OPTICAL AND NEAR-INFRARED POLARIMETRY OF HIGHLY REDDENED Type Ia SUPERNOVA 2014J: PECULIAR PROPERTIES OF DUST IN M82

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ABSTRACT

We present optical and near-infrared multi-band linear polarimetry of the highly reddened Type Ia supernova (SN) 2014J that appeared in M82. SN 2014J exhibits large polarization at shorter wavelengths, e.g., 4.8% in the B band, which decreases rapidly at longer wavelengths, while the position angle of the polarization remains at approximately 40° over the observed wavelength range. These polarimetric properties suggest that the observed polarization is likely predominantly caused by the interstellar dust within M82. Further analysis shows that the polarization peaks at wavelengths much shorter than those obtained for the Galactic dust. The wavelength dependence of the polarization can be better described by an inverse power law rather than by the Serkowski law for Galactic interstellar polarization. These points suggest that the nature of the dust in M82 may be different from that in our Galaxy, with polarizing dust grains having a mean radius of <0.1 μm.

Key words: circumstellar matter – dust, extinction – galaxies: individual (Messier 82) – polarization – supernovae: individual (SN 2014J)

Online-only material: color figures

1. INTRODUCTION

The homogeneity in the photometric properties of normal Type Ia supernovae (SNe Ia) is expected to be related to common physical properties during the onset of thermoequilibrium explosions in the progenitor red white dwarfs with a mass close to the Chandrasekhar limiting mass (see Hillebrandt & Niemeyer 2000 for review). The continuum light from normal SNe Ia is intrinsically weakly polarized (p ≤ 0.3%), although the absorption features, including Si II 6355 and Ca II IR triplets, are often polarized by 0.5%–1.5% (Wang et al. 1996, 1997, 2003, 2006; Wang & Wheeler 2008; Leonard et al. 2005; Chornock & Filippenko 2008; Zelaya et al. 2013; Maund et al. 2013). In fact, an Si II 6355 absorption line with a polarization of p = 1.5% and an equivalent width of 0.011 μm (for SN 2014J near the maximum) gives an additional polarization of only Δp = 0.13% for typical R_c-band polarimetry (Δp = 0.13 μm). Practically, this allows us to use SNe Ia as unique bright unpolarized-light sources within distant galaxies for broadband polarimetry. Thus, an SN Ia has the potential to project the interstellar polarization (ISP) along the line of sight inside the host galaxy when it is subject to a substantial amount of interstellar reddening, as is commonly seen in our Galaxy (e.g., Whittet 2003).

SN 2014J is the closest SN Ia in this quarter century. It was discovered in M82 (at a distance ∼3.9 ± 0.4 Mpc; Sakai & Madore 1999) on 2014 January 21.81 (UT dates are used throughout this Letter) at a magnitude of R = 10.99 ± 0.03 mag (Fossati et al. 2014; Goobar et al. 2014), probably a week after the explosion (Zheng et al. 2014). The apparent brightness exceeds the B-band polarimetry (Fosseye et al. 2014; Goobar et al. 2014), probably a week after the explosion (Zheng et al. 2014). The apparent brightness provides us with an opportunity for various studies, including constraining the early light curve (LC) model (Goobar et al. 2014; Zheng et al. 2014), studying progenitor systems (Kelly et al. 2014; Margutti et al. 2014; Pérez-Torres et al. 2014), and evaluating properties of extragalactic interstellar/circumstellar (CS) media (Amanullah et al. 2014; Foley et al. 2014; Marion et al. 2014; Welty et al. 2014). In addition, this SN provides us with a rare opportunity to probe the ISP within the starburst galaxy M82 because it suffers significant reddening from the host galaxy (E_B−V ∼ 1.3 mag). Prior to SN 2014J, there were only three reddened SNe Ia (E_B−V ≥ 0.5 mag) for which the wavelength dependence of optical polarization had been measured, which are SN 1986G in the peculiar giant S0 galaxy NGC 5128 (Cen A; Hough et al. 1987; E_B−V ∼ 1.6 mag and d ≈ 4 Mpc), SN 2006X in the Virgo Cluster spiral

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galaxy NGC 4321 (Papat et al. 2009; $E_{B-V}^{\text{host}} = 1.5$–1.7 mag and $d \simeq 16$ Mpc), and SN 2008fp in the peculiar spiral galaxy ESO 428-G14 (Cox & Patat 2014; $E_{B-V}^{\text{host}} = 0.6 \pm 0.1$ mag and $d \simeq 26$ Mpc).

The Galactic ISP in ultraviolet (UV) to near-infrared (NIR) wavebands can be approximated by the Serkowski law (Serkowski et al. 1975), a smooth function of wavelength given by

$$p(\lambda) = p_{\text{max}} \exp \left[ -K \lambda^{\lambda_{\text{max}}} \right],$$

where $p_{\text{max}}$ is the peak polarization degree occurring at the wavelength $\lambda_{\text{max}}$ and $K$ is a parameter describing the width of the peak. The polarization observed for SNe 1986G and 2006X can be described by the Serkowski law at optical wavelengths; however, the derived parameters are peculiar, i.e., the wavelengths $\lambda_{\text{max}} = 0.43 \pm 0.01 \mu$m (SN 1986G) and $\lambda_{\text{max}} = 0.35 \pm 0.01 \mu$m (SN 2006X) are significantly shorter than the Galactic value (0.54 ± 0.06 μm; Vrba et al. 1981), and $K = 1.3 \pm 0.1$ (SN 2006X) is not consistent with the value expected from the Wilking law, i.e., $K = (1.66 \pm 0.09) p_{\text{max}}(\mu$m) + (0.01 ± 0.05), for the Galactic ISP (Wilking et al. 1980; Whittet et al. 1992). SN 2008fp exhibits ISP similar to the downscaled polarization of SN 2006X (Cox & Patat 2014). For the Galactic ISP, this $\lambda_{\text{max}}$–$K$ correlation may be interpreted as a narrowing of the size distribution with grain growth (e.g., Whittet 2003). The shorter $\lambda_{\text{max}}$ with these SNe suggests that the size of the dust granules polarizing light in the host galaxies is, on average, smaller than those in the Milky Way. This is also consistent with the smaller values of the total-to-selective extinction ratio, i.e., $R_V = A_V/E_{B-V} \simeq 1.3$–2.6, obtained for some reddened SNe Ia (Phillips et al. 2013, and references therein). If the empirical relation of the Galactic ISP, $R_V = (5.6 \pm 0.3) \lambda_{\text{max}}(\mu$m) (Serkowski et al. 1975; Whittet 2003), still holds for small $\lambda_{\text{max}}$, then the observed values of $R_V \simeq 1.3$–2.6 correspond to $\lambda_{\text{max}} \simeq 0.23$–0.46 μm, which is comparable to $\lambda_{\text{max}}$ observed in SNe 1986G and 2006X.

In this Letter, we report our $BVRC_{\text{IC}}JHK_s$ polarization of SN 2014J before and after the maximum light, along with our photometric and spectroscopic observations. Such multi-band polarimetry including NIR bands for reddened SNe Ia is still quite rare, and therefore this SN may provide us with valuable information concerning the interstellar and/or CS media along the line of sight toward SN 2014J (e.g., Hutton et al. 2014) within M82.

2. OBSERVATIONS AND REDUCTION

We performed imaging polarimetry of SN 2014J using Hiroshima One-shot Wide-field Polarimeter (HOWPol; Kawabata et al. 2008) on 2014 January 22.4 ($t = -11.0$ days relative to the B-band maximum light; see Section 3.1) in the $VR_{\text{IC}}$ bands and Hiroshima Optical and Near IR camera (HONIR; Akitaya et al. 2014) in the $BVRC_{\text{IC}}JHK_s$ bands on January 27.7 ($-5.7$ days), February 16.5 ($+14.1$ days), 25.6 ($+23.2$ days), and March 7.8 ($+33.4$ days). HOWPol employs a wedged double Wollaston prism and is attached to the Nasmyth focus of the 1.5 m Kanata telescope at Higashi-Hiroshima Observatory. HONIR uses a cooled LiYF$_4$ Wollaston prism and is attached to the Cassegrain focus of the same telescope. Each observation consisted of a sequence of exposures at four position angles (P.A.s) of the achromatic half-wave plates, 0°, 22.5°, 45°, and 67.5° for the HOWPol and the last HONIR observations, and at four P.A.s of the instrumental rotator at the Cassegrain focus of the telescope, 0°, 90°, 45°, and 135°, for the first three HONIR observations. These data were calibrated using observations of unpolaredized (HD 94851, HD 98281) and polarized standard stars (HD 30168, HD 150193, HDE 283701, Cyg OB 2 #11; Turnshek et al. 1990; Whittet et al. 1992), including measurements through a fully polarizing filter or a wire grid. Using this procedure, the instrumental polarization ($p \lesssim 0.2$% in HINIR and $p \simeq 3$–4% in HOWPol) was vectorially removed.

In addition, we obtained photometry using HOWPol ($BVRC_{\text{IC}}$) and HONIR ($BVRC_{\text{IC}}JHK_s$) attached to the 1.5 m Kanata telescope, with MITSuME (Kotani et al. 2005) ($g' R_{\text{IC}}$) attached to the 0.5 m telescope at Okayama Astrophysical Observatory (OAO) of the National Astronomical Observatory of Japan, with a Peltier-cooled CCD ($BVRC_{\text{IC}}$) attached to the 0.51 m telescope at Osaka Kyoiku University, and with ISLE (Yanagisawa et al. 2008) ($JHK_s$) attached to the 1.88 m telescope at OAO, respectively. The magnitude in each band was determined relative to the nearby comparison star, BD+70 587, which was flux-calibrated in the $BVRC_{\text{IC}}$ bands using Landolt field stars (Landolt 1992) on a photometric night. For NIR photometry, we used $JHK_s$ magnitudes of the same star in the Two Micron All Sky Survey Second Incremental Release Point Source Catalog. We also collected low-resolution spectra with HOWPol (0.41–0.94 μm, $R = \lambda/\Delta\lambda \simeq 400$) and HONIR (0.5–2.3 μm, $R \simeq 450$–600) on the 1.5 m Kanata telescope. The flux was calibrated using observations of spectrophotometric standard stars obtained on the same nights.

Because SN 2014J is superimposed within the bright region of M82 and we cannot perform template subtraction in image reduction, the observed flux should be more or less contaminated by the inhomogeneity and irregularity of the surface brightness of M82. However, the SN itself is sufficiently bright, and the polarizations obtained during the period from $t = -11$ days to $t = +33$ days from the maximum light should suffer only minor effects from the galaxy light.

3. RESULTS

3.1. Photometric and Spectroscopic Properties

Figure 1 shows the obtained multi-band LCs. The apparent maximum magnitudes in the $BV$ bands are found to be $B_{\text{max}} = 11.99 \pm 0.05$ mag on MJD 56690.4 ± 0.5 (February 2.4 ± 0.5) and $V_{\text{max}} = 10.44 \pm 0.03$ mag on MJD 56691.7 ± 0.5, respectively, as derived by a polynomial fit to the observed data around the maximum light. We also derived the observed $B$-band magnitude decline rate $\Delta m_{15}(B) = 1.02 \pm 0.05$ mag. For extinction toward SN 2014J, Amanullah et al. (2014) estimated the total reddening of $E_{B-V}^{\text{total}} = 1.37 \pm 0.03$ mag and $E_{R-V}^{\text{total}} = 1.4 \pm 0.1$ based on their analysis of the near-maximum–light spectral energy distribution from the UV to NIR wavebands. This reddening is apparently dominated by the host galaxy component $E_{B-V}^{\text{host}}$, because the IR Dustmap suggests that the Galactic component is only $E_{B-V}^{\text{host}} = 0.14$ mag (Schlafly & Finkbeiner 2011). We corrected for extinction using the $E_{B-V}^{\text{host}}$ and $R_{\nu}^{\text{host}}$ total values and the parameterized extinction curve (Cardelli et al. 1989). The absolute magnitudes of $M_{B,\text{max}} = -19.26 \pm 0.26$ mag and $M_{V,\text{max}} = -19.42 \pm 0.25$ mag, as well as its color, are consistent with the empirical relations with $\Delta m_{15}$ (within errors (e.g., Phillips et al. 1999), suggesting that the photometric behavior in SN 2014J is not anomalous. We set the time of the $B$-band maximum to be $t = 0$ days,
which is 18.7 ± 0.5 days after the epoch of the estimated first light (Zheng et al. 2014; Goobar et al. 2014).

Figure 2 shows a time series of spectra from \( t = -11 \) days to \( t = +48 \) days. Compared with the normal SN Ia 2011fe, SN 2014J is characterized by the absence of spectral features due to C\textsuperscript{ii} 6580 and O\textsuperscript{i} 7774, as well as the existence of high-velocity components in the Ca\textsuperscript{ii} IR triplet (\( \sim 20,000 \) km s\(^{-1}\)) during the earliest phase, \( t \lesssim -5 \) days, as pointed out by Goobar et al. (2014). The line velocity and equivalent width of Si\textsuperscript{ii} 6355 around maximum (\( -2 < t < 2 \) days) are \(-11,750 \pm 300\) km s\(^{-1}\) (Figure 2 inset panel) and \( 110 \pm 5\) Å, respectively, which are marginal between those of “normal” and “HV” (high-velocity) SNe (Wang et al. 2009). However, the relation between the \( \Delta m_{15} \)-corrected \( M_{V,\text{max}} \) and \( E_{B-V} \) obtained in SN 2014J (\( \sim -17.9\) mag for \( M_{V,\text{max}} \) and \( \sim 1.23\) mag for \( E_{B-V} \)) is apparently consistent with the branch of the HV group (\( R_{V} \sim 1.6\); Wang et al. 2009). The nearly constant absorption strength (up to \( \sim 3 \) months after discovery) of the interstellar Na\textsuperscript{i} D lines and diffuse interstellar bands (e.g., Welty et al. 2014) indicates that the dust responsible for the extinction toward SN 2014J is located at a site moderately separated from the progenitor (\( \gtrsim 2 \times 10^{16}\) cm).

### 3.2. Polarimetric Properties

The observed polarization is shown in Figure 3. The polarization is relatively strong in the blue bands, e.g., reaching \( \sim 4.8\% \) in the \( B \) band, and decreases rapidly with wavelength; meanwhile, the polarization of P.A. is approximately constant at around 40\(^\circ\). In the NIR bands, the polarization is less significant (\( p \lesssim 1\% \)); however, it is likely that the same polarization component still dominates because it has almost the same P.A. as the optical bands. There is no significant temporal variation in the polarization measured during the period from \( t = -11 \) days to \( t = +33 \) days from the maximum light, and the polarization in optical bands appears to be consistent with the result of spectropolarimetry covering wavelengths from 380 to 880 nm (Patat et al. 2014). Hereafter, we discuss only the averaged polarization (Table 1).

In the \( VRI \) bands, the data are weighted means over five nights from \( t = -11 \) days through \( t = +33 \) days, and in other bands they are over four nights from \( t = -6 \) days through +33 days. The error is predominantly due to either the observational error (\( \sigma \)) in the \( R_{C}-I_{C} \)HK bands or the uncertainty of the polarimetric calibration (instrumental polarization/depolarization) in the \( BV \) bands.

The large polarization measured for SN 2014J suggests that it is predominantly produced within M82 because the Galactic ISP is, at most, 0.18% according to the measurements of six Galactic stars in the vicinity of SN 2014J within \( 10^\circ \) of the all-sky polarization map (Heiles 2000). Furthermore, the nearly constant polarization during the period of our observation would exclude the possibility that it originated in close proximity to the progenitor. Together with the unchanged interstellar absorption
Figure 3. Result of our multi-band polarimetry. The upper panel shows the degree of polarization and the lower panel shows the position angle on the projected sky. The red squares denote the polarization of SN 2014J averaged over all five/four nights (Table 1), and the small symbols show the individual nightly data, as indicated. The curves in the panel show the empirical laws of the wavelength range of our observations, i.e., the Serkowski law, a short λ\text{max}, fitted to the averaged polarization data at optical wavelengths (λ < 1 μm). For comparison, we plot the observed/cataloged polarization (green circles/dots) of the strongly polarized standard star, HD 150193 (Whittet et al. 1992), as a typical p(λ) curve of Galactic ISP. It is clear that the strong wavelength dependence of SN 2014J is not readily explained by the Wilking law.

(A color version of this figure is available in the online journal.)

Figure 4. Polarization curve of SN 2014J as a function of the inverse wavelength plotted on logarithmic axes. The red squares and the black line are the same in Figure 3. The red dashed straight line shows a power-law fit to the polarization data reported in this Letter, except for B-band data. The wavelength dependence of the polarization at regions with λ > 0.5 μm can be better explained by \( \alpha \lambda^{-2.33\pm0.10} \), rather than the Serkowski law (black line).

(A color version of this figure is available in the online journal.)

lines, this favors that the significant polarization of SN 2014J is caused by dust grains at a site remote from the SN. It has been suggested that multiple scattering due to CS dust may account for half of the total extinction (Foley et al. 2014). However, we argue that the CS dust could not be the principal origin of the observed polarization because multiple scattering would effectively depolarize the light and the resulting continuum polarization would also show significant changes with time (see also Patat et al. 2014). In the optical image of M82 (e.g., Ohyama et al. 2002), the P.A. of \( \sim 40^\circ \) seems to align with the direction of the local dust lanes around the SN position, which further strengthens the argument that the polarization is unrelated to the CS matter.

Figure 3 shows that the polarization peak appears outside the wavelength range of our observations, i.e., \( \lambda_{\text{max}} \lesssim 0.4 \mu m \). This \( \lambda_{\text{max}} \) is considerably smaller than the typical value determined from the Galactic ISP. For comparison, we also plotted the polarization curves determined from the Serkowski law with/without the Wilking law in Figure 3. For the Serkowski law, we fitted it with a constant \( K = 1.15 \), typical for Galactic ISP (Serkowski et al. 1975), because the fitted parameters do not converge in the case of free \( K \). We cannot obtain any good fit with the Wilking law. In general, with the Wilking law, a short \( \lambda_{\text{max}} \) leads to small \( K \) (corresponding to broader peak in \( p(\lambda) \) curve); however, the observed steep gradient of \( p(\lambda) \) requires a large \( K \) value. The Wilking law also fails to describe the continuum polarization measured for SN 2006X (Patat et al. 2009). In addition, we find that \( K = 1.13 \pm 0.05 \) and \( \lambda_{\text{max}} = 0.43 \pm 0.01 \mu m \) derived for the SN 1986G data (Hough et al. 1987) do not satisfy the Wilking law. The fact that 5 out of 105 Galactic reddened stars show considerable ISP with \( \lambda_{\text{max}} < 0.4 \mu m \) and the Wilking law holds for 4 of the 5 stars within the errors (Whittet et al. 1992) suggests that the failure of the Wilking law to describe the data may be common for highly reddened SNe Ia, and the dust properties of the host galaxies may differ from those of the Milky Way.

Using only the Serkowski law, we note that there is a systematic difference in the polarization of \( \Delta p = 0.2\%–0.3\% \) between the observed polarization and the fitted curve at longer wavelengths (\( \gtrsim 1 \mu m \), Figure 3). This difference may be explained by considering an analog of the “IR polarization excess” found in the Galactic ISP at longer wavelengths (\( \gtrsim 2 \mu m \)), which is characterized by an inverse power law, i.e., \( p(\lambda) \) (e.g., Nagata 1990). The wavelength dependence of the polarization of SN 2014J at \( \gtrsim 0.5 \mu m \) can be well described by \( p(\lambda) \propto \lambda^{-\beta} \) with an index of \( \beta = 2.23 \pm 0.10 \) (Figure 4). It should be noted that the polarization closely follows a power-law dependence even at optical wavelengths for SN 2014J. For Galactic reddened stars, the index \( \beta \) is typically in a relatively narrow range of 1.5–2.0 and is uncorrelated with the wavelength dependence of optical polarization, e.g., \( \lambda_{\text{max}} \) (Martin et al. 1992; Whittet 2003). The index \( \beta \) obtained for the ISP in M82 appears to be slightly steeper than that for the Galactic ISP. This may be related to the failure of the Wilking law because the polarization peak observed in SN 2014J is clearly sharper than that expected for a Galactic ISP with a similar \( \lambda_{\text{max}} \) (see Figure 3).

4. DISCUSSION

As described above, SN 2014J is a highly reddened SN Ia, similar to SNe 1986G, 2006X, and 2008fp. The blue continuum of these SNe Ia all exhibit significant polarization, which is atypical of a Galactic ISP. To first-order approximation, a small
It is not known whether the empirical relation $R_V = (5.6 \pm 0.3) \lambda_{\text{max}}(\mu m)$ determined for the Galactic ISP (Serkowski et al. 1975; Whittet 2003) holds in the host galaxies of these highly reddened SNe Ia; however, interestingly, it has been shown by, e.g., $\lambda_{\text{max}} \sim 2\pi a_{\text{eff}}(n - 1)$, where $a_{\text{eff}}$ is the effective radius and $n$ is refractive index of the cylindrical grain (e.g., Whittet 2003). Assuming $\lambda_{\text{max}} \lesssim 0.4 \mu m$ and $n = 1.6$ (appropriate for silicates), then the $a_{\text{eff}}$ of the polarizing grains should be $\lesssim 0.11 \mu m$. Although a small $\lambda_{\text{max}}$ (and thus a small $a_{\text{eff}}$) could be the result of a failure of alignment/asphericity only for larger grains, the small $R_V$ inferred for SN 2014J suggests that the effect is not significant and the grain size should be intrinsically small.

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