATEL 5797
 Dolan, J. F. & Tapia, S., 1986, PASP, 98, 792
 D’Odorico, S., di Serego Alighieri, S., Pettini, M., Magain, P., Nissen, P. E. & Panagia, N., 1989, A&A, 215, 21
 Finkelman, I., et al., 2014, MNRAS, in press (arXiv:1008.5149)
 Fitzpatrick, E. L. & Massa, D., 2007, ApJ, 663, 320
 Goobar, A., 2008, ApJL, 686, L103
 Goobar, A., et al., 2014, ApJL, 784, 12
 Foley, R. J., et al., 2014, ApJ, submitted, (arXiv:1405.3677)
 Greaves, J. S., Holland, W. S., Jennes, T. & Hawarden, T. G., 2000, Nature, 404, 732
 Hough, J. H., Mailey, J. A., Rouse, M. F. & Whittet, D. C. B., 1987, MNRAS, 227, 1P
 Hutton, S., et al., 2014, MNRAS, 440, 150
 Jones, T. J., 2000, AJ, 120, 2920
 Kartje, J. F., 1995, ApJ, 452, 565
 Larson, K. A., Whittet, D. C. B. & Hough, J. H., 1996 ApJ, 472, 755
 Leonard, D. C. & Filippenko, A. V., 2001, PASP, 113, 920
 Leonard, D. C., Filippenko, A. V., Chornock, R. & Li, W., 2002, ApJ, 124, 2506
 Leonard, D. C., Li, W., Filippenko, A. V., Foley, R. J., Chornock, R., 2005, ApJ, 632, 450L
 Mathewson, D. S., & Ford, V. L. 1970, MNRAS, 74, 139
 Maund, J. R., Wheeler, J. C., Patat, F., et al., 2007a, MNRAS, 381, 201
 Maund, J. R., Wheeler, J. C., Wang, L., et al., 2010a, ApJ, 722, 1162
 Maund, J. R., et al., 2013, MNRAS, 433, 20
 Martin, P. G. et al., 1992, ApJ, 392, 691
 Martin, P. G., Clayton, G. C. & Wolff, M. J., 1999, ApJ, 510, 905
 Mazzei, P. & Barbaro, G., 2011, A&A, 527, 34
 Meisenheimer, K., 1998, User Guide to the CAFOS 2.2
 Nobili, S. & Goobar, A., 2008, A&A, 487, 19
 Patat, F. 2005, MNRAS, 357, 1161
 Patat, F. & Romaniello, M., 2006a, PASP, 118, 146
 Patat, F., Benetti, S., Cappellaro, E. & Turatto, M., 2006b, MNRAS, 369, 1949
 Patat, F., Baade, D., Höflich, P., et al., 2009a, A&A, 508, 229
 Patat, F., Maund, J. R., Benetti, S., et al., 2010, A&A, 510, 108
 Patat, F. & Taubenberger, S., 2011, A&A, 529, A57, **PT11**
 Patat, F., Höflich, P., Baade, D., Maund, J. R., Wang, L. & Wheeler, J. C., 2012, A&A, 545, 7
 Patat, F., et al., 2014, ATEL, 5830
 Phillips, M. M., et al., 2013, ApJ, 779, 38
 Scarrot, S.M., Ward-Thompson, D. & Warren-Smith, R.F., 1987, MNRAS, 224, 299
 Serkowski, K., 1974, in *Planets, Stars, and Nebulae: Studied with Photopolarimetry*, IAU Colloq. 23, T. Gehrels Ed., University of Arizona Press, 135
 Serkowski, K., Matheson, D. S. & Ford, V.L., 1975, ApJ, 196, 261
 Siebenmorgen, R., Voshchinnikov, N. V. & Bagnulo, S., 2014, A&A, 561, A82
 Smith, P. S., et al., 2011, ApJ submitted (arXiv:1111.6626)
 Sternberg, A., et al., 2014, in preparation
 Valencic, L. A., Clayton, G. C. & Gordon, K. D., 2004 ApJ, 616, 912
 Veron, M.-P. & P. Veron, A&A, 455, 773
 Voshchinnikov, N. V. & Karjukin, V. V., 1994, A&A, 288, 883
 Voshchinnikov, N. V., 2012, JQSRT, 113, 2334
 Voshchinnikov, N. V., Das, H. K., Yakovlev, I. S. & Il’in, V. B., 2013, Astronomy Letters, 39, 421
 Wang, L., et al., 2003, ApJ, 591, 1110
 Wang, L., 2005, ApJL, 635, L33
 Welty, D. E., Ritchey, A. M., Dahlstrom, J. A. & York, D. G., 2014, ApJ, submitted (arXiv:1404.2639v1)
 Wilking, B. A., Lebofsky, M. J. & Rieke, G. H., 1982, AJ, 87, 695
 Wang, L. & Wheeler, J. C. 2008, Ann. Rev. Astr. Ap., 46, 433
 Weitenbeck, A. J., 2008, Acta Astronomica, 58, 433
 White, R. L., 1979, ApJ, 230, 116
 Whittet, D. C. B. & van Breda, I. G., 1978, A&A, 66, 57
 Whittet, D. C. B., Martin, P. G., Hough, J. H., et al., 1992, ApJ, 386, 562
 Whittet, D. C. B., Gerakines, P. A., Hough, J. H. & Shenoy, S. S., 2001, ApJ, 547, 872
 Whittet, D. C. B., 2003, *Dust in the Galactic Environments*, 2nd ed. Bristol: Institute of Physics Publishing
 Zelaya, P., et al., 2013, AJ, 145, 27
 Zelaya, P., et al., 2014, in preparation
 Zellner, B., 1974, in *Planets, Stars, and Nebulae: Studied with Photopolarimetry*, IAU Colloq. 23, T. Gehrels Ed., University of Arizona Press, 867
 Zubko, V. G. & Laor, A., 2000, ApJ, 128, 245