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MULTIPLE LIGHT ECHOES FROM SN 1993J

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ABSTRACT

Using the technique of point-spread function–matched image subtraction, we have analyzed archival *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 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 supernova (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: galaxies: individual (NGC 3031) — ISM: structure — reflection nebulae — supernovae: individual (SN 1993J)

1. INTRODUCTION

SN 1993J was a Type II supernova (SN; Ripero et al. 1993) in the nearby galaxy NGC 3031 (M81), the closest SN seen in the past decade. Its 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 IIb (Nomoto et al. 1993). 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, Bregman, & Seitzer (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 point-spread function (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 8.13 yr after maximum light (UT 1993 April 19; Benson et al. 1994). We make use of publicly 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 1997, private communication; Silvestri et al. 1994) and which agree to within 5%. We measured the SN centroid in the 1994 epoch (with $V \approx 19$), providing its unambiguous position.

3. ANALYSIS AND DISCUSSION

Figure 1*a* shows the F555W image from 2001, and Figure 1*b* shows its difference from the F555W integration of 1995. The 450W image from 2001, with stellar sources removed (§ 2), is shown in Figure 1*c*, and the difference image in F814W (with obviously lower signal-to-noise ratio), counterpart to Figure 1*b*, is shown in Figure 1*d*. These clearly show two echoes from 2001 (*light shading*) as well as a confusion due to poor subtraction within ∼0″.4 of the SN. The outermost echo is seen at radii extending from $\theta = 1''.84$ to 1″.95 from the SN, at position angles 170° < P.A. < 290°, with the largest radii near P.A. 225°. These correspond to distances from the SN sight line $r = \theta D = 32.4$–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 sight line) $z = r^2/2ct - ct/2 = 209$–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 $\theta = 0''.89$ on 1995 January 31, and indeed there is some marginal indication

TABLE 1
WFPC2 Data Used in This Work

Epoch	Detector	Filter	λ_c[a] (Å)	t_{exp}[b] (s)
1994 Apr 18	PC	F555W	5407	300
1995 Jan 31	PC	F439W	4300	1200
	PC	F555W	5407	900
	PC	F814W	7940	900
2001 Jun 4	WF4	F450W	4520	2000
	WF4	F555W	5407	2000
	WF4	F814W	7940	2000

[a] Central wavelength.
[b] Total exposure time.

of such a feature (Figs. 1*b* and 1*d*, *dark shading*) between P.A. 190° and 260°. This is far from definite but may indicate a shrinking of the echo cloud in P.A. at earlier epochs, hence the possibility that the echo cloud does not extend in front of the SN.

The inner echo lies at $\theta \sim 1''.15$ (all at the same radius, to within the errors) in 2001, over $0° < \mathrm{P.A.} < 60°$. 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., $\sigma_{\mathrm{F555W}} = 1.5$ DN pixel^{-1}).

Using the naming convention of Xu et al. (1995), we denote the outer echo as SW 770 and the inner echo as NE 260. M81, with an angular momentum vector inclined 59° along P.A. 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 NE 260 dust sheet is roughly perpendicular to the disk of the galaxy. In comparison, the SW 770 echo is inclined to within ∼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 1 gas scale height (see Brouillet et al. 1998) above the plane. SW 770 sits a roughly constant 110 pc above the disk plane in M81, while NE 260 appears to miss this plane by $\gtrsim 40$ 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 ∼70–90 pc behind the disk.

SW 770 has measurable surface brightnesses over the P.A. range 160°–280°. Over $190° < \mathrm{P.A.} < 250°$, all three bands (F450W, F555W, and F814W) track each other in surface brightness consistently. For $190° < \mathrm{P.A.} < 250°$, $\langle\mu\rangle = 23.3 \pm 0.1$, 23.3 ± 0.1, and 24.6 ± 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 P.A. values. At $\mathrm{P.A.} \approx 270°$, $\mu_{450} = 23.0 \pm 0.1$ and $\mu_{555} = 23.1 \pm 0.1$, while at $\mathrm{P.A.} \approx 180°$, $\mu_{450} = 23.6 \pm 0.2$ and $\mu_{555} = 24.1 \pm 0.2$. In contrast μ_{814} is nearly equally faint at both extremal P.A.'s, $\mu_{814} = 25.1 \pm 0.4$, implying colors at $\mathrm{P.A.} \sim 270°$ of $B-V = 0.5 \pm 0.3$ and $V-I_C = -0.9 \pm 0.5$. In comparison, NE 260 has approximately the same global colors as SW 770 (over $190° < \mathrm{P.A.} < 250°$): $B-V = 0.5 \pm 0.4$ 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 SW 770.

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 light curve (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 NE 260 and SW 770 (with $\mathrm{P.A.} < 250°$) is $\Delta(B-V) = -0.1$ and $\Delta(V-I_C) = -0.7$, while for SW 770 with $\mathrm{P.A.} > 250°$, $\Delta(B-V) = -0.2$ and $\Delta(V-I_C) = -1.6$. The maximal changes in color are imparted in the Rayleighan scattering regime by very small particles. Integration of the scattering efficiency $S(\lambda, a)$ (Xu, Crotts, & Kunkel 1994) using the dust scattering parameters of Weingartner & Draine (2001 and references therein) gives $S \propto \lambda^{-4.3}$ for $a < 0.01$ μm, yielding $\Delta(B-V)_{\max} = -0.96$ and $\Delta(V-I_C)_{\max} = -1.72$. 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 (2002).

Attributing the blue color of SW 770 at $\mathrm{P.A.} > 250°$ to a

[1] Color transformations from STMAG to Johnson-Cousins (VEGAMAG) were determined using SYNPHOT and the Bruzual-Persson-Gunn-Stryker Spectrophotometry Atlas.

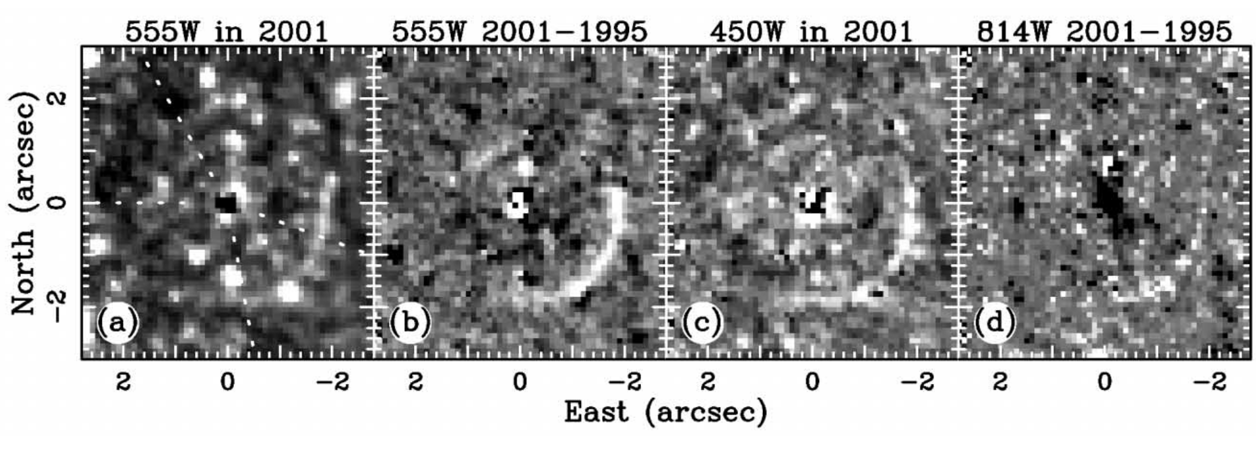

Fig. 1.—*HST* WF4 images of the region surrounding SN 1993J. In all panels, we have subtracted the SN and an adjacent star (P.A. = 347°, $r = 0''.72$), which we found to be variable. (*a*) Direct image in F555W from 2001. (*b*) Difference of F555W images between 2001 and 1995. (*c*) Direct image in F450W from 2001, with all stellar sources removed. (*d*) Same as (*b*), but in F814W (image is scaled to enhance faint pixels). SW 770 is visible between P.A. 160° and 280°. The fainter, inner echo NE 260 is apparent from P.A. 10° to 60° at a radius of ∼1″ in (*b*) and (*c*). A faint negative region around P.A. 190°–260°, $r = 0''.85$ appears in (*b*) and (*d*), suggestive of an echo in the 1995 integration. Dotted white lines in (*a*) show the locations of radial profiles from Fig. 3.

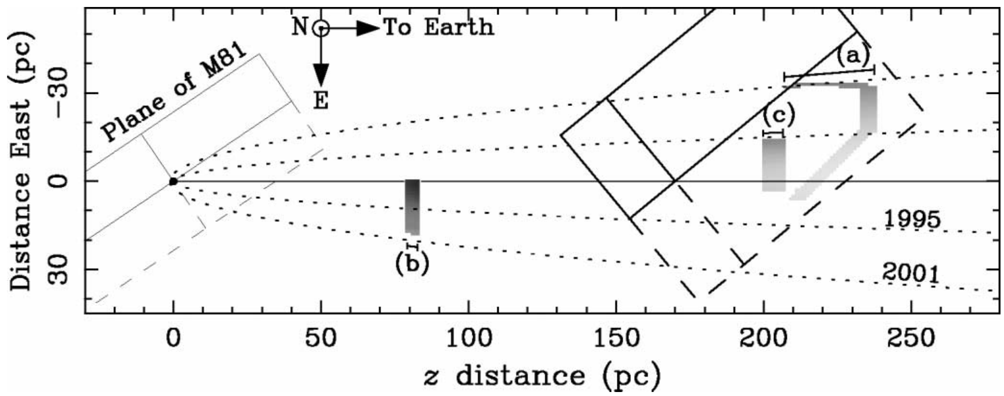

FIG. 2.—Geometry of M81 and the light echoes. Images in Fig. 1 show the projected views of an observer at large *z*-distance. This diagram shows the geometry from far to the north, with the plane of the page separating north from south. SN 1993J is at the origin. The orientation of M81's disk (see text) and the plane containing SW 770 are indicated. Echo parabolas from 1995 and 2001 are drawn with dotted lines. Echoes are marked as follows: (*a*) SW 770 in 2001, (*b*) NE 260 in 2001, and (*c*) SW 770 in 1995. Gray scale indicates height of the echoing material above (below) the page, with darker (lighter) shades indicating greater northern (southern) position.

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 P.A. < 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 $V-I_C$ SW 770 color is near 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, Oliveri, & Schild 1990; Matila 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 ($t_s\,|dz/dt|$), the surface brightness is predicted by Chevalier (1986):

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

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 $R = (z^2 + r^2)^{1/2}$ (the SN-to-cloud distance),

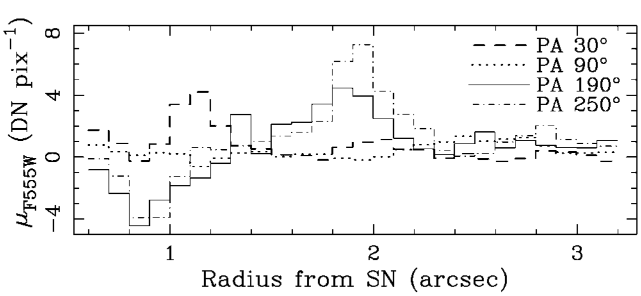

FIG. 3.—Radial profiles of F555W surface brightness measured in 20° wide annular bins centered on the P.A.'s as marked here and in Fig. 1*a*. NE 260 in 2001 is clearly visible above the noise at P.A. 30°, as are SW 770 in 2001 and 1995 at P.A.'s 190° and 250°. For comparison, no such structure is evident at P.A. 90° or at large radii.

α (the scattering angle), and $|dz/dt| = r^2/2ct^2 + c/2$ (describing the depth of the echoing region) are determined precisely by θ from the light travel delay equation of an echo. This leaves the grain scattering efficiency Q_s and geometric cross section σ_d (assumed equal in the two echoing clouds), the dust number density n_d, and the scattering phase function $F(\alpha) = (1 - g^2)/(1 + g^2 - 2g\cos\alpha)^{3/2}$ (Henyey & Greenstein 1941; which does quite well for small α such as here [Witt 1989]), where $g = \langle\cos\alpha\rangle$ is the degree of forward scattering, here assumed to be zero. The ratio of the geometric factors $F(\alpha)|\dot{z}|/R^2$ for the two echoes is 1.52 (inner/outer), but SW 770 is spread over $r_{\rm outer}/r_{\rm inner} = 1.71$ times the area. Since the echoes are underresolved by WFPC2, SW 770 should have about 1.13 times higher observed surface brightness than NE 260, if they have the same dust properties and density. In truth, we measure SW 770 to be about 1.6 times brighter, implying either a 40% higher dust density in SW 770 or that the SW 770 cloud is 40% thicker along the line of sight. If, instead, the clouds are geometrically thin compared to $t_s\,|dz/dt|$, geometric factors would predict an inner echo brightness 2.56 times that of SW 770 (for equivalent dust), implying that the SW 770 cloud contains 4.1 times higher dust surface density. How do these numbers change if we instead invoke a nonzero 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 ($\alpha = 10\overset{\circ}{.}5$ for NE 260 vs. $8\overset{\circ}{.}5$ for SW 770).

The echo's effective width is given by $w = t_s\,dr/dt$, where $dr/dt = c(z + ct/2)/[(2z + ct/2)ct]^{1/2}$ and t_s is the total fluence in V (6.31×10^{-7} ergs cm^{-2} Å^{-1}) divided by the maximum light flux, yielding $t_s = 3.5 \times 10^6$ s and $w = 0.23$ pc. A thin sheet of isotropic reflectors at the position of SW 770 in year 2001 (with 170° < P.A. < 290°) diverts no more than 0.0026% of the SN flux seen at Earth. We observe a flux in F555W of $\sim 4.3 \times 10^{-18}$ ergs cm^{-2} s^{-1} Å^{-1} from the echo, versus a corresponding maximum flux from the SN of 1.8×10^{-13} ergs cm^{-2} s^{-1} Å^{-1}, or about 0.0024%. SW 770, over the position observed, appears to be optically thick. This implies NE 260 also has $A_v \gtrsim \frac{1}{4}$.

For a dust albedo of 0.5 and grain diameter of 0.1 μm (the largest Rayleigh-like particle), unit optical depth corresponds to $\sim 15\ \mu$g cm^{-2} for grains of density 1 g cm^{-3}. If the gas-to-dust ratio is 100, this corresponds to $N_{\rm H} \approx 8 \times 10^{20}$ cm^{-2} for SW 770. At the position of the SN, $N_{\rm H\,I} \approx 10^{21}$ cm^{-2}, so SW

770 structure is consistent with the dominant locus of gas along the Earth-SN sight line.

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 (Marggraf & 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 seem 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 1996) requires 90° 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; A. P. S. Crotts et al. 2002, 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 $\theta < 0''.5$, 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 $\sim 10^6$ yr. Depending on the density of interstellar material into which this wind is propagating, dense circumstellar nebulosity 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 Advanced Camera for Surveys) images would be valuable, particularly in bands near F555W, offering the best sensitivity. Since SW 770 is expanding at a rate corresponding to the PSF width of *HST* every 0.8 yr, an annual visit to image the echoes of SN 1993J will probe 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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REFERENCES

Bartel, N., et al. 1994, Nature, 368, 610
Benetti, S., et al. 1994, A&A, 285, L13
Benson, P. J., et al. 1994, AJ, 107, 1453
Brouillet, N., Kaufman, M., Combes, F., Baudry, A., & Bash, F. 1998, A&A, 333, 92
Cappellaro, E., et al. 2001, ApJ, 549, L215
Chevalier, R. 1986, ApJ, 308, 225
Crotts, A. P. S. 1988, IAU Circ. 4561
Crotts, A. P. S., & Heathcote, S. R. 2000, ApJ, 528, 426
Crotts, A. P. S., Kunkel, W. E., & Heathcote, S. R. 1995, ApJ, 438, 724
Crotts, A. P. S., Sugerman, B. E. K., Lawrence, S. S., & Kunkel, W. E. 2001, in AIP Conf. Proc. 565, Young Supernova Remnants, ed. S. S. Holt & U. Hwang (New York: AIP), 137
Fransson, C., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 461, 993
Freedman, W. L., et al. 1994, ApJ, 427, 628
Henyey, L. G., & Greenstein, J. L. 1941, ApJ, 93, 70
Liu, J.-F., Bregman, J. N., & Seitzer, P. 2002, ApJ, in press (astro-ph/0206070)
Marggraf, O., & de Boer, K. S. 2000, A&A, 363, 733
Matheson, T., Filippenko, A. V., Ho, L. C., Barth, A. J., & Leonard, D. C. 2000, AJ, 120, 1499
Matila, K. 1979, A&A, 78, 253
Nomoto, K., Suzuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., & Saio, H. 1993, Nature, 364, 507
Richmond, M. W., et al. 1994, AJ, 107, 1022
Ripero, J., et al. 1993, IAU Circ. 5731
Rots, A. H. 1975, A&A, 45, 43
Rots, A. H., & Shane, W. W. 1975, A&A, 45, 25
Schmidt, B. P., et al. 1994, ApJ, 434, L19
Silvestri, N. M., et al. 1994, BAAS, 26, 1444
Sparks, W. B. 1996, ApJ, 470, 195
Sparks, W. B., et al. 1999, ApJ, 523, 585
Sugerman, B. E. K. 2002, AJ, submitted
Sugerman, B. E. K., Lawrence, S. S., Crotts, A. P. S., Bouchet, P., & Heathcote, S. R. 2002, ApJ, 572, 209
Toller, G. N. 1981, Ph.D. thesis, SUNY, Stony Brook
Tomaney, A., & Crotts, A. P. S. 1996, AJ, 112, 2872
Vladilo, G., et al. 1994, A&A, 291, 425
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Witt, A. N. 1989, in Interstellar Dust, ed. L. Allamandola & A. Tielens (Dordrecht: Kluwer), 87
Witt, A. N., & Boroson, T. A. 1990, ApJ, 355, 182
Witt, A. N., Oliveri, M. V., & Schild, R. E. 1990, AJ, 99, 888
Xu, J., & Crotts, A. P. S. 1999, ApJ, 511, 262
Xu, J., Crotts, A. P. S., & Kunkel, W. E. 1994, ApJ, 435, 274
———. 1995, ApJ, 451, 806 (erratum 463, 391 [1996])
Zimmerman, H. U., et al. 1994, Nature, 367, 621