LIGHT ECHOES FROM SUPERNOVA 2014J IN M82

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ABSTRACT

Type Ia SN 2014J exploded in the nearby starburst galaxy M82 = NGC 3032 and was discovered at Earth about seven days later on 2014 January 21, reaching maximum light in $V$ around 2014 February 5. SN 2014J is the closest SN Ia in at least four decades and probably many more. Recent Hubble Space Telescope/WFC3 imaging (2014 September 5 and 2015 February 2) of M82 in the vicinity of SN 2014J reveals a light echo at radii of about 0.6 arcsec from the supernova (SN; corresponding to about 12 pc at the distance of M82). Likely additional light echoes reside at a smaller radii of about 0.4 arcsec. The major echo signal corresponds to echoing material about 330 pc in the foreground of SN 2014J and tends to be bright where pre-existing nebular structure in M82 is also bright. The second, likely echo corresponds to foreground distances of 80 pc in front of the SN. Even one year after maximum light, there are indications of further echo structures appearing at smaller radii, and future observations may show how extinction in these affect detected echo farther from the SN, which will affect interpretation of details of the three-dimensional structure of this gas and dust. Given enough data, we might even use these considerations to constrain the near-SN material’s shadowing on distant echoing clouds, even without directly observing the foreground structure. This is in addition to echoes in the near future that might also reveal circumstellar structure around SN 2014J’s progenitor star from direct imaging observations and other techniques.

Key words: galaxies: individual (NGC 3032) – ISM: structure – supernovae: individual (SN 2014J)

1. INTRODUCTION

On 2014 January 14, SN 2014J flared into view in M82 (Zheng et al. 2014), to be discovered on January 21 or 22 (Fossey et al. 2014), perhaps the closest SN Ia since SN 1885 in M31,1 and the closest SN of any type observed since SN 1987A. SN 2014J is also special for its appearance in the highly active starburst galaxy M82 (0.9 kpc from its center), but being an SN Ia, this supernova (SN) will sample a region of space in M82 that is not pre-determined to include a star formation region, as in the case of a core-collapse SN.

Several studies list the extinction to SN 2014J variously as $A_V = 1.85 \pm 0.11$ (Amanullah et al. 2014), $\sim 2–3$ (Brown et al. 2014), and $3.14 \pm 0.11$ (Foley et al. 2014), yielding $A_V = 2.6$ mag when averaged linearly in flux, translating to $A_B \approx 4$ in the other band we primarily consider here (see Foley et al. 2014; Goobar et al. 2014).

2. OBSERVATIONS

These observations result from a Hubble Space Telescope (HST)/WFC3 program (#13626; PI: Crotts) to observe properties of the light echoes and progenitor environment around SN 2014J. They consisted of five series of short exposures, primarily in single-orbit visits, with the idea of finding increasingly deeper imaging structure as the SN fades. In the latest two of these five epochs, the SN was sufficiently faint to reveal the echo signals discussed here without being swamped by the SN source itself. All five visits will be useful for further investigations to be discussed in later work. The primary observations used in this paper are a total of 576 s exposure on 2014 September 5 in the F438W filter, 560 s exposure in the F555W filter, and 512 s in F814W and on 2015 February 2 with 1536 s in F438W and 384 s in F555W. More accurately, these were taken on UT 2014 September 5.9 (= JD 2456906.4 = MJD 56905.9 = 234.2 days after the estimated appearance of SN 2014J on 2014 January 14.75 = MJD 56671.75 and 213 days after maximum in $V$), with the later epoch on UT 2015 February 2.6, or 149.7 days later. The point-spread function for each of these two bands is derived from an 8 s exposure in F814W and 40 s in F438W on 56727.8 (day 56.0 after the outburst), and a 128 s exposure in F555W on 56781.1 (day 109.6). As a point of reference, our photometry of SN 2014J on day 234.2 in F438W, F555W, and F814W (STMAG = 16.70, 16.62, and 16.83, respectively) transforms roughly to ($B$, $V$, $I$) values of 16.9, 16.7, and 16.8, with $B$ more uncertain.

3. ANALYSIS

A light echo at a uniform distance well into the SN foreground will resemble a ring or arc of light of a constant radius of curvature. That ring or arc will appear centered on the SN, unless the sheet of reflecting material is tilted versus the line of sight from the observer to the SN, in which case it will appear as a ring/arc off-center from the SN. Any echo, therefore, is usually composed of a composite of rings or arcs, even in the case of the SN imbedded in reflecting nebulous, in which case these rings/arcs can extend to zero angular radius in an extended fuzz of illumination. Because of these characteristics, echoes have a strong tendency to appear as arcs/rings centered near the SN, unless they are at small angular radii. “Small” angular radii in this case are on the scale of $ct$ at the distance of M82, where $c$ is the speed of light and $t$ is the time since the light pulse maximum (213 days for these observations). At the distance of M82, this corresponds to a 0.023 arcsec diameter, 58% the width of a WFC3/UVIS pixel, hence unresolved and inaccessible for faint surface brightnesses due to the bright point source of the SN.

1 SN 2014J in M82 = NGC 3034 is at a distance of 3.5 \pm 0.3 Mpc, while SN 1885 in M31 was 0.8 Mpc away. SN 1937 C in IC 4182 was 4.0 \pm 0.5 Mpc away. SN 1986 G in Cen A was at 3.9 \pm 1.0 Mpc, while SNe 1895 B and 1972 E in NGC 5253 were at 3.9 \pm 0.7 Mpc.
The foreground distance $z$ of echoing material is approximated by the expression $z = r^2/2ct - ct/2$, where $r$ is the physical distance transverse to the Earth–SN sightline to the echo’s position. This equation for a paraboloid is an accurate approximation for the ellipsoid with one focus at Earth and one focus at the SN, with a major axis longer than the Earth–SN distance by $ct$. One notable characteristic of echoes is that for foreground distance $z \gg ct$, and for a sheet of material roughly perpendicular to the Earth–SN sightline, the apparent transverse motion of the echo is almost always faster than lightspeed, hence a reliable signature for the presence of an echo.

Figure 1 shows several aspects of the field around the SN 2014J seen in bands F438W (for WFC3/UVIS images) and F435W for Advanced Camera for Surveys (ACS)/WFC and all for the same field of view, 8.4 arcsec = 143 pc across. Figure 1(a) shows the field taken by ACS/WFC for a Hubble Heritage image on 2006 March 29 (program #10776; PI: Mountain) 2848 days before SN 2014J’s first light. This view of M82, 0.9 kpc west of the galaxy’s nucleus, is centered on SN 2014J indicated by the circular mark, with a 10 pc diameter, centered on the SN. Note that the SN is centered at one end of a dark lane and sits just west of a particularly bright patch of nebulosity.

Figure 1(a) shows the same 143 pc field in M82 as in Figure 1(a), taken by HST/WFC3/UVIS on 2014 September 5 (213 days after maximum) in F438W as part of program #13626 (PI: Crotts). SN 2014J is indicated as the bright point source in the center. In addition, note the apparent nebulosity out to radii of about 12 pc, especially just to the east of the SN. (The nebulosity of M82 is less apparent than in Figure 1(a) due to the reduced contrast in displaying these data.)

Figure 2(b) corresponds to Figure 1(b) with the SN point source subtracted (as derived from a 8 s F438W WFC3/UVIS SN image from 35 days after maximum). The echo ring at 11–13 pc is even more apparent, mainly south of the SN (at PAs 85–230), and to a lesser extent due north (PA ~40–30), but not significantly to the east and west (PA 50–85, and 230–250 and 275–315, respectively). The echoes are absent from the area noted as the dark lane in Figure 1(a), while they correlate well with bright nebulosity at other PAs. The position of the echo was measured by centroiding the signal in crosscuts across the rings every 5° in PA (1 pixel width at the echo radius), with errors estimated from the dispersion of surrounding pixel values, accounting for the number of pixels across the echo peak. In addition to the prominent echo ellipse at about a 0.6 arcsec radius, we search for other significant, transient bright spots and find one plausible echo candidate at a smaller radius of $r \approx 0.4$ arcsec, PA $\approx 215°$. This is only a $4\sigma$ deviation given the range of PSF-subtraction residuals at this small radius, but we describe this feature in detail shortly.

We had the opportunity to view this same field observed five months later in the same bands and look for arc-like structures moving at apparent superluminal speeds. These are shown most readily by subtracting the 2014 September epoch from the 2015 February epoch, which will reveal brighter echoes as a positive signal in advance of a negative one. New echoes will appear as positive-only signals. This can be seen in Figure 3 for F438W. Where the 11–13 pc ring was strongest in 2014 September, e.g., PA 85–170, it is still strong. At other PAs in this representation, it is marginally detected. Significantly, the hint of an inner echo at $r \approx 0.4$ arcsec, PA $\approx 215°$ is confirmed; in fact, this signal has spread to PA 205–225. Additionally, strong positive-only signals have appeared at similar radii of $0.3$ arcsec $\lesssim r \lesssim 0.5$ arcsec, beyond the range of PSF-subtraction systematic errors, suggesting a complex of structures ranging over about a factor of $\pm 40\%$ in foreground distance $z$.

Figure 4 shows the derived three-dimensional geometry of the echoing material seen in the first epoch and confirmed in the second, showing an extensive structure of about 330 pc in

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**Figure 1.** Left panel (a): view of M82, 0.9 kpc west of the galaxy’s nucleus and centered on SN 2014J, covering a field 8.4 arcsec = 143 pc across (north is up; east is left). The image was taken on 2006 March 29 with HST/ACS/WFC in the F435W band as part of HST program #10776. The central circular mark corresponds to a 10 pc diameter and is centered on the SN. Note that the SN is centered at one end of a dark lane and sits just west of a particularly bright patch of nebulosity. Right panel (b): view of the same 143 pc field in M82 as in Figure 1(a), taken by HST/WFC3/UVIS on 2014 September 5 (213 days after maximum) in F438W as part of program #13626 (PI: Crotts). SN 2014J is indicated as the bright point source in the center. In addition, note the apparent nebulosity out to radii of about 12 pc, especially just to the east of the SN. (The nebulosity of M82 is less apparent than in Figure 1(a) due to the reduced contrast in displaying these data.)
nebulosity seen in Figure 1(a) indicates it is deep within M82 as seen from Earth. These loci are derived as shown in Figure 5(a), with the centroids and error bars of the radius from the SN of the primary echo around SN 2014J as a function of position angle, as of 213 days after maximum light, plus a best-fit ellipse centered on the SN point source. Centroids were made by taking radial (or roughly radial) cross-cuts of pixels, where the echo width along each cross-cut was estimated separately, but corresponded to 2–4 pixels (hence about 3–6 months of echo motion). This is fit with an SN-centered ellipse of nearly north–south orientation and an ellipticity of 0.20.

We used the echo locus in Figure 4 to measure both the surface brightness of the echo on day 213 after maximum in F438W and the corresponding surface brightness in F438W (in ACS) from 2006, before the SN. These are shown in Figure 5(b): the surface brightness at the echo locus of the underlying M82 nebulosity (small crosses) in the ACS/F435W band and the light echo (large dots) in the WFC3/F438W band. The echo surface brightness is not determined (but is consistent with zero) at certain position angles where the width of the echo cannot be measured, as indicated by bars at zero surface brightness near PA = 50°, 240°, and 300°. Surface brightnesses are in units of approximately $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-2}$. We note that the echo surface brightness is well correlated (if not perfectly so) with the underlying brightness of nebulosity, and we discuss the possible significance of this below.

SN 2014J’s light curve was observed at and near maximum light (Goobar et al. 2014; Kawabata et al. 2014; Marion et al. 2014; Tsvetkov et al. 2014; Zheng et al. 2014), including studies using the same WFC3 bands as in this study (Amanullah et al. 2014; Foley et al. 2014). Integrating the fluence over the maximum light peak (within 2 mag of the peak in $B$) produces $m(F438W) - m(F555W) = 1.15$, whereas the F438W/F555W color of the echo itself is 0.75, about 0.4 mag bluer, hence with a wavelength dependence in a scattering efficiency of $Q_{\text{scat}} \approx \lambda^{-1.5}$. This is similar to the echo photometry from SN 1987A, in which the echoes show $B - V = 1.1 - 1.2$ (e.g., Suntzeff et al. 1988), whereas the
maximum light colors of SN 1987A were 1.6 (Menzies et al. 1987; Catchpole et al. 1988; Hamuy et al. 1988), also 0.4 mag redder than its echoes.

4. DISCUSSION

Beyond its geometry, interpretation of the echoes is in large part dependent on the optical depth \( \tau_c \) of the scattering dust, with multiple scattering beginning to dominate for \( \tau_c > 1 \). As cited above, estimates toward SN 2014J itself vary from \( \tau_c = 1.7 \) to 2.9 in V (or F555W), hence up to \( \tau_c \approx 3.7 \) in B (or F438W). Are large optical depths borne out by the behavior of the echoes themselves?

The echo-derived estimates of \( Q_{\text{scat}}, \tau_c \), and other properties will depend on the assumption that the extinction and scattering along the direct sightline from SN to Earth is identical to the reflected path from SN to echoing material to Earth, a deviation of only 2°. However, the environment around the SN is complex, and the SN resides in a dark lane (in projection), while the echoing material does not. Furthermore, while the echo brightness correlates with the brightness of nebular emission, this not a perfect indicator (Figure 5(b)).

Nonetheless, Patat (2005) argues that the average properties of an echo complex can be correlated with the brightness of the SN itself and its extinction environment. Patat calculates (his Figure 6) the ratio of echo brightness to peak SN brightness for a foreground echo sheet, which is strongly a function of \( \tau_c \) but very weakly a function of time since the explosion for the first decades of echoes. Is SN 2014J’s echo similar in behavior for such large optical depths to the (small) sample of other observed SN Ia echoes, which tend to be dominated by foreground material (versus sometimes material in the SN vicinity for core-collapse SNe)? This sample, along with SN 2014J, is limited to published cases SNe 1991T, 1998bu, 1995E, and 2006X. For quoted values of \( E(B - V) \) for these SNe: 0.1, 0.3, 0.7, and 1.4, respectively, values of
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V_{\text{echo}} - V_{\text{SN}} = \text{of 10.8, 10.3, 10.4, and 11.7 are found, with typical errors of about 0.1 mag for all of these quantities. In comparison, Patat would predict $V_{\text{echo}} - V_{\text{SN}}$ values of about 10.8, 10.1, 10.5, and 11.7, respectively, hence typically agreeing to within 10%-20%. In contrast, we measure an $V_{\text{echo}} - V_{\text{SN}}$ value for SN 2014J of 12.1, corresponding to a $E(B - V)$ value of 1.7 mag, or $\tau_c = 4.1$ for $R_V$. Since the these values are in the more heavily extincted domain, the errors are relatively larger, about 20% in $\tau_c$.

The dark lane containing the projected position of SN 2014J is also largely devoid of echo at any radius from the SN. Is this surprising? For now, if we assume a simple slab model of dust for both the SN and dust in the dark lane, we expect the echo surface brightness to follow a relation well approximated by $(1 - 10^{-0.4A_B}) \times 10^{-0.4A_B}$, which rises roughly linearly with extinction up to $A_B \approx 0.5$ and continues to a peak surface brightness at $A_B \approx 1$, falling slowly to 10% of the peak surface brightness value of $A_B = 4$. Thus, the most the echo brightness in other regions could outshine the echoes from the dust lane is by 2.5 magnitudes. Adding a synthetic echo signal in the dark lane at a strength of 10% of the bright echo in the luminous nebulosity east of the SN, this synthetic echo is marginally detected.

The brightest nebulosity to the immediate east of the SN extends over radii of 5–15 pc from the SN, which the echo at $z \approx 330$ pc will traverse by about 2015 April, at which point it will enter another dark lane. Similarly, echoes at this $z$ distance will enter other dark lanes over the next few years. There will be several opportunities to study these dark lanes before the close of this decade. (Note that for the most distant echoes seen, $z \approx 330$ pc, the distance traveled perpendicular to the sightline to Earth is $\sim 0.72[1/(1 \text{yr})]^{1/2}$ arcsec.)

The environment around and in front of SN 2014J appears to be an interesting, unprecedented case in terms of light echo environments. These data appear to show an unfolding, rich interstellar environment, but one that is likely to involve some significant but not prohibitive complexity in separating actual interstellar structure of dust clouds as traced by echoes, as opposed to echo structure that is imposed by shadowing from extinction between the echoing cloud and the SN, extinction which will in itself produce its own echo signal. While echoes from SNe 1987A, 1993J, and 2006X may suffer modestly from such effects (as seen in unpublished work by the authors), SN 2014J is probably a clear case in which a large amount of interstellar structure can be mapped in increasing refinement by collecting data over multiple epochs and then using this to iteratively reconstruct not only the interstellar dust distribution but how clouds are shadowing more distant clouds along the same sightline to SN 2014J. We are developing the techniques required to accomplish this for SN 2014J and other SNe. Given this technique and sufficient data, one might even constrain the solid angular distribution of extinction of circumstellar matter and the environment so close to the SN as to have been missed by echo observations, in support of other probes of near-SN space.

5. CONCLUSIONS

At least one, but most likely two, light echo signals are detected from SN 2014J corresponding material about 330 pc and likely 80 pc in the SN foreground, and the former is well correlated in spatial extent with structures seen in two-dimensional projection. Initial three-dimensional maps of the former structure seem consistent with two inclined planes at nearly the same distance in front of the SN, separated by a dark lane. The inner, probable echo appears likely to form only a small part of what might be a more complex group of echoes at distances of roughly 50–120 pc in the foreground of SN 2014J, and future data on these other possible echo clouds may alter the detailed interpretation of the structure of the more distant echoes by providing more information about the effects of shadowing of light from SN 2014J in this dense dust environment. Future epochs of echo image are expected to clarify these and other issues regarding circumstellar and interstellar structure around and in front of SN 2014J.

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