MULTIPLE LIGHT ECHOES FROM SUPERNOVA 1993J

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ABSTRACT

Using the technique of PSF-matched image subtraction, we have analyzed archival HST/WFPC2 data to reveal details of at least two light-echo structures, including some unknown before now, around SN 1993J in the galaxy M81. In particular, we see one partial sheet of material 81 pc in front of the SN and tilted ∼ 60° relative to the disk plane of M81, and another 220 pc in front of the SN, roughly parallel to the disk. The inferred echoing material is consistent with the H I surface density detected in this region of M81’s disk; however, these data imply a fragmented covering factor for the echoing structures. We discuss prospects for future (roughly annual) visits by HST to image these and yet undiscovered echoes in the interstellar and circumstellar environment of SN 1993J.

Subject headings: supernovae: individual (SN 1993J) — ISM: structure — galaxies: individual (NGC 3031) — reflection nebulae

1. INTRODUCTION

Supernova (SN) 1993J was a type II SN (Ripero et al. 1993) in the nearby galaxy NGC 3031 (M81), the closest SN seen in the past decade. It’s spectrum quickly lost most of its hydrogen emission lines, indicating that most of the progenitor’s hydrogen envelope had been stripped, and justifying classification of the SN as type Ib (Nomoto et al. 1995). The lost material probably formed a circumstellar shell, as evidenced by emission in X-rays (Zimmerman et al. 1994), radio (Bartel et al. 1994), and narrow optical lines (Benetti et al. 1994; Matheson et al. 2000).

Since the SN exploded near a spiral arm in M81, it is expected to illuminate interstellar and circumstellar material in the form of light echoes. Such echoes have been reported for e.g., SN 1998bu (Cappellaro et al. 2001), SN 1991T (Schmidt et al. 1994; Sparks et al. 1999) and SN 1987A (Crotts 1988). Light echoes from SN 1987A have revealed structures on interstellar and circumstellar scales (Crotts, Kunkel & Heathcote 1995; Crotts et al. 2001, and references therein), which have been used to map the surrounding material in three dimensions and tie it to kinematic information (Xu, Crotts & Kunkel 1995; Xu & Crotts 1999; Crotts & Heathcote 2000), offering unique insights into the history of the associated stars and gas.

Recently, Liu et al. (2002) discovered a light echo around SN 1993J based on data taken on 2001 June 4 on the WF4 detector of the Wide Field Planetary Camera 2 (WFPC2) aboard the Hubble Space Telescope (HST). We have reanalyzed these now publicly available data, and others (§2), and have found yet another distinct echo. Using image subtraction and PSF-fitting techniques we have also produced detailed analyses (§3) of the structure and reflectivity of both echoing structures. These results already reveal intriguing details about the interstellar medium in M81, and are likely to continue to do so in the future.

2. OBSERVATIONS AND REDUCTIONS

The SN has been visited with HST/WFPC2 several times: UT 1994 April 18, 1995 January 31 and 2001 June 4, respectively 1.00, 1.79 and 8.13y after maximum light [UT 19 April 1993; Benson et al. (1994)]. We make use of publically-available data listed in Table 1; in other bands and at other epochs, the data are insufficient in exposure time or number of visits for useful comparison.

Pipeline-calibrated images were processed as in Sugerman et al. (2002). When necessary, stars were removed with Tiny Tim model PSFs. All images were geometrically registered to a common orientation with residuals ≤ 0.1 pixel rms. Light echoes are transient sources, and are best detected via difimphot image-subtraction (Tomaney & Crotts 1996), in which Fourier techniques match empirically-derived stellar profiles between images to remove sources of constant flux. Even with PSF-matching, reduced data can be unusually noisy – we could not difference the 1995 F439W from the 2001 F450W images, since the noise from resampling PC images to the highly-undersampled WF4 resolution, and from the different passbands, was greater than any echo signal. Instead, stellar sources were removed from the 2001 F450W integration using daophot. We use standard HST photometric calibrations, which we checked against secondary standards used to monitor SN 1993J (L. Wells, private communication; Silvestri et al. 1994), and which agree to within 5%. We measured the SN centroid in the 1994 epoch (with V ≈ 19), providing its unambiguous position.

3. ANALYSIS AND DISCUSSION

Figure 1a shows the F555W image from 2001, and Figure 1b shows its difference from the F555W integration of 1995. The 450W image from 2001, with stellar sources removed (§2), is shown in Figure 1c, and the difference image in F814W (with obviously lower signal-to-noise ratio) corresponding to panel (b) is show in Figure 1d. These clearly show two echoes from 2001 (lighter shade) as well as a confusion due to poor subtraction within ∼ 0.′′4 of the SN. The outermost echo is seen at radii extending from θ = 1′′84 to 1′′95 from the SN, at position angles 170°<PA<290°, with the largest radii near PA 225°. These correspond to distances from the SN sightline r = θD = 32.4 to 34.3 pc...
(D = 3.63 Mpc: Freedman et al. 1994). Since it is a light echo, one can compute the foreground distance (along the SN sightline) \( z = r^2/2ct - ct/2 = 209 \) to 235 pc, implying a tilt of about 37° with the southwest side farther in front of the SN. An echo at the same \( z \) distance would occur at \( \theta = 0'99 \) on 1995 January 31, and indeed there is some marginal indication of such a feature (dark in Figures 1b and 1d) between PA 190 and 260. This is far from definite, but may indicate a shrinking of the echo cloud in PA at earlier epochs, hence the possibility that the echo cloud does not extend in front of the SN.

The inner echo lies at \( \theta \approx 10'15 \) (all at the same radius, to within the errors) in 2001, over \( \theta < PA < 60 \). In 1995, this same \( z \) would correspond to \( \theta \approx 0'55 \), which is bordering the confusion region of the bright PSF of the SN. The echo lies at a foreground distance \( z = 81 \) pc, and is perpendicular to the line of sight to within about 25°. The geometry of all echoes is shown in Figure 2. Radial profiles through the echoes in F555W are plotted in Figure 3, demonstrating that these detections are above the background noise (e.g. \( \sigma_{F555W} = 1.5 \) DN pix\(^{-1} \)).

Using the naming convention of Xu et al. (1995), we denote the outer echo as SW770 and the inner echo as NE260. M81, with an angular momentum vector inclined 59° along PA 62 (Rots 1975) (such that the southwest side of the disk is closer to Earth), and SN 1993J, southwest of the nucleus of M81, would imply that the tilt of the NE260 dust sheet is roughly perpendicular to the disk of the galaxy. In comparison, the SW770 echo is inclined to within \( \sim 30° \) of the disk plane. The SN, with its massive progenitor contained within a dense gas cloud, is presumed to lie near the disk plane (shown in Fig. 2). We thus detect two dust structures, both extending more than one gas scale-height (c.f. Brouillet et al. 1998) above the plane. SW770 sits a roughly constant 110 pc above the disk, while NE260 appears to miss this plane by \( \geq 40 \) pc and extends at least 60 pc above the disk. Without requiring the SN to lie in the disk plane, one might hypothesize that the disk plane passes near both echoing structures, implying the SN may lie \( \sim 70 \) to 90 pc behind the disk.

SW770 has measurable surface brightnesses over the PA range 160–280. Over 190 < PA < 250, all three bands (F450W, F555W and F814W) track each other in surface brightness consistently. For 190 < PA < 250, \( \mu = 23.3 \pm 0.1, 23.3 \pm 0.1 \) and \( 24.6 \pm 0.2 \) in STMAG, respectively transforming to vegamag colors\(^1\) of roughly \( B - V = 0.6 \pm 0.2 \) and \( V - I_C = 0.0 \pm 0.3 \). The spatial variation in surface brightness is similar in \( B \) and \( V \), both rising with increasing PA values. At PA \( \approx 270, \mu_{450} = 23.0 \pm 0.1 \) and \( \mu_{814} = 23.1 \pm 0.1 \), while at PA \( \approx 180, \mu_{450} = 23.6 \pm 0.2 \) and \( \mu_{555} = 24.1 \pm 0.2 \). In contrast \( \mu_{814} \) is nearly equally faint at both extremal PAs, \( \mu_{814} = 25.1 \pm 0.4 \), implying colors at PA \( \approx 270 \): \( B - V = 0.5 \pm 0.3 \) and \( V - I_C = -0.9 \pm 0.5 \). In comparison, NE260 has approximately the same global colors as SW770 (over 190 < PA < 250): \( B - V = 0.5 \pm 0.4 \) and \( V - I_C = 0.2 \pm 0.4 \), and there is little evidence for such a color gradient. The surface brightnesses themselves are fainter by about 0.5 mag arcsec\(^{-2} \) compared to SW770.

In order to interpret these surface colors in terms of reflectivity, we must know the colors of the incident echoing flux. Integrating over the entire SN lightcurve (Benson et al. 1994; Richmond et al. 1994) from \( 3 \) to \( 127 \) days after core collapse yields \( B - V = 0.73, V - I_C = 0.69 \) for the fluence of the (nearly) entire event. The color change due to dust reflectivity for NE260 and SW770 (with PA < 250) is \( \Delta(B - V) = -0.1 \) and \( \Delta(V - I_C) = -0.7 \), while for SW770 with PA > 250, \( \Delta(B - V) = -0.2 \) and \( \Delta(V - I_C) = -1.6 \). The largest changes in color are imparted in the Rayleigh scattering regime by very small particles. Integration of the scattering efficiency \( S(\lambda, \alpha) \) (Xu, Crotts & Kunkel 1994) using the dust scattering parameters of Weingartner & Draine (2001, and references therein), we find \( S \propto \lambda^{-4.5} \) for \( \alpha < 0.01 \mu m \), yielding \( \Delta(B - V)_{\text{max}} = -0.96 \) and \( \Delta(V - I_C)_{\text{max}} = -1.72 \). As the observed color shifts are smaller, the echoes should be consistent with a galactic dust distribution. Dust modeling will be examined in detail by Sugerman (2003).

Attributing the blue color of SW770 at PA > 250 to a small-grain-only hypothesis is sufficiently improbable as to warrant alternative explanations. Any extinction mechanism for F814W light should more-strongly affect the F450W and F555W bands. One might invoke additional flux from mechanisms beyond direct reflection to increase the flux in F450W and F555W over F814W for PA < 250. Extended red emission (Witt & Boroson 1990) would contribute significantly to the F814W band but not the bluer bands. However, we caution that this very blue \( V - I_C \) color of SW770 is nearly the detection threshold, and we cannot rule out a “hot pixel” or variable star producing an erroneous image-subtraction residual in the F814W image.

For the sake of this discussion, we adopt a dust model with isotropically-scattering grains. We note that this assumption disagrees with some measurements of Galactic interstellar dust (Witt, Oliver & Schild 1990; Matula 1979; Toller 1981). Using this model, we calculate the ratio of dust densities in the two echoes from the surface brightnesses and echo geometry. For an echo cloud that is thick relative to the depth of dust echoing at a given time \( (d_z/dt) \), the surface brightness is predicted by Chevalier (1986):

\[
\mu(\theta) = \frac{n_s Q_s \sigma_d L_\nu t_s}{4\pi D^2} \left| \frac{dz}{dt} \right| F(\alpha),
\]

where the average apparent luminosity \( L_\nu/4\pi D^2 \) over the SN light pulse duration \( t_s \) is observed directly from the SN. The geometric factors \( R = \sqrt{(z^2 + r^2)} \) (the SN-to-cloud distance), \( \alpha \) (the scattering angle), and \( |dz/dt| = r^2/2c^2 + c/2 \) (describing the depth of the echoing region), are determined precisely by \( \theta \) from the light-travel-delay equation of an echo. This leaves: the grain scattering efficiency \( Q_s \) and geometric cross-section \( \sigma_d \) (assumed equal in the two echoing clouds); the dust number density \( n_s \); and the scattering phase function \( F(\alpha) \) (assumed equal in the two echoes). The ratio of the geometric factors \( F(\alpha) z/|dz/dt| \) for the two echoes is 1.52 (inner/outer), but SW770 is spread over \( r_{\text{outer}}/r_{\text{inner}} = 1.71 \) times the area. Since the echoes are undersolved by WFPC2, SW770 should be about 1.13 times higher observed surface brightness than NE260, if

\(^1\) Color transformations from STMAG to Johnson-Cousins (vegamag) were determined using synphot and the Bruzual-Persson-Gunn-Stryker Spectrophotometry Atlas.
they have the same dust properties and density. In truth, we measure SW770 to be about 1.6 times brighter, implying either a 40% higher dust density in SW770, or the SW770 cloud is 40% thicker along the line of sight. If, instead, the clouds are geometrically thin compared to $t_r/\Delta t$, geometric factors would predict an inner echo brightness 2.56 times that of SW770 (for equivalent dust), implying that the SW770 cloud contains 4.1 times higher dust surface density. How do these numbers change if we instead invoke a non-zero $g$? For reasonable values ($g \approx 0.5$), the above brightness ratios change by only 1% or less, since the scattering angles for the two echoes are very similar ($\alpha = 10^\circ$ for NE260 versus 8.5$^\circ$ for SW770.)

The echo’s effective width is given by $w = t_s \, \Delta r/\Delta t$ where $dr/dt = c(z + ct/2)/\sqrt{2(z + ct/2)c}t$, and $t_r$ is the total fluence in $V$ ($6.31 \times 10^{-7}$ ergs cm$^{-2}$ A$^{-1}$) divided by the maximum light flux, yielding $t_r = 3.5 \times 10^8$s and $w = 0.23$ pc. A thin sheet of isotropic reflectors at the position of SW770 in year 2001 (with 170<PA<290) diverts no more than 0.0026% of the SN flux seen at Earth. We observe a flux in F555W of $4.3 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$ from the echo, versus a corresponding maximum flux from the SN of $1.8 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$, or about 0.0024%. SW770, over the position observed, appears to be optically thick. This implies NE260 also has $A_v \gtrsim 1$.

For a dust albedo of 0.5 and grain diameter of 0.1 µm (the largest Rayleigh-like particle), unit optical depth corresponds to $\sim 15$ µg cm$^{-2}$ for grains of density 1 g cm$^{-3}$. If the gas-to-dust ratio is 100, this corresponds to $N_H = 8 \times 10^{20}$ cm$^{-2}$ for SW770. At the position of the SN, $N_{HI} \approx 10^{21}$ cm$^{-2}$, so SW770 structure is consistent with the dominant locus of gas along the Earth-SN sightline.

The velocity structure of this region of the galaxy has been studied in H I 21 cm emission and optical/UV absorption (of the SN itself). This structure is relatively smooth and locally centered near $v_{lsr} = -135$ km s$^{-1}$ (Rots 1975), with some gas over the range $-155 < v_{lsr} < -115$ km s$^{-1}$ (Rots & Shane 1975). In absorption against SN 1993J, the predominant M81 interstellar components are $-119$ and $-135$ km s$^{-1}$, with possible lesser components at $-110$ and $-100$ km s$^{-1}$ (Vladilo et al. 1994). The former two interstellar components are each at least twice as strong in Ca II column density as the latter two (hence containing about 56% and 26% of the interstellar gas), and appear to be cold. In IUE spectra of UV absorption lines (Magggraf & de Boer 2000), a strong component at $-130$ km s$^{-1}$ and a weaker one at $-90$ km s$^{-1}$ is seen in low-ionization species, probably consistent with the Ca II components.

It is possible that the inner and outer echoes correspond to the two dominant absorption features ($-119$ and $-135$ km s$^{-1}$), but this is difficult to state with certainty given the limited amount of data and the partial covering factor of the structures involved. The structure and strength of the echoes seems to imply, however, that major portions of interstellar material in this part of the disk may be broken into fragments and perhaps even propelled a scale height or more out of the disk plane.

4. FUTURE PROSPECTS

One prospect that is unlikely is using these echoes to measure the distance to M81. The maximum-polarization technique (Sparks et al. 1996) requires 90$^\circ$ scattering, a condition unlikely for these echoes, but potentially attainable for circumstellar echoes yet to be observed. (This has been implemented for SN 1987A’s circumstellar echoes, for instance - Crotts et al. in preparation.) The use of interstellar echoes to measure the distance to M81 will require centuries of observation before their power-law expansion behavior begins to break down, and even then the intrinsic geometry of the echoing structure seems unlikely to cooperate in performing a distance determination.

As time progresses, we expect more light echoes will appear. At small radii, one must compete with the bright central source, making echo detection difficult for $\theta < 0.5$ arcsec, or $r < 8$ pc. In year 2002 this radius corresponds to $z \approx 16$ pc and will continue to decrease (roughly as $1/t$). This foreground distance is well beyond the likely circumstellar region around the SN progenitor. Eventually, the echo from the circumstellar material itself might become apparent. The SN progenitor evidently has been emitting a dense wind with outflow velocity of at least $\sim 10$ km s$^{-1}$ (Fransson, Lundqvist & Chevalier 1996), probably for $\sim 10^6$ y. Depending on the density of interstellar material into which this wind is propagating, dense circumstellar nebulousity may extend beyond the PSF of the central source, and more careful analysis may reveal echoes at even smaller radii.

Pursuing these and further echoes around SN 1993J with a series of PC (or ACS) images would be valuable, particularly in bands near F555W, offering the best sensitivity. Since SW770 is expanding at a rate corresponding to the PSF width of HST every 0.8 y, an annual visit to image the echoes of SN 1993J will probe of new material each time. Over the course of a decade or so, we should be able to build a more detailed, three-dimensional view of the interstellar medium in a $\sim 10^6$ pc$^3$ volume of M81’s spiral arm, and begin to glimpse the outer edges of the region affected by the mass loss from SN 1993J’s progenitor.

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Table 1
WFPC2 data used in this work

| Epoch          | Detector | Filter   | $\lambda_c$ | $t_{exp}$ |
|----------------|----------|----------|-------------|-----------|
| 1994 April 18  | PC       | F555W    | 5407        | 300       |
| 1995 January 31| PC       | F439W    | 4300        | 1200      |
|                | PC       | F555W    | 5407        | 900       |
|                | PC       | F814W    | 7940        | 900       |
| 2001 June 4    | WF4      | F450W    | 4520        | 2000      |
|                | WF4      | F555W    | 5407        | 2000      |
|                | WF4      | F814W    | 7940        | 2000      |

$^a$Central Wavelength

$^b$Total exposure time
**Fig. 1.—** *HST* WF4 images of the region surrounding SN 1993J. In all panels, we have subtracted the SN and an adjacent star (PA=347, \( r = 0'72 \)), which we found to be variable. (a) A direct image in F555W from 2001; (b) a difference of F555W images between 2001 and 1995; (c) direct image in F450W from 2001, with all stellar sources removed; (d) same as (b) but in F814W (image is scaled to enhance faint pixels). SW770 is visible between PA 160–280. The fainter, inner echo NE260 is apparent from PA 10–60 at a radius of \( \sim 1'' \) in (b) and (c). A faint negative region around PA 190–260, \( r = 0'85 \) appears in panels (b) and (d), suggestive of an echo in the 1995 integration. Dotted white lines in panel (a) show the locations of radial profiles from figure 3.

**Fig. 2.—** Geometry of M81 and the light echoes. Images in Figure 1 show the projected views of an observer at large \( z \) distance. This diagram shows the geometry from far to the north, with the plane of the page separating north from south. SN 1993J is at the origin. The orientation of M81’s disk (see text) and the plane containing SW770 are indicated. Echo parabolae from 1995 and 2001 are drawn with dotted lines. Echoes are marked as follows: (a) SW770 in 2001, (b) NE260 in 2001, and (c) SW770 in 1995. Grayscale indicates height of the echoing material above (below) the page, with darker (lighter) shades indicating greater northern (southern) position.

**Fig. 3.—** Radial profiles of F555W surface brightness measured in 20°-wide annular bins centered on the PAs as marked here and in figure 1a. NE260 in 2001 is clearly visible above the noise at PA 30°, as are SW770 in 2001 and 1995 at PAs 190° and 250°. For comparison, no such structure is evident at PA 90° or at large radii.