INTERSTELLAR-MEDIUM MAPPING IN M82 THROUGH LIGHT ECHOES AROUND SUPERNOVA 2014J

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ABSTRACT

We present multiple-epoch measurements of the size and surface brightness of the light echoes from supernova (SN) 2014J in the nearby starburst galaxy M82. Hubble Space Telescope (HST) ACS/WFC images were taken ~277 and ~416 days after $B$-band maximum in the filters F475W, F606W, and F775W. Observations with HST WFC3/UVIS images at epochs ~216 and ~365 days are included for a more complete analysis. The images reveal the temporal evolution of at least two major light-echo components. The first one exhibits a filled ring structure with position-angle-dependent intensity. This radially extended, diffuse echo indicates the presence of an inhomogeneous interstellar dust cloud ranging from ~100 to ~500 pc in the foreground of the SN. The second echo component appears as an unresolved luminous quarter-circle arc centered on the SN. The wavelength dependence of scattering measured in different dust components suggests that the dust producing the luminous arc favors smaller grain sizes, while that causing the diffuse light echo may have sizes similar to those of the Milky Way dust. Smaller grains can produce an optical depth consistent with that along the supernova-Earth line of sight measured by previous studies around maximum light. Therefore, it is possible that the dust slab from which the luminous arc arises is also responsible for most of the extinction toward SN 2014J. The optical depths determined from the Milky Way-like dust in the scattering matters are lower than the optical depth produced by the dust slab.

Key words: circumstellar matter – dust, extinction – galaxies: individual (M82) – ISM: structure – polarization – supernovae: individual (SN 2014J)

Supporting material: extended figures

1. INTRODUCTION

Interstellar extinction caused by dust affects most astronomical observations. Light traversing a certain distribution of interstellar medium (ISM) produces an integrated effect on extinction. Extinction traces the dust grains, but also diminishes the starlight and limits our ability to interpret the local and distant universe. The study of interstellar dust provides insight into the properties of the extinction. Since dust is a strong coolant, it also plays a critical role in controlling galaxy evolution and star formation.

Observations of interstellar extinction require a beacon shining through interstellar material. In the Milky Way, a very large number of sightlines are available for this purpose, while in external galaxies there are few point source beacons bright enough to study the local ISM. Supernovae (SNe) are the best, and often only, choice. Light echoes provide additional information because they literally reflect light-scattering properties and do not reach the observer along exactly the same path. If SNe are nearby, even resolved light echoes may be observable.

The extinction (in magnitudes) at a certain wavelength or bandpass, $A_\lambda$, is often expressed as $A_\lambda = R_\lambda \times E(B-V)$. The “total-to-selective” extinction $R_\lambda = A_\lambda / E(B-V)$ depends on the properties of the dust along the line of sight and can be derived by comparing the observed $E(\lambda-V)$ with the extinction curves given by Cardelli et al. (1989). The observed wavelength dependence of interstellar extinction contains information on both the size and composition of the grains. The value of $R_V = 3.1$ (Cardelli et al. 1989) has often been considered the Galactic standard, but with a range from 2.2 to 5.8 (Fitzpatrick 1999) for different lines of sight. There is increasing evidence that extinction curves toward SNe Ia exhibit a steeper wavelength dependence ($R_V < 3$, see Cikota et al. 2016 for a summary on $R_V$ results of earlier studies). Patat et al. (2007) reported the detection of circumstellar material (CSM) in the local environment surrounding the SN Ia SN 2006X in the nearby galaxy M100. Wang (2005), Patat et al. (2006), and Goobar (2008) showed that the scattered light from CSM tends to reduce the value of $R_V$ in the optical. The effect on $R_V$ and the light-curve shape, however, also depends on the geometrical configuration and dust-grain properties (Amanullah & Goobar 2011; Brown et al. 2015). It is of critical importance to understand whether the low $R_V$ values are caused by (1) systematic differences from extragalactic environments, (2) inhomogeneities in the vicinity of the SN-Earth direct line of sight (DLOS), or (3) modifications by CSM scattering.

The most reliable approach in determining the extinction is the “pair method”—comparing spectrophotometry of two sources with the same spectral energy distribution, one of which has negligible foreground extinction. Extragalactic reddening can be
References. (1) Bond et al. (1990), (2) Cappellaro et al. (2001), (3) Crotts (1988), (4) Crotts (2015), (5) Drozdov et al. (2015), (6) Liu et al. (2003), (7) Maund & Smartt (2005), (8) Meikle et al. (2006), (9) Otsuka et al. (2012), (10) Quinn et al. (2006), (11) Schmidt et al. (1994), (12) Sparks et al. (1999), (13) Sugerman & Crotts (2002), (14) Sugerman (2005), (15) Sugerman & Lawrence (2016), (16) Sunteff et al. (1988), (17) Spyromilio et al. (1995), (18) Van Dyk et al. (2006), (19) Van Dyk (2013), (20) Van Dyk et al. (2015), (21) Wang et al. (2008), (22) Welch et al. (2007), (23) Xu et al. (1994).

Table 1

| SN      | Type          | Host Galaxy | Distance (Mpc) | References |
|---------|---------------|-------------|----------------|------------|
| 1987A   | II-Peculiar   | LMC         | 0.05           | 1, 3, 16, 17, 23 |
| 1991T   | Ia 91T-like   | NGC 4527    | 15.2           | 11, 12     |
| 1993I   | IIb           | M81         | 3.6            | 6, 13      |
| 1995E   | Ia            | NGC 2441    | 49.6           | 10         |
| 1998bu  | Ia            | M96         | 9.9            | 2          |
| 1999ev  | II-P          | NGC 4274    | 9.9            | 7          |
| 2002hh  | II-P          | NGC 6946    | 5.5            | 8, 22      |
| 2003gd  | II-P          | M74         | 9.5            | 14, 18     |
| 2004et  | II-P          | NGC 6946    | 5.5            | 9          |
| 2006X   | Ia            | M100        | 15.9           | 21         |
| 2007af  | Ia            | NGC 5584    | 22.5           | 5          |
| 2008bk  | II-P          | NGC 7793    | 3.7            | 19         |
| 2012aw  | II-P          | M95         | 10.0           | 20         |
| 2014J   | Ia            | M82         | 3.5            | 4          |
| 2016adj | IIb           | NGC 5128    | 3.7            | 15         |

References. (1) Bond et al. (1990), (2) Cappellaro et al. (2001), (3) Crotts (1988), (4) Crotts (2015), (5) Drozdov et al. (2015), (6) Liu et al. (2003), (7) Maund & Smartt (2005), (8) Meikle et al. (2006), (9) Otsuka et al. (2012), (10) Quinn et al. (2006), (11) Schmidt et al. (1994), (12) Sparks et al. (1999), (13) Sugerman & Crotts (2002), (14) Sugerman (2005), (15) Sugerman & Lawrence (2016), (16) Sunteff et al. (1988), (17) Spyromilio et al. (1995), (18) Van Dyk et al. (2006), (19) Van Dyk (2013), (20) Van Dyk et al. (2015), (21) Wang et al. (2008), (22) Welch et al. (2007), (23) Xu et al. (1994).

measured by comparing observed SNe Ia to a zero-reddening locus (e.g., Riess et al. 1996; Phillips et al. 1999). However, information acquired through this pair method is limited to single sightlines. Photons scattered by dust travel a slightly different path compared to the directly transmitted light. Therefore, scattered photons provide chances to test the scattering properties of the dust in a bidimensional space.

1.1. Light Echoes

Light echoes are the scattered light of a transient event that arises from dust clouds. Here we consider the case of an SNe Ia and CSM/ISM. Because of the high initial brightness of SNe, searches for late-time off-source flux excesses have been the main approaches to detect light echoes; close to the SNe, i.e., the slowly fading light-curves of SN 1991T (Schmidt et al. 1994; Sparks et al. 1999), SN 1998bu (Cappellaro et al. 2001), and SN 2006X (Wang et al. 2008). Outside the solar system, spatially resolved light echoes have been rare events. The first one reported arose around Nova Persei 1901 (Kapteyn 1901; Ritchey 1901), followed by Nova Sagittarii 1936 (Swope 1940). Echoes were also found from the Galactic Cepheid RS Puppis (Havlen 1972) and, with Hubble Space Telescope (HST) angular sampling, from the eruptive star V838 Monocerotis (Bond et al. 2003). Vogt et al. (2012) reported the detection of an infrared echo near the Galactic supernova remnant Cassiopeia A. Additionally, spectroscopic observations of nearby light echoes provide unique opportunities to probe the progenitor properties of historical transients (Rest et al. 2008; Davidson & Humphreys 2012) and in some cases the three-dimensional structure of the explosion, for instance, an ancient eruption from η Carinae (Rest et al. 2012), or asymmetry in the outburst of SN 1987A (Sinnott et al. 2013) and Cassiopeia A (Grefenstette et al. 2014). In recent years, the number of light echoes from extragalactic SNe has grown rapidly, mostly thanks to HST. Table 1 provides an overview of the events recorded to date, updated from Table 1 of Van Dyk et al. (2015).

Photons from spatially resolved light echoes travel a slightly different path than the DLOS from the SN to Earth. Therefore, observations of a resolved light echo around a nearby SN provide a unique opportunity to measure the extinction properties of the dust along the DLOS and the scattering properties of the echo-producing dust independently and simultaneously. As the SN fades, outer echoes (echoes with larger angular diameter) associated with ISM at large distances to the SN will become less contaminated by its bright light, and any inner echoes associated with ISM at small distances to the SN, and even the CSM, will become detectable. The expansion with time of the light echoes maps out the 3D structure of ISM along and close to the line of sight.

Detailed introductions to the relation between two-dimensional light echoes and three-dimensional scattering dust distributions has been given in various studies (Chevalier 1986; Sparks 1994; Sugerman 2003; Tyndela 2004; Patat 2005). Here, we briefly define the geometry used throughout this paper, also shown in Figure 1, which considers the SN event as an instantaneous flash of radiation. The locus of constant light travel time is an ellipsoid with the supernova at one focus, which we refer to as an iso-delay surface. The ellipsoid grows with time as the light propagates in space.

The angular radius of the light echo (α) can be easily measured in two-dimensional images. The SN is centered at the origin of the plane, the x and y give the coordinates of the scattering materials in the plane of the sky. The projected distance (ρ = √(x² + y²)) of scattering material to the SN perpendicular to the DLOS is related to the distance (D) to the SN as tan α = ρ/D, φ gives the position angle (PA). Because D is significantly larger than other geometric dimensions, the light echo can be very well approximated by a paraboloid, with the SN lying at its focus. ρ can be obtained by

\[ \rho = \sqrt{ct(2z + ct)}. \]  

Here t is the time since the radiation burst, z gives the foreground distance of the scattering material along the line of sight, and c denotes the speed of light. The distance r of the scattering material from the SN is

\[ r = \frac{1}{2} \left( \frac{\rho^2}{ct} + ct \right). \]  

The scattering angle can be obtained from cos θ(ρ, t) = z/(z + ct) or from tan θ = ρ/z.

1.2. Supernova 2014J in M82

The nearby SN Ia 2014J in M82 (3.53 ± 0.04 Mpc, Dalcanton et al. 2009) offers the rare opportunity to study the physical properties and spatial distribution of dust particles along and close to the DLOS and also in the vicinity of the SN. SN 2014J suffers from heavy extinction (A_V = 2.07 ± 0.18, Foley et al. 2014) and is located behind a large amount of interstellar dust (Amanullah et al. 2014). Additionally, the absorption profiles of Na and K lines from high-resolution spectroscopy exhibit more than ten extragalactic absorption components, indicating that the extinction along the DLOS is caused by the combined presence of a large number of distinct interstellar dust clouds along the DLOS (Patat et al. 2015). SN 2014J was discovered on January 21.805 UT by Fossey...
et al. (2014). Later observations constrained the first light of the SN to January 14.75 UT (Goobar et al. 2014; Zheng et al. 2014).

SN 2014J reached its B-band maximum on February 2.0 UT (JD 2,456,690.5) at a magnitude of 11.85 ± 0.02 (Foley et al. 2014). Continuous photometric and spectroscopic observations through late phases have been made by various groups (Johansson et al. 2014; Lundqvist et al. 2015; Bonanos & Boumis 2016; Porter et al. 2016; Sand et al. 2016; Srivastav et al. 2016).

There is clear evidence that the strong extinction measured from SN 2014J is caused primarily by interstellar dust (Brown et al. 2015; Patat et al. 2015), although a mix of interstellar and circumstellar dust is also possible (Foley et al. 2014; Bulla et al. 2016). Several independent studies, including photometric color fitting from Swift/UVOT and HST (Amanullah et al. 2014), near-UV/optical grism spectroscopy from Swift UVOT (Brown et al. 2015), HST STIS spectroscopy and WFC3 photometry (Foley et al. 2014), reddening curve fitting near the SN maximum using the silicate-graphite model (Gao et al. 2015), as well as optical spectroscopy from Goobar et al. (2014) found an $R_V \sim 1.4$ toward SN 2014J. Moreover, ground-based broadband imaging polarimetry (Kawabata et al. 2014; Srivastav et al. 2016) and spectropolarimetry (Patat et al. 2015; Porter et al. 2016) have shown that the polarization peak that is due to interstellar dust extinction is shortward of ~0.4 μm, which indicates that this line of sight has peculiar Serkowski parameters (see Patat et al. 2015). This polarization wavelength dependence can be interpreted in terms of a significantly enhanced abundance of small grains (Patat et al. 2015). Models considering both interstellar dust and circumstellar dust simultaneously and fitted to observed extinction and polarization (Hoang 2015) find that a significant enhancement (w.r.t. the Milky Way) in the total mass of small grains (<0.1 μm) is required to reproduce low values of $R_V$. Multiple time-invariant Na I D and Ca II H&K absorption features as well as several diffuse interstellar bands have also been identified (Graham et al. 2015; Jack et al. 2015). These are most likely associated with multiple dust components of interstellar material along the DLOS.

The nature (amount and distribution) of CSM is of interest when probing the possible diversity of progenitors of SNe Ia and for accurately correcting the extinction when using SNe Ia as standard candles. Johansson et al. (2014) found no evidence of heated dust in the CSM of SN 2014J with $r < 10^{17}$ cm (~39 light days). Graham et al. (2015) reported variable interstellar K I lines in high-resolution spectra, which may form about 10 light years (~10$^{19}$ cm) in front of the SN.

The extremely dusty environment in M82 and its relative proximity to Earth lead to the expectation of complex and evolving light echoes if SN 2014J exploded inside the galactic disk. In fact, Crotts (2015) discovered the first light echoes surrounding SN 2014J in HST images from 2014 September 5, 215.8 days past B-band maximum light (referred to as +216 d hereafter) on JD = 2456690.5 (Foley et al. 2014). The echo signal tends to be associated with pre-explosion nebular structures in M82 (Crotts 2015).

In the following, we present the evolution of multiple light echoes of SN 2014J as revealed by new HST ACS/WFC multiband and multi-epoch imaging around ~277 days and ~416 days past B-band maximum (referred to as +277 d and +416 d below). We also qualitatively discuss similar archival WFC3/UVIS images obtained on +216 d and +365 d.

2. OBSERVATIONS AND DATA REDUCTION

Late-time observations of the light echoes around SN 2014J discussed in this paper result from a HST Wide Field Camera 3 UVIS channel (HST WFC3/UVIS) program (#13626; PI: Crotts) to observe properties of the light echoes and progenitor environment around SN 2014J and an Advanced Camera for Surveys/Wide Field Channel (HST ACS/WFC) program (#13717; PI: Wang) to probe the dusty environment surrounding SN 2014J in M82. A log of observations is assembled in Table 2.

We use bright H II regions to align exposures in different filter combinations and epochs through Tweakreg in the Astrodrizzle package (Gonzaga et al. 2012). Observations obtained with three polarizers are needed to calculate the Stokes vectors, but the intensity maps (Stokes I) are the only input to this analysis.

$$I = \frac{2}{3} [r(\text{POL0}) + r(\text{POL60}) + r(\text{POL120})],$$

(3)

where $r(\text{POL0})$, etc. are the count rates in the images obtained through the three polarizers. Figure 2 shows the field around SN 2014J.

![Figure 1: Schematic diagram identifying the geometrical parameters used in this paper. The paraboloid represents the iso-delay light surface at some arbitrary epoch after the supernova explosion. The observer located along the z-axis and beyond the right edge of the diagram would see light echoes in the x-y plane (the y is perpendicular to the drawing). The SN is located at the origin, and θ denotes the scattering angle.](image-url)
We perform background subtraction to better reveal the faint and time-variant light-echo signals. For observations on +277 d and +416 d with \textit{HST} ACS/WFC and filters F475W, F606W, and F775W, we found no pre-SN \textit{Hubble} images of the region through filters consistent with our observations. The most recent \textit{HST} images of SN 2014J obtained on 2016 April 8, (+796 d) with the same photometric and polarimetric filter combinations were subtracted from the observations on +277 d and +416 d. For the observations on +216 d and +365 d with \textit{HST} WFC3/UVIS in passbands F438W, F555W, and F814W, pre-SN images obtained on 2006 March 29 (program \#10776; PI:Mountain) with \textit{HST} ACS/WFC in the F435W, F555W, and F814W were used as background templates, respectively. For each band, the background templates were scaled and subtracted from the intensity map.

The resulting images (Figure 3) clearly reveal the shape of the light echoes around SN 2014J. Negative signals (black in Figure 3) represent the light echoes on +796 d, while positive (white) signals trace the light echoes on +277 d and +416 d, respectively. In each subpanel of Figure 3, we show the light echoes with background removed (labeled “Image” at the bottom), the scaled and distortion-corrected point-spread function (PSF) (labeled “PSF” on the left), and the residual around the SN after PSF subtraction (labeled “Res” on the right). PSF appropriate to the SN position were generated for each bandpass and epoch with TinyTim (Krist 1993; Krist & Hook 2008). The upper row displays the observations at earlier epochs (+216 d for F438W and F555W, +277 d for F475W, F606W, and F775W), and the lower row depicts the observations at later epochs (+365 d for F438W and F555W, +416 d for F475W, F606W, and F775W). For better visibility, Figure 4 provides a zoom-in of the PSF-subtracted images (“Res”) in each panel of Figure 3.

3. ANALYSIS AND RESULTS

3.1. Total Flux of the SN

Photometry of SN 2014J at four epochs was performed in the background-subtracted images described above, and shown in Table 3. Measurements were made with a circular aperture of

| HST Camera | Filter | Polarizer | Date of 1st Obs. (UT-2014) | Exp. Time (s) | Epoch\(^a\) (Days) | Date of 2nd Obs. (UT-2015) | Exp. Time (s) | Epoch\(^a\) (Days) |
|------------|--------|-----------|-----------------------------|--------------|-----------------|-----------------------------|--------------|-----------------|
| WFC3/UVIS\(^b\) | F438W  | N/A       | 09-05 19:12:57              | 8 × 64       | 215.8           | 02-02 05:24:41             | 12 × 128     | 365.2           |
| F555W      | N/A    |           | 09-05 19:29:44              | 4 × 64       | 215.8           | 02-02 05:06:06             | 12 × 32      | 365.2           |
| F555W      | N/A    |           | 09-05 22:05:11              | 8 × 32       | 215.9           | N/A                        | N/A          | N/A             |
| F814W      | N/A    |           | 09-05 20:32:05              | 8 × 64       | 215.9           | N/A                        | N/A          | N/A             |

Notes.

\(^a\) Days after B maximum on 2014 February 2.0 (JD 2 456 690.5).

\(^b\) Observations result from \textit{HST} WFC3/UVIS, program (\#13626; PI: Crotts).

\(^c\) Observations result from \textit{HST} ACS/WFC, program (\#13717; PI: Wang).
Figure 3. Background-subtracted images of the SN ("Image"), the TinyTim PSF (Krist 1993; Krist & Hook 2008), and the residuals around the SN after PSF subtraction ("Res"). Background structures in F438W and F555W were removed by subtracting scaled pre-SN archival F435W and F555W HST images. Background in F475W, F606W, and F775W was corrected for by subtracting the respective most recent +796 d image; therefore, the +796 d echoes appear as negative structures. Note the different orientations.

Figure 4. A zoom-in view of the background-corrected light echoes shown in Figure 3. North is up and east is left. The distance between each little tickmark is 0.1. Each square measures 3.4 = 58 pc along its sides. The diffuse and radially extended light-echo profiles can be clearly identified in all panels except for F438W (+216 d) and F775W (all epochs). Note the uneven signal distribution with position angle in the rings and the consistency of the overall patterns at different epochs. A luminous arc is visible in the lower left quadrant and not resolved in the radial direction. This is at variance with the appearance of the complete, radially diffuse rings.

Table 3

|       | F438W<sub>SN</sub>          | F555W<sub>SN</sub>          | F814W<sub>SN</sub>          | F438W<sub>LE</sub>          | F555W<sub>LE</sub>          |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 215.8 | 17.610 ± 0.016              | 16.446 ± 0.011              | 15.301 ± 0.011              | 22.05 ± 0.36                | 21.12 ± 0.06                |
| 365.3 | 19.735 ± 0.011              | 18.715 ± 0.013              | N/A<sup>b</sup>             | 21.53 ± 0.13                | 20.87 ± 0.06                |
|       | F475W<sub>SN</sub>          | F606W<sub>SN</sub>          | F775W<sub>SN</sub>          | F475W<sub>LE</sub>          | F606W<sub>LE</sub>          |
| 276.5 | 17.467 ± 0.002              | 17.343 ± 0.002              | 16.354 ± 0.005              | 21.16 ± 0.03                | 20.73 ± 0.08                |
| 415.6<sup>c</sup> | 19.568 ± 0.002 | 19.516 ± 0.004 | 17.888 ± 0.008 | 21.37 ± 0.02 | 20.98 ± 0.05 |

Notes.
<sup>a</sup> Days after B maximum, 2014 February 2.0 (JD 245 6690.5).
<sup>b</sup> SN 2014J was not observed in F814W at +365 d.
<sup>c</sup> +417.9 d for F606W, +418.0 d for F775W.

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0′′.4 (8 pixels in the ACS/WFC FOV and 10 pixels in the WFC3/UVIS FOV) in the WFC3/UVIS F438W, F555W, F814W images from +216 d, and the F438W and F555W images from +365 d. We applied aperture corrections according to Hartig (2009) and Sirianni et al. (2005) to estimate the total flux from SN 2014J. The photometric uncertainties in Table 3 include the Poisson noise of the signal, the photon noise of the background, the readout noise contribution (3.75 electrons/pixel for ACS/WFC), and the uncertainties in aperture corrections. These quantities were added in quadrature. The magnitudes are presented in the Vega system with zero points from the CALSPEC archive. The total flux of the source within the aperture equals the product Total Counts × PHOTFLAM, where PHOTFLAM is the inverse sensitivity (in erg cm⁻² s⁻¹ Å⁻¹ and representing a signal of 1 electron per second). For WFC3/UVIS images, we adopted the values of the PHOTFLAM keyword in the image headers. However, for the ACS/WFC polarizer images, which were corrected for the throughputs of the polarizers to generate the intensity maps, we discarded the default PHOTFLAM values. Instead, we adopted the most up-to-date PHOTFLAM values in the ACS filter bands for images obtained without polarizers (Bohlin 2012). This is required by the mismatch between (i) the polarizer throughput curves used by SYNPHOT for unpolarized sources and (ii) the values found by comparing unpolarized sources in both the polarization and nonpolarizing filters (Cracraft & Sparks 2007). Therefore, the PHOTFLAM keywords in ACS/WFC polarized images are not applicable to intensity maps derived from polarized images. Polarization properties of SN 2014J will be discussed in a separate paper (Y. Yang et al., in preparation).

### 3.2. Residual Images

Two main echo components are evident. In Figure 4 we show a luminous quarter-circle arc and a diffuse ring at angular distance larger than 0′′.3 from the SN. Closer to the SN, uncertainties in the PSF correction prevent reliable detections. On +277 d, the most notable features of the light echoes in F475W are three luminous clumps at angular radius \( \alpha = 0.′′60 \) and PAs 80°, 120°, and 150°, measured from north (0°) through east (90°). These clumpy structures are already present on +216 d at the same PAs, but appear smoother and more extended. They eventually evolve into a fairly continuous luminous quarter-circle arc seen on both +365 d and +416 d extending from PA = 60°−170°. Images obtained on +216 d with F438W and F555W show the luminous arc at angular radii \( \alpha = 0.′′54 \) and \( \alpha = 0.′′69 \) over roughly the same range in PA, in agreement with Crotts (2015). However, for the arc we find a foreground distance of the scattering material that ranges from 226 to 235 pc in the four epochs (Table 4) and has a mean value of 228 ± 7 pc. This is different from the foreground distance of ~330 pc discussed for this prominent echo component by Crotts (2015). This discrepancy may be due to the difficulties and uncertainties in subtracting the PSF in earlier epoch when the SN is still bright, or in distinguishing the multiple light-echo components identified in our multi-epoch data.

To enable a more quantitative description of the light echoes and their evolution, we performed photometry on them in background-subtracted images (Figure 4). We measured the surface brightness of the light-echo profile at different radii and over different ranges in PA. Fan-shaped apertures centered on the SN were used to sample the intensity. The width in PA of each aperture is 45°. In contrast to the luminous arc, the diffuse echo can be seen over the full range in PA from 0° to 360°, but it does not exhibit a common radial profile (Figures 5 and 6).

In the following subsections, we use these measurements to investigate the evolving profile of the light echoes, conduct geometric and photometric analyses, and estimate the dust distribution and scattering properties responsible for the observed light echoes along and close to the DLOS. A function characterizing the properties of the scattering material is constructed to represent the brightness evolution of the observed light echoes on +277 d and +416 d.

### 3.3. Geometric Properties of the Light Echoes

A comprehensive discussion of the formation of light-echo arcs is available from Tylenda (2004). In the context of this paper, it is sufficient to recall that a circular light echo is created from the intersection of the dust slab with the iso-delay paraboloid. Any uneven distribution of material in the slab results in an uneven flux distribution along the circle, and the light echo may be composed of incomplete arcs. A dust slab always produces a (complete or incomplete) circular light echo, regardless of its inclination with respect to the line of sight. When a dust slab is not perpendicular to the line of sight, the center of the light-echo circle will not coincide with the SN position, and it moves with time.

The luminous arc echo is unresolved with a full width at half maximum of the radial profile approximately that of the SN measured in the same images, i.e., ~0′′.1 (2 pixels). Therefore, we consider that the luminous arc was formed by a thin dust slab intersecting the line of sight. We have fitted circles to the positions of the luminous arc at all available epochs. None of them are significantly decentered from the SN. This implies

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**Table 4**

| LE # | Epoch[a] | Angular Radius \( \alpha \) (°) | Offset (°) | Foreground Distance \( z \) (pc) | Projected Radius \( \rho \) (pc) | Scattering Angle \( \theta \) (°) |
|------|---------|-----------------|---------|--------------|-----------------|-----------------|
| Arc  | 215.8   | 0.539 ± 0.020   | 0.009 ± 0.014 | 234.6 ± 18.2 | 9.22 ± 0.36 | 2.25 ± 0.20 |
|     | 276.5   | 0.599 ± 0.014   | 0.006 ± 0.015 | 226.3 ± 11.8 | 10.25 ± 0.27 | 2.60 ± 0.15 |
|     | 365.3   | 0.689 ± 0.020   | 0.011 ± 0.014 | 226.4 ± 14.1 | 11.79 ± 0.37 | 2.98 ± 0.21 |
|     | 415.6   | 0.735 ± 0.012   | 0.012 ± 0.010 | 226.6 ± 9.0  | 12.58 ± 0.25 | 3.18 ± 0.14 |

[a] Days after \( B \) maximum on 2014 February 2.0 (JD 245 6690.5).
that the dust slab producing the arc echo is fairly perpendicular to the line of sight. Table 4 summarizes the geometric properties measured from the luminous arc.

In addition to the luminous arc, a radially extended and diffuse structure is identified, which on +277 d is present in F475W and F606W and spread over $\alpha = 0^\circ 40$ to $\alpha = 0^\circ 90$. This structure can also be noted on +365 d in F438W and F555W (from $\alpha = 0^\circ 47$ to $\alpha = 1^\circ 08$). It appears more clearly on +416/417 d in F475W and F606W (from $\alpha = 0^\circ 50$ to $\alpha = 1^\circ 03$) because for these observations longer exposure times were used. The epochs of observation and the exclusion of the inner 0.3 limit the explored foreground distances from $z = 100$ pc to $z = 500$ pc. On +216 d, the diffuse component cannot be identified in F438W, but is marginally seen in F555W. However, the inner and outer radii of the diffuse structure cannot be well determined because of uncertainties in the PSF subtraction. The diffuse light echo observed on +277 d can be produced by a dust cloud intersecting the iso-delay surface over a wide range in foreground distance. The line-of-sight extent of this diffuse dust cloud is indicated by the filled profile of the echoes. This shows that a continuous dust distribution over a certain range of foreground distances along the line of sight is required.

In each panel of the radial profiles in Figures 5 and 6, the radially resolved positive flux excesses (on +277 d and +416 d), and also the radially extended negative flux that is due to the subtraction of the light echo on +796 d, suggest the presence of an extended and inhomogeneous foreground dust distribution. Outside the $\sim 0^\circ 3$ region, as discussed earlier, the imperfect PSF subtraction makes the detection of echoes unreliable. The most prominent structure with an intensity peak at the second and third curve near the top in Figure 5 can be clearly seen on +277 d with an angular radius of $\sim 0^\circ 60$, which at the distance of M82 ($3.53 \pm 0.04$ Mpc, Dalcanton et al. 2009) is at a radius $\rho = 10.3$ pc from the SN in the plane of the sky. By +416 d, the radius has increased to $\sim 0^\circ 735$ or $\rho = 12.6$ pc from the SN. The scattering angles are 2°6 and 3°2, respectively.

### 3.4. Light-echo Mapping of the Foreground Dust Distribution

To our knowledge, and with the exception of SN 1987A in the Large Magellanic Cloud (Crotts 1988; Suntzeff et al. 1988), this is the first radially extended light echo detected from any SN. For epochs discussed in this paper, the diffuse echo component around SN 2014J reveals the SN-backlit ISM over $\sim 40$ pc $\times$ 40 pc around the DLOS. Standard methods for estimating the optical properties of the ISM toward the supernova only consider the extinction along the DLOS. They include the spectrophotometric comparison between the observed SN and an unreddened SN or template, and comparing the integrated echo flux with the surface brightness.
calculated from the scattering properties of various dust models. The resolved dust echoes of SN 2014J and their temporal evolution in the gas-rich and very nearby galaxy M82, however, provide an unprecedented opportunity to do better. In the following, we take advantage of this to measure the scattering properties of the ISM at different foreground distances and PAs relative to SN 2014J.

We assume that dust scattering follows the Henyey–Greenstein phase function (Henyey & Greenstein 1941):

$$\Phi(\theta) = \frac{1 - g^2}{(1 + g^2 - 2g \cos \theta)^{3/2}},$$

(4)

where $g = \cos \theta$ is a measure of the degree of forward scattering. With $L_{\lambda}(t)$ as the number of photons emitted per unit time by the SN at a given wavelength, $F_{\nu}(t) = L_{\lambda}(t)/4\pi D^2$ is the number of photons observed at time $t$. $D$ is the distance to the SN. For the modeling of our observations, $t$ is the time of the light-echo observation, $t_e$ denotes the time when photons emitted by the SN would be directly observed along the DLOS, and $F_{\nu}(t - t_e)$ is the brightness of the SN at $t - t_e$.

For a single short flash of light of duration $\Delta t_e$ emitted by the SN at $t_e$, $F_{\nu}(t - t_e) = 0$ for $t < t_e$ and $\int_{t_e}^{t} F_{\nu}(t - t_e) dt_e = F_{\nu}(t - t_e)|_{t_e} \Delta t_e$. Then, the surface brightness, $\Sigma$, of a scattered light-echo at frequency $\nu$ and arising from an infinitely short ($\delta$ function) light pulse is given by

$$\Sigma_{\nu}(\rho, \phi, t) = n_d Q_s \sigma_d \frac{F_{\nu}(t - t_e)|_{t_e} \Delta t_e}{4\pi r^2} \left| \frac{dz}{dt} \right| \Phi(\theta)$$

(5)

Here $n_d$ is the volume number density of the scattering material in units of cm$^{-3}$; $Q_s$ is a dimensionless number describing the scattering efficiency of the dust grains; $\sigma_d$ is the geometric cross section of a dust grain, $\Phi(\theta)$ is the unitless scattering phase function. This means that the surface brightness at a certain instance of the light echo at $t = t_e + (t - t_e)$ is determined by the flux emitted from the SN at $t_e$ together with the local geometric properties of the iso-delay surface at $t - t_e$.

In reality, the SN emission has a finite duration. $F_{\nu}(t - t_e)$ is no longer a $\delta$ function, and the surface brightness of the light echo unit at a certain frequency $\Sigma_{\nu}$ is the time integral of $F_{\nu}(t - t_e)$ from 0 to $t$:

$$\Sigma_{\nu}(\rho, \phi, t) = \frac{Q_s \sigma_d}{4\pi} \int_0^t n_d F_{\nu}(t - t_e) dt_e \left| \frac{dz}{dt} \right| \Phi(\theta).$$

(6)

By recalling that

$$z = \frac{\rho^2}{2ct} - \frac{ct}{2},$$

(7)

Figure 6. Same as Figure 5, but for the epoch of +416 d.
one can easily find

\[
\frac{dz}{dt} = -c \left( \frac{r^3}{c^2} + 1 \right), \quad r = z + ct = \frac{c^2}{2} \left( \frac{r^3}{c^2} + 1 \right).
\]

Therefore,

\[
\Sigma_d(\rho, \phi, t) = \frac{Q_0}{2\pi} \int_0^t \frac{n_d(\rho, \phi, t) \Phi(\theta) F_r(t - \tau) dt}{c^2t^2 + \rho^2}.
\]

Because of the relative proximity of M82, some light echoes around SN 2014J are resolved by HST at late phases, and each pixel represents the surface brightness of the light echo multiplied by the physical area covered by the pixel in the sky.

Therefore, in order to compare the model flux distribution with the flux in a two-dimensional image, one needs to integrate the model flux over the physical depth covered by the pixel. Since each pixel has size \( \Delta x \Delta y \), and \( \Delta x = \Delta y \), this implies

\[
\text{Im}_d(x, y, t) = \int_{x-\Delta x/2}^{x+\Delta x/2} \int_{y-\Delta y/2}^{y+\Delta y/2} \Sigma(x, y, t) dx dy.
\]

The geometric factor is determined by the radial distance to the SN, \( \rho = \sqrt{x^2 + y^2} \). Therefore, in the tangential direction inside each pixel, we approximate the integration by assuming that \( n_d(x, y, t) \) is invariant over the angle \( \Delta \phi \) subtended by a single pixel. Furthermore, the angular size of each ACS/WFC pixel is 0\(^{\circ}\)05. At the distance of \( D = 3.53 \pm 0.04 \) Mpc, the corresponding physical pixel size in the sky is

\[
\text{pixscale} = (3.53 \pm 0.04) \text{ Mpc} \times \tan(0^\circ05) = (0.86 \pm 0.01) \text{ pc} = \Delta x = \Delta y.
\]

We recall the geometric configuration of the iso-delay light surface at \(+277 \) d presented by Figure 1. In Figure 7 we modify this schematic diagram to demonstrate how we use a two-dimensional image to map the ISM in three dimensions. The gray-shaded fields on the vertical axis show the pixelation of the sky view by the camera, with each pixel measuring 0.86 pc on both sides. \( \Delta z \) is the position-dependent line-of-sight extent of the foreground column covered by each pixel. Gray-shaded rectangles superimposed on the iso-delay light surface mark columns of ISM that would be responsible for the respective light echoes as projected onto the sky. The fixed size of the sky pixels leads to varied lengths of the foreground columns of ISM. If the ISM is homogeneously distributed in the \( x/y \) plane, then the total per-sky-pixel extinction of the scattering materials as revealed by the light echo can be estimated by summing the extinction along each rectangular column of ISM intersecting the iso-delay light paraboloid. Comparison of the extinction by the scattering materials to the extinction along the DLOS (marked by the gray line on the \( z \)-axis in Figure 7) may reveal whether they are caused by the same dust mixture and perhaps even the same dust cloud.

Now we can compare the intensity map obtained from the observations with the light echo modeled at each physical position for a given time \( t \) of the observation as follows:

\[
\text{Im}_d(x, y, t) = \int_{x-\Delta x/2}^{x+\Delta x/2} \int_{y-\Delta y/2}^{y+\Delta y/2} \Sigma(x, y, t) dx dy.
\]

### 3.5. Extinction of the Scattering Materials

The optical properties of the dust grains that are responsible for the light echoes around SN 2014J can be deduced within each observed pixel. We estimate the extinction properties of the scattering materials based on an approach that combines single scattering with attenuation (see Section 5 of Patat 2005 for more details). Conversions from the intensity map to the number-density map (“nd”) are presented by Figure 8 based on Equation (12). We follow the sampling in Figures 5 and 6 and present the deduced optical properties of the dust grains for the PA sector 45°–90°, which includes the brightest part of the luminous arc, and PA sector 315°–360°, which covers the diffuse echo ring observed with the highest S/N. They are shown in Figure 9 for F475W and Figure 10 for F606W, both on +277 d. In these diagrams, the rectangular coordinates \( x \) and \( y \) are replaced with the polar coordinates \( \rho \) and \( \phi \), and the abscissa corresponds to the physical distances in the plane of the sky. The left ordinate represents the quantity \( \omega C_{\text{ext}} n_d(\rho, \phi, t) \), which is determined by the optical properties of the dust grains. The right ordinate shows \( \omega C_{\text{ext}} n_d dz = \omega \tau \), where \( \tau \) is the optical depth of the dust mapped onto a single pixel. By looking at the entire echo profile, we found that a major part of the luminous-arc echo spreads over 45°–180° in PA, and the diffuse echo ring attained the highest S/N over 270°–360° in PA.
We applied a Galactic extinction model with $R_V = 3.1$ to the scattering materials and compare the reproduced extinction properties with the extinction along the DLOS. Discrepancies between the derived quantities and the assumed model will indicate that the extinction properties of the scattering dust are different from the Milky Way dust with $R_V = 3.1$. For each photometric bandpass its pivot wavelength was used in interpreting the parameters from dust models. The extinction curve is obtained from Weingartner & Draine (2001) and Draine (2003a, 2003b).\textsuperscript{11} For $C_{\text{ext}}$, the extinction cross section per hydrogen nucleon H, we adopted $5.8 \times 10^{-22}$ cm$^2$/H for $F475W$, and $4.4 \times 10^{-22}$ cm$^2$/H for $F606W$; for the scattering

\textsuperscript{11} ftp://ftp.astro.princeton.edu/draine/dust/ mix/kext_albedo_WD_MW_3.1_60_D03.all
phase function, we adopted \( g = 0.555 \) for \( F475W \), and \( g = 0.522 \) for \( F606W \), and \( n_d \) is the H volume number density in units of \( \text{cm}^{-3} \).

For a uniform dust distribution in the \( x/y \) direction (in the plane of the sky), integrating \( \omega \tau \) over each position angle will provide a rough estimate of the product of the total optical depth and the scattering albedo, which is the main value added by the separate analysis of light echoes. We applied the same depth and the scattering albedo, which is the main value added to provide a rough estimate of the product of the total optical extinction measured along the DLOS to the scattered light-by the separate analysis of light echoes. We applied the same

Using \( \omega = f(\phi) \) as an example, for \( F475W \) and \( F606W \), the optical depth of the materials from extinction measured along the DLOS to the scattered light-by the separate analysis of light echoes. We applied the same

\[ \tau = \int_{\text{LOS}} n_d(z)dz. \]

Therefore, \( n_H \) can be obtained by dividing the total optical depth per bin in position angle by \( \omega \) (Figure 9 for \( F475W \) and Figure 10 for \( F606W \)). For example, for \( F475W \) and \(+277\,\text{d}\), the maximum value of \( \omega \tau \) is observed to be around 0.58. Using \( \omega \sim 0.65 \) for the Milky Way dust model with \( R_V = 3.1 \) given by Weingartner & Draine (2001), \( n_H \) can be estimated to be

\[ n_H \sim 0.58/\omega = 0.58/(0.65 \times 5.8 \times 10^{-22} \text{cm}^2/\text{H}) \sim 1.5 \times 10^{21} \text{H cm}^{-2}, \]

in the bin that shows the densest part of the dust slab producing the luminous arc echo. This is \( ~15 \) times denser than the scattering material in the foreground of the Type II plateau SN 2008bk (Van Dyk 2013), for which the visual extinction of the dust responsible for the echo is \( A_V \approx 0.05 \). It is also \( ~4 \) times denser than the ISM in the foreground of the Type II plateau SN 2012aw (Van Dyk et al. 2015), for which the dust extinction in the SN environment responsible for the echo is consistent with the value that was estimated from observations of the SN itself at early times, i.e., \( A_V = 0.24 \).

### 3.6. Scattering Wavelength Dependence of the ISM

From the scattering properties of the dust, its optical properties can be estimated by comparing the quantity \( \omega C_{\text{ext}} n_d \) derived for \( F475W \) and \( F606W \). Figure 11 presents the division of the profiles of Figure 9 by Figure 10. This yields the wavelength dependence of the extinction cross section. As the ordinate of Figure 11 we use \( \omega T_{\text{F}475W}/\omega T_{\text{F}606W} \). Overplotted histograms show (in red) the number density of the scattering material derived from the strength of the echoes in \( F475W \). The horizontal gray dashed lines mark the value of \( T_{\text{F}475W}/T_{\text{F}606W} = A_{\text{F}475W}/A_{\text{F}606W} = 1.66, 1.30, \) and 1.19 for Milky Way-like dust with \( R_V = 1.4, 3.1, \) and 5.5, respectively, according to the algorithm determined by Cardelli et al. (1989). For completeness, extended versions of Figures 9, 10, and 11 over the entire eight bins of PA are available in the online journal.

Plausible estimates of \( \omega T_{\text{F}475W}/\omega T_{\text{F}606W} \) can only be made in regions of the echoes with high S/N. In the left panel of Figure 11, the luminous arc at \( \rho = 10 \sim 11 \,\text{pc} \) has an average value \( \omega T_{\text{F}475W}/\omega T_{\text{F}606W} \sim 1.7 \) (dimensionless), shown by the black histograms. For the diffuse structure, the right panel indicates an average value \( ~1.3 \). This difference in the wavelength dependence measured from the scattering optical depth indicates that the size of the grains in the thin dust slab producing the luminous arc is different from the grain sizes in the foreground extended dust cloud producing the diffuse echo. While this difference is significant, one should be cautious about the inferred absolute values of \( R_V \) in this approach, considering the low S/N and the large uncertainties.

Figure 12 presents the three-dimensional dust distribution estimated for SN 2014J. Data points show the number densities as derived from two iso-delay paraboloids. Scattering materials producing the luminous arc and the diffuse echo were mapped by

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*Figure 10.* Same as Figure 9, but for F606W. (An extended version of this figure is available.)
out at epochs +277 d (inner layer) and +416 d (outer layer), respectively.

### 4. DISCUSSION

The diffuse echo component favors a higher $R_V$ than the luminous arc, corresponding to a less steep wavelength dependence of the extinction in the diffuse echo compared to the luminous arc. In general terms, this implies that the grains in the dust slab producing the luminous arc are smaller than those in the extended, diffuse ISM. The $R_V$ value measured from the diffuse echo at $\rho \sim 10 - 14$ pc to the position of SN 2014J, i.e., $R_V \sim 3$, is close to that found by Hutton et al. (2015) by modeling the attenuation law based on near-ultraviolet and optical photometry of M82 at large.

Accordingly, the dust grains in the extended foreground ISM producing the diffuse echo ring are similar in size to those in the Milky Way. Extinction in the luminous arc, however, favors a lower $R_V$ value, similar to the extinction law deduced from the SN itself, represented by $R_V \sim 1.4$. This similarity indicates that the grain size distribution in the slab of the ISM producing the luminous arc is similar to the ISM responsible for the extinction measured toward the SN at early epochs.

The optical depth due to light scattered by the ISM can be estimated as follows. If they have similar properties as Milky Way-like dust with $R_V = 3.1$, $\tau_{475W}$ ranges from 0.3 at PA $225^\circ - 270^\circ$, covering part of the diffuse ring, to 0.9 at PA $45^\circ - 90^\circ$, where the luminous arc is brightest. These optical depths are lower than the depth along the DLOS. One possible
explanation for the discrepancy can be an overestimate of the degree of forward scattering. At +277 d, the scattering angle is \( \sim 2\,^\circ 6 \) for the luminous arc-producing dust. A dramatic increase in forward scattering occurs with increasing grain size, while smaller grains scatter light more isotropically, leading to a lower value of the phase function, see Chapter 5 of van de Hulst (1957). Therefore, to produce a light echo of the same strength, smaller dust grains in the ISM responsible for the luminous arc require a higher optical depth than larger Milky Way-like dust grains.

To illustrate the dependence of the degree of forward scattering on the optical depth, we investigate the Heyney–Greenstein phase function characterizing the angular distribution of scattered light intensity as shown by Equation (4). Figure 13 demonstrates the fraction of scattered light at small scattering angle, i.e., \( 2\,^\circ 6 \) as a function of scattering asymmetry factor, \( g \). In this figure, values of \( g = 0.439 \) and \( g = 0.345 \) are indicated for astronomical silicate and graphite grains with radius of 0.1 \( \mu m \) according to calculations based on Draine & Lee (1984) and Laor & Draine (1993).

When the grains are significantly smaller than the wavelength of light, the classical Rayleigh scattering limit is reached. The asymmetry factor for Rayleigh scattering is \( g = 0 \), and the phase function becomes unity, indicating no directional preference of scattering. This is the case for the luminous arc, while the phase function has a value of 7.8 for Milky Way dust with \( R_V = 3.1 \). This means that the optical depth calculated for the case of Rayleigh scattering is 7.8 times larger than for Milky Way dust with \( R_V = 3.1 \). The densest part of the scattering material will attain a value of \( \sim 7.0 \) in F475W, significantly larger than the optical depth measured along the DLOS. On the other hand, the asymmetry factor \( g \) approaches unity for larger grains, and the efficiency of forward scattering increases substantially.

The grain size distribution in the extinction-producing material toward SN 2014J itself is similar to that of the luminous arc-producing material, as inferred from the similarity of \( R_V \) found in both of the two ISM components. Considering this low \( R_V \) and the lower optical depth found in the scattering material responsible for the luminous arc, we infer that these scattering materials are also responsible for the extinction toward SN 2014J. Our result is consistent with the relationship between the host galaxy extinction \( A_V \) and their measured \( R_V \) (Mandel et al. 2011), which, for SNe with low extinction, \( A_V \lesssim 0.4, R_V \approx 2.5–2.9 \) is favored, while at high extinction, \( A_V \gtrsim 1, \) low values of \( R_V < 2 \) are favored. Owing to the lack of knowledge about the detailed distribution and optical properties of the dust in M82, we cannot rule out the possibility that the different extinctions along the scattering line of sight of the materials and the DLOS may partly also be caused by a denser ISM along the DLOS. The extinction along the DLOS may also be due to dust at small foreground distances, which would produce light echoes too close to the SN to be detected. Additionally, it is possible that the extinction can be generated by interstellar dust clouds placed too far in front of the SN. We recall that Equations (8) and (9) showed that the luminosity of the light echo resulting from a dust slab intersecting the DLOS decreases as \( 1/r \) (where \( r \) is the distance between the SN and the dust slab). Considering that numerous Na, Ca, and K features have been seen along the DLOS (Patat et al. 2015), we cannot rule out the possibility that there are dust clouds placed more than 500 pc away from the SN and that they can hardly be detected in current images.

The smaller grains found in the dense dust slab seem to be inconsistent with the grain size distribution in dense regions inferred by Cardelli et al. (1989) and Whittet et al. (1992), who offered the qualitative explanation that coagulation inside the dense interstellar dust clouds removes the smaller particles and results in higher \( R_V \). It is possible that the dense dust slab and the porous diffuse dust cloud belong to different components of the ISM, which are formed by different mechanisms and at significantly different episodes of the history of M82. For instance, considering the possibility that the dense dust slab that produced the luminous arc echo was formed more recently, i.e., around an episode of intense star formation at \( \sim 60 \) Myr ago (Gallagher & Smith 1999), the size growth may not be significant in the dense dust slab considering the relatively long time of the grain growth, i.e., see Figure 8 of Mattsson (2016).

The presented light-echo model is necessarily only a simplified approximation of reality. Our model attempts to reproduce the optical depth of the scattering material over a projected area of \( \sim 40 \) pc \( \times \) 40 pc in the plane of the sky and compares it to the optical depth measured for the DLOS. One major source of uncertainty is the assumption of single scattering (Wood et al. 1996; Patat 2005). In view of the large extinction measured toward SN 2014J, a Monte Carlo simulation with various grain size distributions should give a better representation of the real scattering process. Another uncertainty results from using the extinction measured along the DLOS around maximum light for the echo-producing material as well. Additionally, the assumption of Galactic \( R_V \) values may not be realistic for M82.

5. SUMMARY

The geometric and photometric evolution of resolved light echoes around SN 2014J was monitored with HST. Two main constituents were found. From a luminous arc, a discrete slab of dust was inferred at a foreground distance of 228 \( \pm 7 \) pc. In addition, a resolved diffuse ring-like light echo implies that another foreground ISM component is widely distributed over distances of \( \sim 100–500 \) pc. If the scattering material suffers the same extinction as along the DLOS, then the densest part has a number density of \( \sim 1.5 \times 10^{21} \) cm\(^{-2} \), based on an approach
that combines single scattering with attenuation. The scattering material is unevenly distributed with PA. The wavelength dependence of the scattering optical depth is steeper in the luminous arc than in the diffuse ring. The former favors a small material is unevenly distributed with PA. The wavelength that combines single scattering with attenuation. The scattering properties of Milky Way-like dust with average behavior of the extinction law in the host galaxy.

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REFERENCES

Amanullah, R., & Goobar, A. 2011, ApJ, 735, 20
Amanullah, R., Goobar, A., Johansson, J., et al. 2014, ApJL, 788, L21
Bohlin, R. C. 2012, Flux Calibration of the ACS CCD Cameras IV. Absolute Fluxes, Instrument Science Report ACS 2012-01, Tech. Rep. (Baltimore, MD: STScI)
Bonanos, A. Z., & Boumis. P. 2016, A&A, 585, A19
Bond, H. E., Gilmozzi, R., Meakes, M. G., & Panagia, N. 1990, ApJL, 354, L49
Bond, H. E., Henden, A., Levay, Z. G., et al. 2003, Natur, 422, 405
Brown, P. J., Smitka, M. T., Wang, L., et al. 2015, ApL, 805, 74
Bulla, M., Sim, S. A., Pakmor, R., et al. 2016, MNRAS, 455, 1060
Cappellaro, E., Patat, F., Mazzali, P. A., et al. 2001, ApJL, 549, L215
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chevalier, R. A. 1986, ApJ, 308, 225
Cikota, A., Deustua, S., & Marleau, F. 2016, ApJ, 819, 152
Cracraft, M., & Sparks, W. B. 2007, ACS Polarization Calibration—Data, Throughput, and Multidrizzle Weighting Schemes, Instrument Science Report ACS 2007-10, Tech. Rep.
van de Hulst, H. C. 1957, Light Scattering by Small Particles (New York: Wiley)
Van Dyk, S. D. 2013, AJ, 146, 24
Van Dyk, S. D., Lee, J. C., Anderson, J., et al. 2015, ApJ, 806, 195
Van Dyk, S. D., Li, W., & Filippenko, A. V. 2006, PASP, 118, 351
Vogt, F. P. A., Besel, M.-A., Krause, O., & Dullemond, C. P. 2012, ApJ, 750, 155
Wang, L. 2005, ApJL, 635, L33

Wang, X., Li, W., Filippenko, A. V., et al. 2008, ApJ, 677, 1060
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Welch, D. L., Clayton, G. C., Campbell, A., et al. 2007, ApJ, 669, 525
Whittet, D. C. B., Martin, P. G., Hough, I. H., et al. 1992, ApJ, 386, 562
Wood, K., Bjorkman, J. E., Whitney, B. A., & Code, A. D. 1996, ApJ, 461, 828
Xu, J., Crotts, A. P. S., & Kunkel, W. E. 1994, ApJ, 435, 274
Zheng, W., Shivvers, I., Filippenko, A. V., et al. 2014, ApJL, 783, L24