Hubble Space Telescope Observations of Oxygen#rich Supernova Remnants in the Magellanic Clouds. II. Elemental Abundances in N132D and 1E 0102.2-7219

Citation

Blair, William P., Jon A. Morse, John C. Raymond, Robert P. Kirshner, John P. Hughes, Michael A. Dopita, Ralph S. Sutherland, Knox S. Long, and P. Frank Winkler. 2000. "Hubble Space Telescope Observations of Oxygen#rich Supernova Remnants in the Magellanic Clouds. II. Elemental Abundances in N132D and 1E 0102.2-7219." *The Astrophysical Journal* 537 (2): 667-89. <https://doi.org/10.1086/309077>.

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HUBBLE SPACE TELESCOPE OBSERVATIONS OF OXYGEN-RICH SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS. II. ELEMENTAL ABUNDANCES IN N132D AND 1E 0102.2–7219¹

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Received 1999 November 30; accepted 2000 February 9

ABSTRACT

We present *Hubble Space Telescope* (*HST*) Wide Field and Planetary Camera 2 images and Faint Object Spectrograph data of two young supernova remnants in the Magellanic Clouds, N132D (LMC) and 1E 0102.2–7219 (SMC). The spectra cover essentially the entire UV/optical range available to *HST* and provide the first true comparison of UV/optical line intensities from astrophysical shocks that do not depend on scalings from different aperture sizes or instruments. For the spectra, we isolated specific knots and filaments that contain fast-moving debris of nuclear-processed material that are devoid of hydrogen and appear to have originated from the cores of the progenitor stars. In N132D we also observed a knot on the outer rim of the remnant that represents a shocked interstellar cloud. In the debris from both remnants, we identify only the elements O, Ne, C, and Mg. We find no evidence for oxygen-burning products, such as S, Ca, Ar, etc., which are seen in Cas A and are expected from models of Type II supernovae. We suggest that the progenitor stars of N132D and 1E 0102.2–7219 had large, oxygen-rich mantles (perhaps Wolf-Rayet stars) and may be the products of Type Ib supernovae. Shock modeling demonstrates systematic differences in the relative abundances in the O-rich debris, possibly pointing to different progenitor masses for these two objects. The shocked interstellar knot in N132D shows that we are probably seeing a range of conditions within the $\sim 1''$ aperture and that no evidence is present for enrichment by a precursor star wind.

Subject headings: ISM: individual (1E 0102.2–7219, N132D) — Magellanic Clouds — shock waves — supernova remnants

1. INTRODUCTION

There is a small class of young supernova remnants (SNRs), known as “oxygen-rich” (or “O-rich”) SNRs, in which stellar interior fragments are exposed to direct investigation, providing us with an opportunity to make direct tests of stellar evolution and nucleosynthesis models of massive stars. These SNRs, mostly found over the past couple of decades, have debris with characteristic high velocities ($V > 1000 \text{ km s}^{-1}$) and highly elevated abundances of oxygen, neon, carbon, magnesium, and sometimes other elements. The observations are consistent with the origin of this material within the helium-burned layers of massive ($> 10 M_{\odot}$) progenitor stars. Cas A in our Galaxy is

the prototype of this class (e.g., Chevalier & Kirshner 1979), and other members include the Galactic objects G292.2+1.8 (Goss et al. 1979) and Puppis A (or a portion of it; Winkler & Kirshner 1985), N132D (Lasker 1978, 1980) and SN 0540–69.3 (Kirshner et al. 1989) in the LMC, 1E 0102.2–7219 (Dopita & Tuohy 1984) in the SMC, and an unresolved object in the galaxy NGC 4449 (Balick & Heckman 1978; Kirshner & Blair 1980; Blair, Kirshner, & Winkler 1983). The remnant of SN 1957d in M83 was also considered a member of this class (Long, Blair, & Krzeminski 1989), but the temporal variability displayed by this object (Long, Winkler, & Blair 1992) makes it more likely that the observed broad oxygen lines had more to do with the late stages of the fading supernova than with the supernova remnant per se.

Even within this small group, the characteristics of the objects vary considerably, and their accessibility to investigation at various wavelengths across the electromagnetic

¹ Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

spectrum is a strong function of foreground extinction. The Galactic objects are all heavily reddened, precluding observations in the ultraviolet. Also, the Puppis A SNR appears to be considerably more evolved than the other members of the class and hence hard to compare directly. The objects in galaxies outside the Local Group are unresolved and possibly contaminated by circumstellar material. The Magellanic Cloud objects thus become the best ones for combined UV/optical investigation. Of the three candidate objects, SN 0540–69.3 is unique in that it has characteristics of both O-rich and Crab Nebula-like classes (but with an outer shell that the Crab does not obviously have). However, UV observations of SN 0540 to date have not met with success. Thus, the two objects N132D in the LMC and 1E 0102.2–7219 in the SMC (hereafter E0102), which were both detected with *IUE* (Blair et al. 1989; Blair, Raymond, & Long 1994), are the best objects for a UV/optical study. These SNRs also offer the opportunity to improve our understanding of the dynamics of supernova explosions and mixing in the ejecta (e.g., Arnett, Fryxell, & Müller 1989). The ejecta in these objects reflect nucleosynthesis in a low-metallicity regime of initial abundances, which may also find application to studies of high-*z* galaxies.

The combination of spatial resolution and UV/optical sensitivity of the *Hubble Space Telescope* (*HST*) offers a tremendous advantage for studying these objects. The high spatial resolution allows us to remove the extensive stellar contamination and confusion (especially in N132D) and study the fine-scale structure of the debris, isolating stellar ejecta from shocked circumstellar or interstellar material. UV/optical spectrophotometry of individual knots is needed to determine the excitation mechanisms operating in young SNRs, which in turn allows us to determine reliable elemental abundances. The UV spectroscopy is crucial because it provides access to additional ionization stages of O and Ne that help to discriminate between collisional ionization and photoionization models. The UV also provides abundance information for C, Mg, and Si that cannot be obtained from optical spectra alone (e.g., Blair et al. 1989, 1994).

In Paper I of this series (Morse et al. 1996), we reported the results of *HST* WFPC2 imagery of N132D. In this work, we expand on the results of Paper I by presenting [O III] $\lambda 5007$ WFPC2 imagery of E0102 in the SMC and UV/optical *HST* Faint Object Spectrograph (FOS) spectroscopy of ejecta knots in both N132D and E0102. In addition, we present UV/optical data for a shocked interstellar cloud on the outermost rim of N132D, which provides the most complete and self-consistent observational data set to date for comparison to shock models. During our analysis, we adopt a distance to the LMC and N132D of 50 kpc (e.g., Panagia et al. 1991; Bertelli et al. 1993) and a distance to the SMC and E0102 of 59 kpc (e.g., Laney & Stobie 1994; Cole 1998). The corresponding spatial scales are $1'' \approx 7.5 \times 10^{17}$ cm (LMC) and $\approx 8.9 \times 10^{17}$ cm (SMC).

2. OBSERVATIONS AND DATA REDUCTION

2.1. E0102 Imaging

In Paper I we presented Wide Field and Planetary Camera 2 (WFPC2) imagery of N132D in the light of [S II] $\lambda 6724$, [O II] $\lambda 3727$, [O III] $\lambda 5007$, and a continuum band (F547M filter). Since no fast-moving [S II] ejecta have been identified in N132D (Lasker & Golimowski 1991), the [S II]

image provided the best means for identifying shocked interstellar (or circumstellar) material and distinguishing it from the O-rich ejecta. Perhaps because it is considerably younger than N132D, E0102 requires no such diagnostic; the optically emitting material is dominated by the O-rich debris from the massive progenitor.

We have used the WFPC2 with F502N (which passes [O III] $\lambda 5007$) and F547M (continuum) filters to obtain images of the region including E0102. The angular size of the optical emission in E0102 (about $30''$ or ~ 8 pc) allowed us to center the object on the PC1 chip of the camera. The observations were obtained on 1995 April 7. The coordinates centered on PC1 were R.A. (J2000) = $01^{\text{h}}04^{\text{m}}01^{\text{s}}.4$, decl. (J2000) = $-72^{\circ}01'54''$. We obtained a sequence of five 1400 s exposures in F502N and two 500 s exposures in F547M. The data were reduced using the techniques described in Heathcote et al. (1996) and in Paper I. Using IRAF² tasks, the pipeline-calibrated exposures with each filter were carefully checked for alignment and combined to reject cosmic rays as described in Paper I. The F547M “continuum” file revealed very little stellar confusion with the SNR knots, so it was not necessary to subtract it from the [O III] (F502N) emission-line image. The [O III] image is shown in Figure 1, where the entire mosaic of WFPC2 chips (created using the STSDAS³ task WMOSAIC) is displayed. The top panel of Figure 2 shows a close-up of the line-emitting filaments from the SNR.

By comparing the F502N and F547M images of E0102, we are confident that even the faintest emission knots in the emission-line image are real. However, as with N132D, the relative intensities of some of the knots and filaments are affected by the finite F502N filter bandpass owing to the high velocity of the expanding ejecta. Ground-based Fabry-Perot data in the light of [O III] $\lambda 5007$ provide some insight into this situation, although not at the spatial scale of the *HST* data. This comparison was important in selecting the position for FOS spectroscopy, described below.

The *HST* image of E0102 bears a striking resemblance to optical ground-based pictures of Cas A (cf. van den Bergh & Kamper 1985 and references therein). A chaotic partial ring of knotty filaments is observed, with perhaps an indication of a broken extended structure on the southwest side that might mimic the so-called jet in Cas A (cf. Fesen & Gunderson 1996). At first glance, it appears that the general morphology seen in Cas A (age ~ 320 yr; diameter ~ 2.8 pc for the bright ejecta, assuming a distance of 3.4 kpc) extends almost directly to E0102, which is ~ 3 times larger in size and older in dynamical age.

In Paper I, we showed how the soft X-ray shell observed with the *ROSAT* HRI (see Hughes 1994) that marks the blast wave in N132D fitted precisely inside the stationary shell of photoionized precursor gas and overlapped with many of the bright radiative filaments where denser clouds are being shocked. However, there appeared to be very little, if any, X-ray emission coming from the optically emitting O-rich ejecta in N132D. That the X-rays indicate where circumstellar/interstellar material is being shocked by the

² IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

³ The Space Telescope Science Data Analysis System (STSDAS) is distributed by the Space Telescope Science Institute.

FIG. 1.—*HST* WFPC2 [O III] $\lambda 5007$ (F502N) image of the O-rich remnant E0102 in the SMC. A faint point source near the center of the remnant at position (0, 0) lies at coordinates R.A. (J2000) = $1^{\text{h}}04^{\text{m}}01^{\text{s}}.4$, decl. (J2000) = $-72^{\circ}01'54''$. North is toward the top, and east is toward the left, as indicated in the lower right-hand corner. The panel shows the entire WFPC2 field of view, with E0102 centered in the PC1 camera. A partial shell of diffuse emission, first studied by Tuohy & Dopita (1983), is offset from the main ring of ejecta and probably represents a photoionized precursor.

blast wave in N132D is further borne out by the X-ray spectroscopic results (Hughes, Hayashi, & Koyama 1998; Hwang et al. 1993), which showed that the abundances in the hot outer rim are generally consistent with normal LMC ISM abundances.

The situation is quite different in E0102. The center panel of Figure 2 shows a *Chandra* ACIS-S calibration image (no grating in the optical path) with a live-time exposure of about 11 ks. The *Chandra* X-ray image has been aligned to the *HST* optical image with the IRAF task SREGISTER using the astrometry in the image headers. The *HST* and *Chandra* coordinates should be accurate to within $\sim 1''$. The bottom panel of Figure 2 overlays contours of the X-ray image on top of the WFPC2 image of E0102, showing a general correspondence between the bright optical filaments and the X-ray shell. The ACIS-S image captures primarily soft X-ray emission in the energy range 0.6–1.5 keV that includes several O and Ne emission lines (see Fig. 9). Some regions around the E0102 shell contain both bright optical and X-ray emission, but others, particularly in the

northern and western quadrants, contain considerable X-ray emission but little optical emission. A faint plateau of X-ray emission extends outward from the main X-ray/optical rim, nearly filling the optical emission-free gap between the compressed filaments and the diffuse outer halo (Fig. 1; see also Tuohy & Dopita 1983). Again, this situation is morphologically similar to that of Cas A. Furthermore, the abundances derived from the *ASCA* spectrum of E0102 (Hayashi et al. 1994) indicate that the X-ray emission is dominated by highly metal-rich plasma.

Comparing the 843 MHz radio map of E0102 by Amy & Ball (1993) with the optical and X-ray images indicates that the main shell of radio emission appears to align slightly *outside* the main X-ray and optical shells. Like the faint X-ray plateau, the radio emission falls within the inner part of the emission-free gap in the optical image between the compressed filaments and the diffuse halo (cf. Fig. 1). The outer boundary of the X-ray plateau is rather sharp and smooth, especially around the northern, eastern, and southern rims. We suggest that this boundary demarcates

FIG. 2.—*Top panel*: Close-up of the E0102 line-emitting ejecta, which appear very similar to Cas A in our Galaxy. The filament observed with the FOS is indicated near the center of the remnant. *Center panel*: Gray scale of the soft X-ray emission observed with the *Chandra* ACIS-S. *Lower panel*: Duplication of the optical image and with overlaid contours of the X-ray emission. The X-rays largely coincide with the optical shell, though the northern and western regions contain significant X-rays with little optical emission. As with Fig. 1, position (0, 0) is at coordinates R.A. (J2000) = $1^{\text{h}}04^{\text{m}}01^{\text{s}}.4$, decl. (J2000) = $-72^{\circ}01'54''$ in both the optical and X-ray images.

the main SNR blast wave expanding outward into the interstellar/circumstellar medium. The bright inner X-ray boundary that interfaces or overlaps with the compressed optical SNR filaments is far more knotty and chaotic in appearance, like the optical filaments, perhaps indicating Rayleigh-Taylor instabilities at the reverse shock and contact discontinuity.

Hughes (1994) detected excess soft X-ray emission at the center of E0102 in a *ROSAT* HRI image. The X-ray emission distribution in the *Chandra* ACIS-S image in Figure 2 shows that these X-rays emanate primarily from a knotty filament extending from the outer southwestern rim to the center of the shell. In fact, there are several other very faint X-ray filaments extending from the shell to the center with a quasi periodicity of $\sim 20^\circ$, like spokes on a wheel. Alternatively, these features may represent ringlike structures on the surface of the expanding shell; such features have been identified in the optical velocity data cubes of Cas A (e.g., Reed et al. 1995; Lawrence et al. 1995).

Amy & Ball (1993) suggested the presence of a plerion source at the center of the radio ring in E0102 where they detected excess radio emission. The X-ray peaks in the center of the SNR shell are in close proximity to several faint point sources in the WFPC2 F502N and F547M images. One of these point sources may be a candidate compact remnant of the SN explosion. However, no point sources coincide with the brightest X-ray peak in the center at R.A. (J2000) = $1^{\text{h}}04^{\text{m}}02^{\text{s}}.2$, decl. (J2000) = $-72^{\circ}01'56''$.

Finally, we note the serendipitous observation of several background galaxies in the F547M continuum image toward E0102. The brightest examples include two early-type galaxies near R.A. (J2000) = $1^{\text{h}}04^{\text{m}}01^{\text{s}}.7$, decl. (J2000) = $-72^{\circ}01'14''$, and two face-on spirals at R.A. (J2000) = $1^{\text{h}}03^{\text{m}}56^{\text{s}}.4$, decl. (J2000) = $-72^{\circ}01'25''$ and R.A. (J2000) = $1^{\text{h}}04^{\text{m}}19^{\text{s}}.9$, decl. (J2000) = $-72^{\circ}02'29''$. The galaxies may prove useful as background light sources for absorption-line investigations of the ISM in the vicinity of E0102 or possibly as astrometric tie points in future SMC proper-motion studies.

2.2. N132D and E0102 Spectroscopy

The narrowband imagery of N132D reported in Paper I and of E0102 (described above) was used in conjunction with ground-based data to select target filaments for UV/optical spectroscopy with the FOS and to measure accurate positions relative to offset stars. Selection criteria included filament brightness,⁴ relatively “clean” velocity structure (as judged from Fabry-Perot data; cf. Morse, Winkler, & Kirshner 1995 for N132D, unpublished data for E0102), and, in the case of N132D, the desire to sample both shocked “interstellar” and “ejecta” material. In E0102 we selected a bright, centrally located filament, as indicated in the top panel of Figure 2. For N132D, where time was granted for observations of three positions, we selected one bright interstellar knot on the western limb (hereafter position 1), and two bright knots in the O-rich ejecta (hereafter positions 2 and 3). Figure 3 shows a portion of the F502N ([O III]) exposure of N132D from Paper I with the three selected knots indicated. The knot in E0102 and at position 3 in N132D are not particularly impressive in the *HST*

⁴ Note that even with the considerable capabilities of *HST*, the need for photons was not a small concern, in order to keep integration times reasonable.

FIG. 3.—*HST* WFPC2 [O III] λ 5007 (F502N) image of N132D in the LMC. Some regions of the SNR along the northern and western rims could not be fitted into the WFPC2 field of view. The position (0,0) is at coordinates R.A. (J2000) = $5^{\text{h}}25^{\text{m}}01^{\text{s}}.4$, decl. (J2000) = $-69^{\circ}38'31''$, roughly the center of the outer X-ray shell. North is rotated 12.06 counterclockwise, as indicated in the upper right-hand corner. The three spectroscopic positions are marked. Position P1 samples emission from a radiative shocked ISM cloud on the western outer rim. Positions P2 and P3 capture emission from O-rich filaments designated R2 and B4, respectively, in Morse et al. (1995). (Figure adapted from Morse et al. 1996.)

images because the bulk of their emission was Doppler-shifted out of the filter bandpass. We deliberately selected ejecta knots with high Doppler velocities so that ejecta emission lines could be distinguished kinematically from stationary interstellar lines emitted by the surrounding H II regions and SNR precursors (e.g., see Paper I).

The FOS observations are summarized in Table 1. For N132D, the $1''.0$ circular aperture (post-COSTAR dimension $0''.86$ diameter) was used, which was sufficiently small to isolate the filaments of interest while being large enough to (1) minimize concerns about exact aperture placement and (2) maximize throughput. For E0102, we decided to use the $1''.0$ square aperture instead (about 20% more area assuming a filled aperture). Acquisitions were accomplished by performing a peak-up on a selected offset star for each

object and using a blind offset maneuver to place the filament of interest into the observing aperture. Positional accuracy should be better than $0''.15$ in each case. Observations were obtained throughout the UV/optical range, as indicated in Table 1. Most of the integration time was with the FUV grating FOS/BL-G160L. Although higher dispersion would have been desirable to study the kinematics of the UV lines and to separate doublets such as C IV $\lambda\lambda 1548, 1551$ and C III $\lambda\lambda 1907, 1909$, the increased efficiency of one grating setting for the entire FUV was deemed a better use of the available time. All positions were then observed with FOS/RD and the G270H, G400H, and G570H gratings. G780H was used only for E0102 and at the “ISM” position in N132D to cover additional diagnostic lines. (Ground-based observations indicated relatively low priority for

TABLE 1
HST/FOS OBSERVATIONS OF N132D AND E0102

Position ID and Date	Side and Disperser		Number of Data Sets	Total Integration Time (s)
N132D-P1 (ISM)				
1995 Aug 23	FOS/BL	G160L	4	6000
	FOS/RD	G270H	3	3400
	FOS/RD	G400H	1	1000
	FOS/RD	G570H	3	1400
	FOS/RD	G780H	1	1500
N132D-P2 (Central O-rich)				
1995 Aug 24	FOS/BL	G160L	5	7800
	FOS/RD	G270H	3	3400
	FOS/RD	G400H	1	1000
	FOS/RD	G570H	3	1510
N132D-P3 (Eastern O-rich)				
1995 Aug 26	FOS/BL	G160L	4	7100
	FOS/RD	G270H	3	3400
	FOS/RD	G400H	1	1000
	FOS/RD	G570H	3	1510
E0102 (O-rich)				
1996 Sep 26	FOS/BL	G160L	3	6627
	FOS/RD	G270H	1	1857
	FOS/RD	G400H	1	1875
	FOS/RD	G570H	1	1800
	FOS/RD	G780H	1	1821

G780H observations at the O-rich knot positions in N132D.)

Data manipulations were accomplished with the IRAF/STSDAS software package. The pipeline-processed data were read from the GO tapes and individual exposures were inspected. We wanted to combine the total flux-calibrated data from each grating into a single file for measurement,

with a correct error array associated, to permit χ^2 fitting of the emission lines (see below). This turned out to be less than straightforward, especially since the separate exposures were often of different length. J. Eisenhamer (1995, private communication) of STScI kindly modified an existing STSDAS task PCOMBINE to produce a task that would perform this step correctly, for which we are grateful.

FIG. 4a

FIG. 4b

FIG. 4c

FIG. 4d

FIG. 4.—(a) Overall UV/optical spectrum of N132D-P1, a shocked interstellar knot on the western limb of the SNR. Some of the strongest emission lines are identified, and details are shown in Fig. 5. (b) Same as (a), but for N132D-P2, the centrally located O-rich knot. Details are shown in Fig. 6. (c) Same as (a), but for N132D-P3, the northeastern O-rich knot. Details are shown in Fig. 7. (d) Same as (a), but for the E0102 position. Details are shown in Fig. 8.

FIG. 5a

FIG. 5b

FIG. 5c

FIG. 5d

FIG. 5e

FIG. 5.—Individual FOS grating spectra for N132D-P1: (a) G160L spectrum; (b) G270H spectrum; (c) G400H spectrum; (d) G570H spectrum; (e) G780H spectrum. Panels include enlargements where necessary to show detail, and most of the strong lines are marked. Refer to Table 2 for details.

The combined flux and error arrays were then attached to the wavelength array using the MKMULTISPEC task. Finally, we output ASCII vectors of wavelengths, fluxes, and associated errors for measurement and plotting (see below). To provide an overview of each data set, we used the IRAF task ONEDSPEC.COMBINE, which equalizes the dispersion, for showing the data on the correct relative scale. Figures 4a–4d show these overall spectra at each position with a few important lines marked for reference. All measurements were made on the unsmoothed data from

each individual grating. Figures 5a–5e, 6a–6d, 7a–7d, and 8a–8e show the individual reduced FOS spectra of the three N132D positions and the E0102 filament, respectively, enlarged when necessary to show the details in the data.

The emission-line intensities in the combined, reduced data sets have been measured with the χ^2 minimization routine SPECFIT (Kriss 1994), which is now implemented as a task within the STSDAS.CONTRIB.SPFITPKG package. This task permits one to fit a variety of assumed input formats to a data set and to adjust parameters in

FIG. 6a

FIG. 6b

FIG. 6c

FIG. 6d

FIG. 6.—Individual FOS grating spectra for N132D-P2: (a) G160L spectrum; (b) G270H spectrum; (c) G400H spectrum; (d) G570H spectrum. Panels include enlargements where necessary to show detail, and most of the strong lines are marked. Refer to Table 3 for details.

allowed ranges to produce the best fit. It also produces error estimates based on the statistical properties of the data. In most cases, important lines are not badly blended, and we have been able to make the simple assumption of Gaussian line profiles and a linear underlying component (to remove any contamination by scattered light). The ability to deblend line components has been used where necessary. In particular, for some of the strongest lines such as [O III] $\lambda 5007$ an additional kinematic component of emission is sometimes seen at a low level. The main advantage of this measuring technique is the quantitative nature of the results, which permit a better assessment of relative line intensities than available previously. The results of our measurements are presented in Tables 2, 3, 4, and 5 for N132D positions P1, P2, and P3, and the E0102 position, respectively.

3. ANALYSIS AND MODEL COMPARISON

The data discussed above are the first UV/optical spectroscopic data for a supernova remnant to have been obtained with the same instrument and the same size aperture in the same spatial position. All previous data sets, combining (for instance) *IUE* or *HUT* data with optical ground-based spectra, have suffered from the problem of different slit sizes or orientations and very different calibration scenarios for the UV and optical data. Since SNR emission filaments are rife with spatially variable character-

istics, especially on the spatial scale we can sample at the distance of the Magellanic Clouds, there has always been some concern about the accuracy of these comparisons. The current data set circumvents these problems and provides the cleanest examples of the characteristic UV/optical emission from SNR blast waves available to date. Furthermore, we have sampled two very different types of emission filaments in this way: the ISM cloud shock of N132D-P1, and the O-rich material sampled at the other positions. We discuss these spectra separately below.

3.1. N132D-P1: A Shocked Interstellar Cloud

The spectrum at N132D-P1, summarized in Figure 4a and shown in detail in Figures 5a–5e, is the best UV/optical data set ever obtained on a shocked interstellar cloud. Located on the western limb of N132D, this cloud represents a density enhancement in the outer shell where the primary blast wave is encountering the cavity wall (cf. Paper I). It is possible that this cloud and nearby knots may comprise part of a ring of presupernova mass loss, as suggested by Sutherland & Dopita (1995a, 1995b); however, the elemental abundances we derive below are consistent with interstellar values found in other parts of the LMC, rather than enhanced photospheric values from a progenitor stellar wind (as with the inner ring of SN 1987A).

In Table 6 we show the observed and dereddened line intensities for the stronger lines at this position, scaled rela-

FIG. 7a

FIG. 7b

FIG. 7c

FIG. 7d

FIG. 7.—Individual FOS grating spectra for N132D-P3: (a) G160L spectrum; (b) G270H spectrum; (c) G400H spectrum; (d) G570H spectrum. Panels include enlargements where necessary to show detail, and most of the strong lines are marked. Refer to Table 4 for details.

tive to $H\beta = 100$. We have applied the Fitzpatrick (1985) LMC “30 Doradus” extinction curve⁵ assuming $E(B-V) = 0.12$ and $R = 3.2$, which corrects the $H\alpha/H\beta$ ratio to a theoretical value of 3.0.

This spectrum shows the classical indications of shock heating: a broad range of ionization stages of several intermediate mass elements (e.g., O I to O IV, N I to N V, etc.); strong optical [S II] and [O I] emission relative to $H\alpha$ (although [S II] is somewhat lower than often seen in SNRs); a high [O III] electron temperature ($T \sim 43,000$ K using the formulation of Osterbrock 1989); and strong optical and UV lines of comparable intensity. The mean electron density over the sampled cloud is near the high-density limit of the [S II] doublet, at several thousand per cm^3 (with some uncertainty). The collisional de-excitation of $\lambda 6716$ at this position is largely responsible for the relatively low [S II] $\lambda\lambda 6724/H\alpha$ ratio observed compared with many SNRs. The S^+ emission arises in the compressed postshock flow behind the shock and implies a preshock cloud density of greater than 100 cm^{-3} . This value is in line with the observed high surface brightness of this filament (see Fig. 3) and the predictions from Paper I that the radi-

ative shocks in the outer shell should have preshock densities greater than 25 cm^{-3} . The higher density and shorter cooling time has allowed filaments such as this one to enter the radiative phase before the remainder of the shell.

We have experimented with a wide range of shock model calculations in order to account for the relative line intensities observed in N132D-P1. These models have been calculated using the shock code of Raymond (1979), including some updates to atomic rates and charge exchange reactions (Cox & Raymond 1985; Hartigan, Morse, & Raymond 1994), as well as the option of separate electron and ion temperatures. The code follows the gas as it is heated and ionized, then cools, recombines, and absorbs the ionizing photons produced in hotter parts of the flow. The model output includes fluxes for all major coolants in the ultraviolet, optical, and infrared of all the ionization states of the 13 most abundant elements. Shock velocities of order $\sim 200 \text{ km s}^{-1}$ are needed to generate the emission from high-ionization species such as O IV, N V, Ne IV, and Ne V. Such shocks produce sufficient high-energy photons in the postshock region to ionize the upstream gas before it enters the shock (Shull & McKee 1979; Hartigan, Raymond, & Hartmann 1987; Sutherland, Bicknell, & Dopita 1993). We therefore assumed complete preionization of H and 85% preionization of He to He^+ .

The elemental abundances were initially based on estimates such as those of Vancura et al. (1992) for the supernova remnant N49 and Russell & Dopita (1990) for H II regions and SNRs in the LMC and then iterated to values

⁵ N132D is located in the LMC bar $\sim 1^\circ$ from the core of 30 Dor. However, we point out that there are substantial differences between the 30 Dor and general LMC extinction curves. Hence, relative intrinsic UV-to-optical line intensities are uncertain at a level larger than just the statistical errors.

FIG. 8a

FIG. 8b

FIG. 8c

FIG. 8d

FIG. 8e

FIG. 8.—Individual FOS grating spectra for E0102: (a) G160L spectrum; (b) G270H spectrum; (c) G400H spectrum; (d) G570H spectrum; (e) G780H spectrum. Panels include enlargements where necessary to show detail, and most of the strong lines are marked. Refer to Table 5 for details.

that best match our observed spectrum (see below). These abundance sets are summarized in Table 7, where our adopted abundances are listed in the far right-hand column. The presence of many ionization states makes the abundances determined here fairly reliable, particularly for those elements, such as C, which are difficult to detect in optical H II region spectra. Some abundances, such as for Mg, Fe, and Ca, are uncertain because they are based on matching the flux of only one line in the spectrum. The hope is that by reproducing the general ionization state of the emitting region within the aperture using the many lines of O, Ne,

and C, the relative abundances of other species that have only one or two lines in the spectrum can be reliably determined. We did not consider the match to resonance lines of C and Ca when determining abundances (see below). But for Mg, the only line available is the resonance doublet Mg II $\lambda\lambda 2798, 2802$. By matching this feature, we are probably establishing a lower limit to the Mg abundance, as some emission is likely scattered out of our sight line to the shocked cloud. The Fe abundance we find is especially dubious because we consider the atomic rates in the code for Fe II and Fe III to be very uncertain.

TABLE 2
N132D-P1 OBSERVED EMISSION LINES

Ion	λ (Å)	$\lambda(\text{obs}) \pm \sigma$ (Å)	$F(\lambda) \pm \sigma^a$	$\text{FWHM} \pm \sigma$ (km s ⁻¹)
G160L				
N v	1240	1239.1 ± 6.1	198 ± 80	2977 ± 1565
O I _{ag}	1304	1305.5 ± 1.1	175 ± 58	1563 ± 875
C II	1335	1336.0 ± 2.9	76 ± 32	2038 ± 1000
O IV], Si IV	1400	1405.0 ± 1.2	527 ± 85	3578 ± 541
N IV]	1486	1489.0 ± 2.5	150 ± 64	2849 ± 1055
C IV	1549	1549.5 ± 0.6	940 ± 92	2622 ± 286
He II	1640	1642.2 ± 1.3	392 ± 68	3133 ± 786
O III]	1664	1666.3 ± 1.1	376 ± 62	2500 ± 514
N III]	1750	1753.5 ± 2.9	75 ± 36	2073 ± 979
Si III]	1885	1887.2 ± 2.6	281 ± 69	3036 ± 868
[C III]	1909	1909.3 ± 0.6	765 ± 78	2131 ± 236
C II]	2325	2329.6 ± 0.2	692 ± 24	1968 ± 71
[Ne IV] + Ly α _{2nd}	2430	2430.6 ± 0.3	408 ± 18	2060 ± 99
[O II]	2470	2474.4 ± 0.3	277 ± 14	1644 ± 93
G270H				
C III	2297	2301.0 ± 0.4	36 ± 7	618 ± 326
C II]	2325	2330.1 ± 0.1	777 ± 17	599 ± 13
Si II]	2334	2339.0 ± 0.2	67 ± 7	524 ± 65
Fe II	2343	2348.9 ± 0.4	40 ± 6	451 ± 121
[O III]	2382	2387.3 ± 0.2	61 ± 6	472 ± 71
?	2404	2409.4 ± 0.3	23 ± 4	400 ± 139
[Ne IV]	2425	2427.1 ± 0.1	200 ± 9	620 ± 29
[O II]	2470	2474.6 ± 0.1	410 ± 11	424 ± 10
Fe II	2586	2592.		
Fe II	2599	2604.6 ± 0.1	41 ± 4	332 ± 36
Fe II	2614	2617.0 ± 0.6	33 ± 6	946 ± 296
Fe II	2628	2633.5 ± 0.4	56 ± 6	828 ± 79
?	2660	2665.		
?	2675	2680.		
Mg II	2795	2800.7 ± 0.1	740 ± 12	335 ± 5
Mg II	2802	2807.9 ± 0.1	382 ± 9	334 ± 7
?	2830	2835.		
Mg I	2852	2858.		
[Ne V]	2972	2972.0 ± 0.7	16 ± 4	609 ± 172
He I	3188	3193.0 ± 0.3	30 ± 4	430 ± 85
He II	3203	3208.8 ± 0.4	22 ± 4	350 ± 88
G400H				
[Ne III], [NeV]	3342	3348.		
[Ne V]	3425	3431.0 ± 0.3	70 ± 10	651 ± 124
[O II]	3727	3732.8 ± 0.1	2330 ± 33	490 ± 6
H9	3770	3776.4 ± 0.4	15 ± 4	201 ± 89
H8	3797	3804.6 ± 0.4	30 ± 6	330 ± 53
H7	3835	3841.6 ± 0.2	48 ± 6	291 ± 55
[Ne III]	3869	3874.5 ± 0.1	376 ± 15	397 ± 14
H6	3889	3895.1 ± 0.1	170 ± 10	391 ± 26
Ca II	3934	3940.6 ± 0.1	110 ± 9	311 ± 28
[Ne III], He, Ca II	3970	3974.8 ± 0.1	317 ± 13	444 ± 16
He I	4026	4032.		
[S II]	4069	4075.1 ± 0.1	396 ± 15	356 ± 15
[S II]	4076	4083.2 ± 0.2	138 ± 10	321 ± 25
H δ	4101	4108.0 ± 0.1	212 ± 11	386 ± 20
[Fe II]	4245	4251.3 ± 0.3	41 ± 6	271 ± 36
[Fe II]	4287	4294.4 ± 0.4	29 ± 6	326 ± 91
H γ	4340	4347.4 ± 0.1	422 ± 16	358 ± 13
[O III]	4363	4369.0 ± 0.3	163 ± 10	423 ± 28
[Fe II]	4416	4422.6 ± 0.4	54 ± 7	407 ± 54
He I, [Fe II]	4471	4479.4 ± 0.5	47 ± 7	470 ± 84
Mg I]	4571	4578.4 ± 1.7	23 ± 8	625 ± 689
[Fe III]	4658	4665.8 ± 0.3	56 ± 7	300 ± 48
He II	4686	4693.6 ± 0.3	60 ± 8	248 ± 43

TABLE 2—Continued

Ion	λ (Å)	$\lambda(\text{obs}) \pm \sigma$ (Å)	$F(\lambda) \pm \sigma^a$	$\text{FWHM} \pm \sigma$ (km s ⁻¹)
G570H				
[Fe III]	4658	4667.1 ± 0.5	62 ± 8	659 ± 104
He II	4686	4693.6 ± 0.6	62 ± 9	587 ± 112
[Fe III]	4755	4762.6 ± 0.5	16 ± 4	262 ± 70
[Fe II], [Fe III]	4814	4822.7 ± 0.6	18 ± 5	325 ± 163
H β	4861	4868.7 ± 0.1	951 ± 24	473 ± 11
H β _{br}	4861	4876.7 ± 2.2	170 ± 16	3042 ± 371
[O III]	4959	4965.6 ± 0.1	638 ± 19	437 ± 12
[O III] _{br}	4959	4969.9 ± 2.7	97 ± 33	3206 ± 1124
[O III]	5007	5013.8 ± 0.1	2000 ± 39	411 ± 7
[O III] _{br}	5007	5020.0 ± 4.4	148 ± 42	2671 ± 534
[Fe II]	5158	5167.6 ± 0.2	104 ± 9	345 ± 31
[Fe II]	5262	5269.9 ± 0.4	36 ± 7	285 ± 57
[Fe II], [Fe III]	5272	5280.1 ± 0.6	53 ± 8	469 ± 74
[Fe XIV]	5303	5309.6 ± 1.6	28 ± 7	716 ± 169
[Fe II]	5334	5342.1 ± 0.7	28 ± 6	352 ± 79
[Fe II]	5376	5384.1 ± 1.0	12 ± 4	281 ± 91
He II, [Fe II]	5411	5420.2 ± 0.7	18 ± 5	276 ± 70
[Fe II]	5528	5535.6 ± 0.5	26 ± 6	267 ± 99
[F III]?	5721	5728.1 ± 1.8	21 ± 7	568 ± 185
[N II]	5755	5762.5 ± 1.7	12 ± 6	311 ± 106
He I	5876	5883.9 ± 0.4	122 ± 13	408 ± 43
[Cr III]?	5945	5949.2 ± 2.0	10 ± 6	297 ± 104
[O I]	6300	6309.3 ± 0.1	902 ± 31	317 ± 11
[O I]	6364	6373.1 ± 0.2	257 ± 18	331 ± 27
[N II]	6548	6557.0 ± 0.1	305 ± 21	328 ± 20
H α	6563	6571.8 ± 0.1	3230 ± 63	344 ± 6
[N II]	6583	6592.7 ± 0.1	858 ± 34	361 ± 15
He I	6678	6688.1 ± 2.1	10 ± 4	320 ± 120
[S II]	6716	6727.0 ± 0.2	383 ± 25	335 ± 23
[S II]	6731	6741.3 ± 0.1	788 ± 34	275 ± 11
G780H				
[O I]	6300	6313.9 ± 0.1	887 ± 23	453 ± 11
[O I]	6364	6377.3 ± 0.2	317 ± 15	466 ± 25
[N II]	6548	6562.8 ± 0.7	492 ± 54	528 ± 43
H α	6563	6575.2 ± 0.1	3250 ± 68	442 ± 9
[N II]	6583	6596.1 ± 0.1	897 ± 25	462 ± 13
[S II]	6716	6730.3 ± 0.2	510 ± 24	444 ± 26
[S II]	6731	6744.8 ± 0.1	846 ± 27	371 ± 13
He I	7065	7077.0 ± 1.4	69 ± 13	608 ± 87
[A III]	7135	7149.0 ± 1.3	103 ± 18	657 ± 155
[Fe II]	7155	7168.7 ± 0.4	184 ± 19	371 ± 52
[Fe II]	7172	7184.6 ± 0.8	49 ± 12	305 ± 125
[Ca II]	7291	7305.3 ± 0.3	313 ± 22	414 ± 33
[O II], [Ca II]	7325	7337.4 ± 0.2	1060 ± 37	598 ± 16
[Ni II]	7380	7393.6 ± 0.9	121 ± 18	484 ± 66
[Fe II]	7452	7465.7 ± 0.9	62 ± 14	278 ± 68
[Fe II]	7638	7649.9 ± 1.3	40 ± 16	250 ± 112
[A III]	7751	7766.0 ± 2.6	50 ± 22	430 ± 141
[Cr II]	8000	8017.9 ± 2.9	50 ± 29	362 ± 269

^a Fluxes expressed in units of 10⁻¹⁷ ergs cm⁻² s⁻¹.

We took $T_e/T_i = 0.4$ at the shock, as fairly weak electron heating is typical of shocks in the solar wind and has been inferred for the fast shock in SN 1006 (Raymond, Blair, & Long 1995; Laming et al. 1996). For the modest shock speeds here, Coulomb collisions are sufficiently rapid that the choice of electron-ion equilibration in the shock has little effect on the calculated spectrum. (However, this is not the case for the metal-rich shocks; see § 3.2.)

TABLE 3
N132D-P2 OBSERVED EMISSION LINES

Ion	λ (Å)	$\lambda(\text{obs}) \pm \sigma$ (Å)	$F(\lambda) \pm \sigma^a$	FWHM $\pm \sigma$ (km s ⁻¹)
G160L				
N v	1240	1245.	<300	2300
O I _{ag}	1304	1306.7 $\pm$ 1.1	242 $\pm$ 102	2209 $\pm$ 1834
C II	1335	1340.	<100	2300
O IV]-Si IV	1400	1408.0 $\pm$ 1.0	268 $\pm$ 49	3123 $\pm$ 478
N IV]	1486	1495.	<75	2300
C IV	1549	1560.0 $\pm$ 1.2	194 $\pm$ 41	2837 $\pm$ 788
He II	1640	1650.	<60	2300
O III]	1664	1672.2 $\pm$ 1.0	194 $\pm$ 30	2371 $\pm$ 397
N III]	1750	1760.	<50	2300
Si III]	1885	1894.	<50	2300
[C III]	1909	1917.	<50	2600
C II]	2325	2335.9 $\pm$ 1.4	39 $\pm$ 9	1923 $\pm$ 530
[Ne IV] + Ly α _{2nd}	2430	2433.9 $\pm$ 0.2	438 $\pm$ 11	2097 $\pm$ 56
[O II]	2470	2484.1 $\pm$ 1.5	106 $\pm$ 10	2437 $\pm$ 304
G270H				
C II]	2325	2337.0 $\pm$ 0.4	53 $\pm$ 6	914 $\pm$ 114
?	2396	2407.2 $\pm$ 0.9	16 $\pm$ 4	904 $\pm$ 222
[Ne IV]	2425	2436.7 $\pm$ 0.2	147 $\pm$ 8	742 $\pm$ 38
[O II]	2470	2484.0 $\pm$ 0.1	107 $\pm$ 5	586 $\pm$ 29
Fe II	2599	2614.	<10	650
Fe II	2630	2645.	<10	650
Mg II	2795	2811.0 $\pm$ 0.2	134 $\pm$ 7	636 $\pm$ 40
Mg II	2802	2818.5 $\pm$ 0.3	56 $\pm$ 6	525 $\pm$ 64
[Ne V]	2972	2988.	<10	650
G400H				
[Ne V]	3425	3443.0 $\pm$ 2.5	50 $\pm$ 17	951 $\pm$ 418
[O II]	3727	3746.6 $\pm$ 0.6	2570 $\pm$ 132	659 $\pm$ 23
[Ne III]	3869	3888.1 $\pm$ 0.9	175 $\pm$ 35	668 $\pm$ 126
Ca II	3934	3950.	<20	600
[Ne III], Ca II	3970	3989.8 $\pm$ 1.2	60 $\pm$ 25	708 $\pm$ 150
[S II]	4069	4090.	<20	600
[S II]	4076	4097.	<20	600
[O III]	4363	4387.0 $\pm$ 1.2	75 $\pm$ 12	500 $\pm$ 999
Mg I]	4571	4578.7 $\pm$ 0.0	< 20	600
G570H				
[Fe III]	4658	4670.	<10	715 $\pm$ 167
He II	4686	4690.	<10	600
H β	4861	4863.4 $\pm$ 1.0	31 $\pm$ 5	600
[O III] _{e1}	4959	4964.5 $\pm$ 1.6	19 $\pm$ 4	668 $\pm$ 223
[O III] _{e2}	4959	4986.6 $\pm$ 0.1	608 $\pm$ 13	637 $\pm$ 12
[O III] _{e1}	5007	5010.1 $\pm$ 0.9	47 $\pm$ 5	601 $\pm$ 125
[O III] _{e2}	5007	5034.8 $\pm$ 0.1	1750 $\pm$ 26	647 $\pm$ 8
[Fe Xrv]	5303	5302.4 $\pm$ 0.8	23 $\pm$ 4	573 $\pm$ 132
He I	5876	5884.	< 10	600
[O I]	6300	6334.2 $\pm$ 0.5	89 $\pm$ 9	536 $\pm$ 53
[O I]	6364	6394.2 $\pm$ 2.3	20 $\pm$ 7	752 $\pm$ 178
H α	6563	6565.4 $\pm$ 0.4	77 $\pm$ 8	314 $\pm$ 41
[N II]	6583	6584.	<15	600
[S II]	6716	6730.	<10	600
[S II]	6731	6745.	<10	600

^a Fluxes expressed in units of 10⁻¹⁷ ergs cm⁻² s⁻¹.

We calculated planar shocks of varying velocities to compare with N132D-P1. In general, we do not find a good match between single-velocity models and the observed spectrum. The fifth column of Table 6, for instance, shows results for a 180 km s⁻¹ reference model with preshock density of 200 cm⁻³. Many of the high-ionization UV lines

are relatively too strong in the model and many key line ratios, such as [O II] λ 3727/[O III] λ 44959 + 5007, [O III] λ 4363/ λ 5007, etc., are not well matched.

There are any number of complicating factors that could cause single-velocity models to fail. As discussed in Paper I, there is considerable ionizing radiation present in the region in addition to the ionizing radiation from the local shock itself. In addition, the high inferred density argues for a short cooling time and possibly a very recent encounter between the shock and cloud we observe. The observed region could thus involve some incomplete shocks (where the full cooling and recombination zones are not yet present) and possibly regions that represent thermally unstable cooling (e.g., Chevalier & Imamura 1982; Innes, Giddings, & Falle 1987; Gaetz, Edgar, & Chevalier 1988; Innes 1992). Some evidence for the former possibility may be present in the imagery in Paper I, where a leading edge or rim of [O III] emission appears to be resolved in the WFPC2 image of the P1 knot. Indeed, we find that the cooling time needs to be restricted in our shock calculations to a few hundred years in order to keep the models from overpredicting emission from low-ionization and neutral species, such as [O I], [S II], and C II]. It appears that, even with the 1" circular aperture used here, a range of conditions are being sampled.

To keep the analysis tractable and still provide a reasonably accurate approximation, we have used the technique described by Vancura et al. (1992) to fit the N132D-P1 spectrum. Vancura et al. (1992) introduced a power-law distribution of shock speeds to match combined *IUE*/optical spectra of N49, where the flux from each shock is weighted according to $(V_{\text{sh}}/100)^{-\alpha}$. The slowest shocks produce little UV emission and systematically produce the cooler, low-ionization lines, while faster shocks dominate the production of the hottest ions. While there is nothing particularly physical about adding the differing velocity shocks with a power-law combination technique, by changing the exponent one can assess the relative fractions of high- and low-velocity shocks contributing to a given spectrum. A relatively steep (positive value of α) power law emphasizes the emission produced by slower shocks, while a flat spectrum includes more emission from faster shocks. One difference in our method from that of Vancura et al. is that we assumed the ram pressure of the blast wave is constant over the spatial scales sampled in the aperture. Hence, we maintained $nV^2 = \text{constant}$ for each planar shock model in our grid, normalized such that $n = 200 \text{ cm}^{-3}$ at 180 km s⁻¹. Our choice of power-law index then should indicate the distribution of preshock densities within the aperture. We also used a constant magnetic parameter $B/(n^{1/2}) = 0.1 \mu\text{G cm}^{3/2}$ (weak B field) for each model. The preshock density and magnetic parameter were chosen such that we could approximately reproduce the observed [S II] λ 6716/ λ 6731 line ratio but not collisionally quench [O II] λ 3727, which is among the strongest lines in the UV/optical spectrum (see Fig. 4a) but has a relatively low critical density.

Models were calculated from 40 to 240 km s⁻¹ (with a corresponding preshock density range of 4050 to 112 cm⁻³) at 20 km s⁻¹ intervals. Models with shock velocities higher than 240 km s⁻¹ were only partially radiative and did not contribute substantially to the UV/optical line ratios. We then combined the models using the Vancura et al. (1992) technique, testing different power-law exponents until a rea-

TABLE 4
N132D-P3 OBSERVED EMISSION LINES

Ion	λ (Å)	$\lambda(\text{obs}) \pm \sigma$ (Å)	$F(\lambda) \pm \sigma^a$	$\text{FWHM} \pm \sigma$ (km s ⁻¹)
G160L				
N v	1240	1246.	<100	3000
O I _{ag}	1304	1309.9 ± 2.0	251 ± 54	3480 ± 1356
C II	1335	1343.	<65	3000
O IV]-Si IV	1400	1409.7 ± 2.0	353 ± 61	4502 ± 1250
N IV]	1486	1495.	<50	3000
C IV	1549	1559.3 ± 3.0	146 ± 39	3089 ± 1256
He II	1640	1645.	<50	3000
O III]	1664	1670.6 ± 1.3	287 ± 34	3455 ± 1202
N III]	1750	1754.1 ± 11.6	<50	3000
Si III]	1885	1889.0 ± 12.5	<50	3000
[C III]	1909	1912.3 ± 3.6	87 ± 24 ^b	3032 ± 1010
C II]	2325	2339.1 ± 1.4	32 ± 10	1867 ± 809
[Ne IV] + Ly α _{2nd}	2430	2433.9 ± 0.2	380 ± 9	2028 ± 49
[O II]	2470	2479.9 ± 0.5	101 ± 6	2111 ± 171
G270H				
C II] ^c	2325	2328.4 ± 0.9	41 ± 6	1426 ± 245
[Ne IV] _{e1}	2425	2422.1 ± 2.1	29 ± 15	697 ± 353
[Ne IV] _{e2}	2425	2429.0 ± 0.8	131 ± 17	883 ± 151
[O II] _{e1}	2470	2469.9 ± 1.4	28 ± 10	945 ± 232
[O II] _{e2}	2470	2477.0 ± 0.3	90 ± 10	620 ± 78
Fe II	2599	2602.	<10	700
Fe II	2630	2633.8	<10	700
Mg II _{e1}	2795	2791.7 ± 0.8	25 ± 5	816 ± 183
Mg II _{e1,e2}	2798	2802.4 ± 0.3	95 ± 7	2731 ± 190
Mg II _{e2}	2802	2810.5 ± 0.1	71 ± 5	393 ± 27
[Ne V]	2972	2971.6 ± 2.4	<10	700
He II	3203	3209.1 ± 23.1	<10	700
G400H				
[Ne V] ^c	3425	3432.4 ± 2.4	77 ± 27	1201 ± 623
[O II] _{e1}	3727	3723.1 ± 1.2	535 ± 116	788 ± 153
[O II] _{e2}	3727	3735.4 ± 0.3	2300 ± 149	686 ± 48
[Ne III] _{e1}	3869	3868.9 ± 4.1	81 ± 50	1034 ± 533
[Ne III] _{e2}	3869	3878.2 ± 0.8	100 ± 50	356 ± 178
[Ne III] _{e2} ^c	3970	3977.3 ± 0.6	38 ± 14	244 ± 117
[O III]	4363	4371.5 ± 1.5	63 ± 20	600 ± 141
He I, [Fe II]	4471	4478.	<20	500
Mg I]	4571	4579.	<30	500
G570H				
H β	4861	4867.4 ± 2.1	9 ± 4	539 ± 195
[O III] _{e0}	4959	4952.4 ± 0.4	59 ± 7	370 ± 42
[O III] _{e1}	4959	4963.3 ± 0.5	177 ± 23	509 ± 58
[O III] _{e2}	4959	4972.8 ± 0.2	394 ± 21	469 ± 26
[O III] _{e0}	5007	5000.9 ± 0.5	201 ± 21	496 ± 43
[O III] _{e1}	5007	5011.1 ± 0.3	441 ± 47	471 ± 43
[O III] _{e2}	5007	5020.6 ± 0.2	1190 ± 41	507 ± 18
[O I] _{e1}	6300	6301.4 ± 2.7	52 ± 16	808 ± 295
[O I] _{e2}	6300	6316.6 ± 0.8	58 ± 15	432 ± 97
[O I] _{e1}	6364	6362.9 ± 8.6	6 ± 13	564 ± 385
[O I] _{e2}	6364	6376.5 ± 4.9	24 ± 10	796 ± 322
H α	6563	6568.8 ± 1.4	47 ± 5	697 ± 114
[N II]	6583	6588.	<25	500
[S II]	6716	6722.	<15	500
[S II]	6731	6735.	<15	500

^a Fluxes expressed in units of 10⁻¹⁷ ergs cm⁻² s⁻¹.

^b Could be a blend of Si III] and [C III].

^c Fitted as a single feature.

TABLE 5
E0102 OBSERVED EMISSION LINES

Ion	λ (Å)	$\lambda(\text{obs}) \pm \sigma$ (Å)	$F(\lambda) \pm \sigma^a$ (km s ⁻¹)	FWHM $\pm \sigma$
G160L				
N v	1240	1240.	<100	3000
O I ^b	1304	1297.0 $\pm$ 2.1	1046 $\pm$ 50	4554 $\pm$ 1222
C II	1335	1335.	<50	3000
O I	1356	1358.0	222 $\pm$ 67	3121 $\pm$ 1280
O IV ^c	1400	1400.1 $\pm$ 3.3	371 $\pm$ 66	3508 $\pm$ 1245
N IV	1486	1486.	<65	3000
C IV	1549	1550.3 $\pm$ 3.3	344 $\pm$ 44	3089 $\pm$ 1275
He II	1640	1640.	<50	3000
O III	1664	1667.4 $\pm$ 2.3	166 $\pm$ 38	2503 $\pm$ 1146
N III	1750	1750.	<50	3000
[C III] ^d	1909	1914.4 $\pm$ 4.5	143 $\pm$ 24	3440 $\pm$ 1010
G270H				
C II ^e	2325	2323.9 $\pm$ 1.3	89 $\pm$ 5	2452 $\pm$ 446
[Ne IV] _{e1}	2425	2418.4 $\pm$ 2.1	152 $\pm$ 8	1116 $\pm$ 153
[Ne IV] _{e2}	2425	2429.6 $\pm$ 0.8	63 $\pm$ 10	795 $\pm$ 143
[O II] _{e1}	2470	2465.6 $\pm$ 1.4	52.0 $\pm$ 8	1450 $\pm$ 232
[O II] _{e2}	2470	2476.5 $\pm$ 0.3	45.7 $\pm$ 8	1280 $\pm$ 211
Fe II	2599	2599.	<10	1000
Mg II _{e1}	2795	2791.5 $\pm$ 0.3	116 $\pm$ 12	924 $\pm$ 195
Mg II _{e2,e1}	2798	2799.5 $\pm$ 0.3	26.9 $\pm$ 7	330 $\pm$ 90
Mg II _{e2}	2802	2808.4 $\pm$ 0.3	38.5 $\pm$ 9	944 $\pm$ 141
[Ne V]	2972	2972.	<10	1000
G400H				
[Ne V] ^e	3425	3432.4 $\pm$ 2.8	69 $\pm$ 12	1857 $\pm$ 314
[O II] _{e1}	3727	3721.2 $\pm$ 1.3	949 $\pm$ 88	1481 $\pm$ 210
[O II] _{e2}	3727	3725.0 $\pm$ 1.3	688 $\pm$ 107	922 $\pm$ 151
[Ne III] ^e	3869	3865.6 $\pm$ 4.1	179 $\pm$ 50	2325 $\pm$ 356
[Ne III] ^e	3970	3964.6 $\pm$ 3.6	52 $\pm$ 14	2592 $\pm$ 312
[O III]	4363	4358.4 $\pm$ 3.5	63 $\pm$ 18	2244 $\pm$ 235
Mg I	4571	4571.	<30	1000
G570H				
H β ^f	4861	4861.	<10	594
[O III] _{e1}	4959	4946.0 $\pm$ 1.6	198 $\pm$ 13	1140 $\pm$ 43
[O III] _{e2}	4959	4966.6 $\pm$ 1.6	138 $\pm$ 15	1140 $\pm$ 43
[O III] _{e1}	5007	4995.2 $\pm$ 1.4	602 $\pm$ 35	1140 $\pm$ 62
[O III] _{e2}	5007	5016.9 $\pm$ 1.4	328 $\pm$ 45	1140 $\pm$ 62
[O I]	6300	6287.2 $\pm$ 3.7	61 $\pm$ 20	1200 $\pm$ 195
[O I]	6364	6365.3 $\pm$ 7.7	20 $\pm$ 15	1200 $\pm$ 195
G570H				
H α	6563	6562.7 $\pm$ 1.2	51 $\pm$ 5	594 $\pm$ 89
[N II] ^g	6583	6592.7 $\pm$ 1.5	6.7:	605 $\pm$ 96
[S II] ^g	6716	6700.0 $\pm$ 2.1	7.6:	820 $\pm$ 115
[S II] ^g	6731	6747.5 $\pm$ 2.1	14.6:	820 $\pm$ 115
[O II] ^h	7320,30	7315.1 $\pm$ 8.6	68 $\pm$ 15	1790 $\pm$ 385
[Fe II] ⁱ	7638	7644.6 $\pm$ 4.2	72 $\pm$ 18	958 $\pm$ 134

^a Fluxes expressed in units of 10^{-17} ergs cm⁻² s⁻¹.

^b Line variable in time, attributed to airglow.

^c Could contain blended Si IV].

^d Could contain blended Si III].

^e Weak double-peaked feature fitted as a single Gaussian.

^f H β upper limit assumes same width observed for H α .

^g Not clear that these features are real; wavelengths not accurate for [N II] or [S II].

^h May also contain Ca II.

ⁱ ID of this feature uncertain. A stronger Fe II line at λ 7452 is not present.

sonable fit was achieved. Part of this process included, once the relative ratios such as O II:O III:O IV could be matched, varying the abundances and iterating. In all, we calculated 12 separate grids before reaching the results shown in Table 6. As discussed earlier, we truncated the shock models at an “age” of 250 yr ($\sim 1/10$ th the age of the SNR; e.g., see Morse et al. 1995) to prevent the flux in neutral species that radiate strongly in the coolest regions of the flow from becoming severely overpredicted.

In performing an exercise such as this, one has some flexibility in choosing what it is one tries to fit, and a number of considerations enter into the discussion. The lower velocity cutoff in the grid and the already somewhat arbitrary age cutoff imposed tell us that the neutral lines should not be used heavily in constraining the best fit; they are sensitive to too many parameters. Also, it has been known for years that many of the resonance lines such as C II λ 1335, C IV λ 1550, and others, can be adversely affected by line-of-sight column depth (i.e., resonance scattering), a problem that can be even worse for LMC sight lines where both Galactic and LMC ISM absorption can be significant. Hence, depending on the line-of-sight velocity structure and the velocity spreading in the shock itself, such lines are observed considerably weaker than predicted by shock models and again are not drivers for a good fit. Finally, one must be wary of line comparisons separated too far in wavelength due to uncertainties in the extinction correction applied (or at least loosen the tolerances for what is considered a reasonable fit).

We rely on certain key line ratios that are mostly free of these problems and that tell us something about the global physical properties sampled within the aperture at N132D-P1. The last column of Table 6 shows what we consider to be a reasonable match to the N132D-P1 spectrum, using the abundance set shown at right in Table 7. In this particular model, which used a power law with $\alpha = 1.0$, we were driven largely by the [O II] λ 3727/H β and [O III] λ 5007/H β ratios (and hence, the ratio of [O II] to [O III]), the [O III] λ 4363/ λ 5007 temperature-sensitive ratio, and the [S II] λ 6717/ λ 6731 density-sensitive ratio, all of which fit the observations as well or considerably better than the 180 km s⁻¹ single-velocity model.

We note, however, that all lines are not fitted accurately by the grid. The strengths of the resonance lines of N v, C II, C IV, and Ca II are overpredicted, pointing to the effects of resonance scattering. This is not surprising since the N132D-P1 knot lies at the periphery of the shocked outer shell, where motions are transverse to the line of sight and the mean wavelengths are not Doppler-shifted relative to the local ISM. A more troubling difference is the ratio of O III λ 1664/ λ 5007, which is a factor of 2 higher in the grid model than in the observation. This is indicative of the need for a lower temperature, or at least the admixture of a significant component at very low temperature. The prime suspect would be emission from a photoionized precursor. The spectra of these precursors have been modeled extensively by Sutherland et al. (1993) and Dopita & Sutherland (1996), though for different elemental abundances. In Paper I, we detected and modeled the photoionized precursor outside the main blast wave of N132D. The precursor is most prominent around the western and southern sections of the outer rim, including at the N132D-P1 position. The brightest (limb-brightened) precursor emission is excluded from the FOS aperture, which was deliberately centered on

TABLE 6
N132D-P1 REDDENING CORRECTION AND MODEL COMPARISON

Ion	λ	$F(\text{H}\beta = 100)$	$I(\text{H}\beta = 100)^a$	$I(180)^b$	$I(\text{grid})^c$
N v	1240	20.8	53.6	222.	60.5
C II	1335	8.0	18.9	115.	157.
O IV], Si IV	1400	55.4	116.	379. ^d	133. ^d
N IV]	1486	15.8	30.8	34.3	16.8
C IV	1549	98.8	182.	385.	232.
He II	1640	41.2	73.9	60.4	81.5
O III]	1664	39.5	69.8	220.	144.
N III]	1750	7.9	14.0	34.9	27.7
Si III]	1892	29.5	49.9	89.8	128.
C III]	1909	80.4	133.	169.	179.
C II]	2325	81.7	129.	117.	136.
Si II]	2335	6.9	10.9	11.8	10.6
[Ne IV]	2425	21.0	31.6	113.	35.3
[O II]	2470	43.1	62.7	71.5	93.5
Mg II ^e	2800	77.8	147.8	215.	150.
[Ne V]	3426	7.4	8.3	42.6	7.4
[O II]	3727	245.	275.	235.	282.
[Ne III]	3869	39.5	43.7	38.9	28.3
Ca II	3934	11.6	12.8	190.	113.
[S II] ^e	4072	41.6	61.1	69.5	58.7
[O III]	4363	17.1	18.0	31.1	21.2
[Fe III]	4658	5.9	6.1	4.2	6.4
H β	4861	100.	100.	100.	100.
[O III]	4959	67.1	66.5	96.0	68.9
[O III]	5007	210.	208.	288.0	207.
[N I]	5200	1.0	1.0	13.9	8.0
[N II]	5755	1.3	1.2	3.2	3.5
He I	5876	12.8	12.0	12.5	11.5
[O I]	6300	94.8	86.7	233.	153.
[O I]	6364	27.0	24.6	77.7	51.0
[N II]	6548	32.1	28.4	29.0	24.5
H α	6563	340.	300.	307.	313.
[N II]	6583	90.2	80.0	87.0	73.4
[S II]	6716	40.3	35.5	57.8	41.6
[S II]	6731	82.9	72.9	102.	75.7
[Ar III] ^f	7135	16.1	13.8	12.3	12.5
[Ca II]	7291	32.9	28.2	35.9	24.3
[O II], [Ca II]	7325	112.	95.7	95.5 ^g	125. ^g
$F, I(\text{H}\beta)^h$	4861	0.95	1.33	...	...

^a Reddening correction assumes $R_v = 3.2$ and $E(B - V) = 0.12$ with a Fitzpatrick 1985 30 Dor LMC extinction curve.

^b Single-velocity 180 km s⁻¹ planar shock including preionization; see text for details.

^c Summed velocity grid of planar shocks including preionization and $nV^2 = \text{constant}$; power law $\alpha = 1.0$; $V_{\min} = 40 \text{ km s}^{-1}$; $V_{\max} = 240 \text{ km s}^{-1}$. See text for details.

^d Model listing is for O IV] only.

^e Both lines of doublet combined.

^f Listings for data and model include both $\lambda 7135$ and $\lambda 7751$ flux.

^g Model flux does not include Ca II, which would add about 20%.

^h H β flux corresponding to 100, in units of $10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$.

the bright radiative knot. However, all positions within and interior to the X-ray shell contain some precursor emission along sight lines through the foreground and background precursor shell. Hence, some emission, particularly in the strongest optical lines, may originate from the precursor, rendering the UV lines somewhat weaker than the pure shock model predicts.

Some of the selected parameters could be played off against each other to change relative line intensities. A somewhat higher density, for instance, would provide a better match to the [S II] ratio, but the densities are already high enough in the scheme we have used to de-excite partially [O II] $\lambda 3727$. Hence, a higher density will decrease $\lambda 3727$ relative to other O II lines (some of which are already

too strong relative to $\lambda 3727$) and make the overall fit worse. We feel that the grid model shown in Table 6, while perhaps not unique, is nonetheless representative of N132D-P1. This shocked material appears to be a dense ISM cloudlet recently overrun by the SNR blast wave. The high preshock densities we used in our models are consistent with the high surface brightness and large electron densities observed in the HST data.

As mentioned above, our model grid implies a ram pressure at the N132D-P1 knot of $nV^2 \approx (200 \text{ cm}^{-3}) \times (180 \text{ km s}^{-1})^2 \approx 6.5 \times 10^6 \text{ km}^2 \text{ s}^{-2} \text{ cm}^{-3}$. This can be compared to the value found in Paper I for the X-ray rim about 30" south of the N132D-P1 position of $nV^2 \approx (3 \text{ cm}^{-3}) \times (800 \text{ km s}^{-1})^2 \approx 2 \times 10^6 \text{ km}^2 \text{ s}^{-2} \text{ cm}^{-3}$. While we advise caution in

TABLE 7
ABUNDANCE SET COMPARISONS IN TERMS OF $12 + \log N(X/H)$

Element	Cosmic ^a	Solar ^c	R&D LMC ^c	Vancura N49 ^d	Hughes N132D ^e	N132D-P1 ^f
H	12.00	12.00	12.00	12.00	12.00	12.00
He	10.93	...	10.96	11.13	...	10.93
C	8.52	8.62	(7.66)	8.14	...	7.75
N	7.96	7.94	7.07 (7.45)	7.47	...	7.30
O	8.82	8.84	8.37 (8.25)	8.54	8.17	8.45
Ne	7.92	7.99	7.68 (7.50)	7.84	7.55	7.64
Mg	7.42	...	...	6.88	7.06	6.75
Si	7.52	7.58	(7.48)	7.45	7.08	7.00
S	7.20	7.27	6.87 (6.62)	7.17	6.71	6.63
Ar	6.80	6.60	6.07 (6.59)	6.45	...	6.50
Ca	6.30	6.37	(6.05)	6.40	...	6.10
Fe	7.60	7.53	(7.22)	7.00	7.05	6.85

^a Allen 1973, p. 31 cosmic abundances.

^b Cameron 1982 solar abundances.

^c Russell & Dopita 1990, Table 8 Ave. H II values, and in parentheses Table 12 Ave. SNR values.

^d Vancura et al. 1992 LMC ISM abundances, derived from N49 model fits similar to this paper.

^e Average values derived from *ASCA* X-ray spectral data for N132D from Table 2 of Hughes et al. 1998.

^f LMC ISM abundances derived in this paper, from shock model fitting of N132D-P1 UV-visible spectral data.

making this comparison, our results from these independent analyses—one based on the UV/optical spectroscopy of a radiative shocked cloud, and one based on the X-ray luminosity of the blast wave shell—show roughly similar ram pressures over large scales around the blast wave rim.

Having varied abundances as well and looked at the results, we estimate an accuracy of ± 0.1 dex in our derived abundances. In particular, adjusting the abundances of key coolants, such as O, Ne, and C, outside of this range resulted in a noticeably poorer overall fit to the observed spectrum. It is interesting to note that within this uncertainty our abundances in Table 7 generally match the SNR-based values derived by Russell & Dopita (1990) using completely independent data. Our abundances also compare favorably with those reported in Hughes et al. (1998) based on *ASCA* spectral data of N132D, with the possible exception of O and Mg. For Mg, we discussed above how our abundance value is probably a lower limit since it is based on matching only the Mg II $\lambda 2800$ resonance lines; Hughes et al. derive a value 0.3 dex higher, consistent with our suspicions. For O, Hughes et al. derive an abundance that is about 0.3 dex lower than our value. Their abundance for O in N49 is also 0.13 dex below that derived by Vancura et al. (1992). It is not clear why a lower O abundance is being derived from the X-ray data, though the discrepancies are within a factor of less than 2.

Another significant difference we find in abundances compared with the Russell & Dopita work is for Si, where we obtain a considerably lower value. In this case, our value agrees fairly well with that obtained by Hughes et al. (1998). The Si abundance we derive was largely driven by the desire to fit the Si II] intercombination line at 2335 Å. However, even with our relatively low abundance, we overpredict Si III] $\lambda 1892$, and so an even lower abundance might produce a better fit. The shock speed indicated by the strong N V and [Ne V] emission is high enough that even refractory grains will be destroyed (Jones et al. 1994). However, given the relatively recent shock-cloud interaction, it is probable that grain destruction has not yet reached an advanced state in this particular cloud. We reiterate that the abundances of refractory elements such as

C, Si, and Mg derived here are likely to be lower limits to the true interstellar medium abundances of these elements.

Perhaps the most significant result from this analysis is that we see *no evidence* for peculiar or enhanced abundances from the material in the shocked circumstellar shell or cavity wall of N132D. In particular, the lines from [N I] through N V provide no evidence for an enhanced nitrogen abundance, as might be expected if the massive progenitor star had undergone significant presupernova mass loss of CNO processed material.

3.2. The O-rich Ejecta

In stark contrast to the ISM position above, the FOS spectra of the ejecta in N132D (Figs. 4b, 4c, 6a–6d, and 7a–7d) and E0102 (Figs. 4d and 8a–8e) show only lines of oxygen, neon, carbon, and magnesium. No lines from nitrogen, sulfur, or Si-group elements are seen. It is also clear from the line widths and centroids of the faint Balmer lines in some of the spectra that the hydrogen emission is not associated with the O-rich ejecta but comes from elsewhere along the line of sight. The observed knots represent essentially pure ejecta from the interior of the progenitor stars, as seen in Cas A in our Galaxy, still visible even though these remnants are some 3 (E0102) and 10 (N132D) times the age of Cas A. Unlike Cas A, however, no lines of sulfur or nitrogen are seen; Cas A's optical spectrum is dominated by oxygen and sulfur lines, and although neon has been seen in the infrared (Lagage et al. 1996), it appears to be much lower in abundance than in the objects we have observed. In addition, recent analysis of *Chandra* X-ray data of Cas A (Hughes et al. 2000) has shown the presence of Si-rich and Fe-rich ejecta from explosive O-burning and Si-burning, respectively. Hence, there are key differences between the two Magellanic Cloud objects and the prototype of the O-rich class.

In Table 8, we tabulate reddening-corrected line intensities for the FOS spectra of O-rich material in N132D and E0102. All line intensities are scaled relative to the sum of [O III] $\lambda\lambda 5007$ and 4959 equal to 100, with the conversion to absolute units provided at the bottom of the table. The correction for the N132D positions follows directly from

TABLE 8
 REDDENING-CORRECTED LINE INTENSITIES FOR O-RICH POSITIONS

Ion	λ	N132D-P2 $I([\text{O III}] = 100)^a$	N132D-P3 $I([\text{O III}] = 100)^a$	E0102 $I([\text{O III}] = 100)^b$
N V	1240	<31.2	<11.2	...
O I	1304	23.3	26.0	...
C II	1335	<9.3	<6.5	...
O IV], Si IV	1400	23.4	33.0	52.9
N IV]	1486	<6.1	<4.3	...
C IV	1549	15.0	12.1	44.3
He II	1640	<4.4	<3.9	...
O III]	1664	14.1	22.4	20.4
N III]	1750	<3.5	<3.8	...
Si III]	1885	<3.5	<3.7	...
[C III]	1909	<3.5	6.5	16.9
C II]	2325	3.5	2.9	9.9
[Ne IV]	2425	9.2	10.7	22.7
[O II]	2470	6.5	7.6	9.5
Fe II	2599	<0.5	<0.6	...
Mg II _{tot}	2800	10.0	10.8	17.3
[Ne V]	2972	<0.5	<0.5	...
[Ne V]	3425	2.4	4.0	6.1
[O II]	3727	122.	145.	145.
[Ne III]	3869	8.3	9.1	15.3
Ca II	3934	<0.9	<0.9	...
[Ne III]	3970	2.8	2.5	4.4
[S II] _{tot}	4070	<1.8	<1.8	...
[O III]	4363	3.4	3.0	5.2
Mg I]	4571	<0.9	<1.4	...
[Fe III]	4658	<0.4	<0.6	...
H β^c	4861	1.1	0.6	...
[O II] _{tot}	5000	100.	100.	100.
[O I] _{tot}	6300	4.3	5.8	6.0
H α^c	6563	3.2	1.9	3.6
[N II]	6583	<0.6	<1.0	<0.5
[S II] _{tot}	6725	<0.8	<1.2	<1.0
[O II]	7325	...	...	4.9
[Fe II]	7638	...	...	2.7
$I(\text{O III})^d$	5000	3.28E-14	3.06E-14	1.65E-14

^a Reddening correction assumes $R_v = 3.2$ and $E(B - V) = 0.12$ with a Fitzpatrick 1985 30 Dor LMC extinction curve.

^b Reddening correction assumes a combination $E(B - V) = 0.04$ (from SMC; using Prevot et al. 1984 extinction curve) and 0.04 (Galactic; Cardelli et al. 1989 curve).

^c We attribute the H α and H β emission to the stationary precursor and H II region gas along our sight lines to the ejecta knots. The Balmer emission is distinguished kinematically from the ejecta emission. Assuming the Balmer-emitting gas is in the vicinity of the SNR, the adjusted flux ratios provide a check on our extinction correction in N132D.

^d Intrinsic [O III] flux through the FOS aperture that corresponds to 100, in units of ergs $\text{cm}^{-2} \text{s}^{-1}$.

the ISM position observed in this object, assuming no significant differential extinction. For E0102, we follow the prescription of Blair et al. (1989), assuming $E(B - V) = 0.08$ and attributing half to foreground (Milky Way) extinction and half to the SMC. The SMC correction applied the Prevot et al. (1984) extinction curve, while we used the Cardelli, Clayton, & Mathis (1989) curve for the Galactic component.

A cursory comparison of Table 8 shows that there are similarities as well as systematic differences between the spectra of the two objects. The relative strengths of the oxygen lines of different ionization stages are quite similar between the two objects, indicating similar overall ionization. However, the carbon, neon, and magnesium lines in E0102 are considerably stronger compared with the oxygen lines than we see in N132D, while the two N132D positions are quite similar to each other. This points toward real

differences in the relative abundances between N132D and E0102. We investigate this further below using new shock model calculations.

The optical and UV spectra of O-rich SNRs have been modeled as shock waves (Itoh 1981, 1986; Dopita, Binnette, & Tuohy 1984; Borkowski & Shull 1990), as cool gas photoionized by the SNR X-rays (Blair et al. 1989, 1994), or as the combination of a shock wave and its photoionized precursor (Sutherland & Dopita 1995a, 1995b). The photoionized models predict low ratios of UV to optical emission lines, especially for N132D and have a hard time explaining the observed [O III] $\lambda 4363/\lambda 5007$ temperature-sensitive ratio. We therefore concentrate on shock models to address the observed line ratios.

Shock waves in highly metal-rich plasmas differ from shock waves in ordinary astrophysical plasmas in that the radiative cooling rate is enormous, at least at temperatures

low enough that oxygen and neon remain in ionization states below He-like (e.g., Sutherland & Dopita 1995b). The cooling rates are so large that even if the electrons are heated in the shock itself, they quickly drop to lower temperatures where electron cooling due to collisional excitation of ions balances the heating by Coulomb collisions with the ions. A second consequence of the high cooling rates is that recombination times are much longer than the radiative cooling times, so that the cooling gas can be much farther from ionization equilibrium than in normal abundance shocks. It is not clear how closely a Maxwellian electron distribution can be maintained, but for computational simplicity, we assume Maxwellian ion and electron distributions throughout our discussion below.

The outstanding problem with past shock models of O-rich plasmas has been that the electron temperature is fairly constant through much of the emitting region, and the ionization state established there does not have time to respond when the temperature finally drops. Thus a single shock tends to produce bright emission from one or two ionization states, while SNR knots show a range of ionization stages, for instance, O I through O IV. The observations presented here make it clear that this is a real effect and not just one due to spatial sampling of diverse regions within a given spectrograph aperture. We assert that even a knot observed at *HST* resolution contains a range of shock speeds. While this could be modeled as a bow shock (e.g., Hartigan et al. 1987), it is likely that dynamical instabilities shred the dense knot of ejecta, causing a range of shock velocities even within an individual knot. Therefore, we instead invoke a power-law distribution of shock speeds, as done above for N132D-P1 (see also Vancura et al. 1992). We can then select the exponent of the power-law distribution and the upper and lower shock velocity cutoffs to try to match the observed line intensities and ratios.

A second problem is the weakness of the O I recombination lines at 7774 Å and 1356 Å. Itoh (1988) showed that a shock model that produces the observed [O III] emission will produce strong O I recombination lines after the gas cools, recombines, and begins to absorb the ionizing photons produced upstream. He was forced to introduce an arbitrary cutoff to the photoionization zone to match the observed spectra. We believe that this cutoff can be attributed to a breakdown in the planar shock model over the timescale required for recombination. It could result from turbulent shredding of the cold gas, thermal evaporation, or expansion of the shocked gas to lower density as a result of magnetic forces. All of these possibilities are more complex than the scope of our current models. We therefore simply cut off the model calculations when the temperature drops below ~ 300 K. This leads to an underestimate of the [O I] and O I recombination lines from the photoionization zone. As we are primarily interested in determining the shock speeds and elemental abundances from the higher temperature part of the flow, the photoionization zone does not affect our interpretation.

The O-rich model computations were made with a revised version of the shock model code described in Raymond (1979) and Raymond & Cox (1985). The code follows an element of gas through the shock jump (using the standard jump conditions) and the subsequent cooling, including time-dependent ionization balance calculations and including photoionization. It follows the electron and ion temperatures separately, with Coulomb collisions trans-

ferring energy between them. The degree of electron heating in the shock front by plasma turbulence or other means is poorly understood, but it is expected that the electron temperature just behind the shock is some fraction (10%–50%) of the ion temperature (Cargill & Papadopoulos 1988; Scudder 1995; Raymond et al. 1995; Laming et al. 1996). In the models presented here, we have assumed an initial fraction $T_e/T_i = 0.4$. Other modifications to the shock code include a more sophisticated scheme for choosing the time steps for the integration and the inclusion of $O^{++} + O^0 \rightarrow 2O^+$ charge transfer (Fox & Victor 1981). These models are much like the models of Itoh (1988) and Dopita et al. (1984), except that we do not include the region of secondary temperature rise when photoionization heating becomes important (to avoid the overprediction of O I recombination radiation as described above) and we have varied the elemental abundances to match the *HST* spectra. Also, we do not include thermal conduction. Borkowski & Shull (1990) showed that thermal conduction is important in shocks in enriched gas if it is not suppressed by a magnetic field. If conduction is included, it transfers energy to cooler parts of the flow, tending to increase the emission of the lower ionization stages.

Grids of models for an assumed set of abundances, preshock densities, magnetic fields, and shock velocities were calculated and were then combined assuming differing power-law distributions, as described by Vancura et al. (1992). We then iterated the abundance set, as we did for N132D-P1 above. Separate grids were used to model ejecta positions in N132D and E0102. The N132D spectrum we modeled was for the main kinematic component at the P3 position (N132D-P3c2). The relative line ratios and ionization distribution of this component most resembled those shown in the E0102 spectrum, allowing us to restrict the scope of the modeling and to vary as few parameters as possible when comparing the N132D and E0102 abundances. Our model results for the N132D and E0102 ejecta spectra are shown in Table 9, where the derived logarithmic abundances used for each object are indicated in the table notes. We have been able to construct models that match the UV/optical spectra quite well except for the neutral oxygen, which is largely emitted beyond the point at which the models are truncated. While we cannot claim that the details are unique, the fact that we can match the ratios O II:O III:O IV and Ne III:Ne IV:Ne V with reasonable accuracy indicates that the temperature and ionization structure are matched well enough that the inferred elemental abundances are reliable. We are also able to match the temperature-sensitive [O III] line ratio with high precision using this technique.

The preshock densities used to model the N132D ejecta were normalized at $n = 1 \text{ cm}^{-3}$ at a shock velocity of 100 km s^{-1} . We held $nV^2 = \text{constant}$ throughout the grid and applied a magnetic parameter $B/n^{1/2} = 0.1 \mu\text{G cm}^{3/2}$. In order to reproduce the observed line ratios, we combined planar shock models with velocities ranging from $V_{\min} = 30 \text{ km s}^{-1}$ to $V_{\max} = 160 \text{ km s}^{-1}$ (corresponding to preshock density range of $11\text{--}0.4 \text{ cm}^{-3}$), using a power-law index of $\alpha = 0.4$. Varying the upper shock velocity cutoff by $\pm 20 \text{ km s}^{-1}$ or the power-law index by ± 0.1 resulted in similar though slightly inferior matches to the observed line ratios. In particular, if the upper shock velocity cutoff becomes too high, then too much emission is predicted from high-ionization species such as [Ne V] or [Ne IV]. The relatively

TABLE 9
COMPARISON OF O-RICH OBSERVATIONS TO MODELS

Ion	λ	N132D P3c2	Model N1 ^a	E0102 Obs	Model E1 ^b
[O I]	6300,64	0.048	0.00	0.06	0.001
O I	7774	0.00:	0.023	0.02:	0.025
[O II]	2470	0.081	0.078	0.095	0.109
[O II]	3727	1.63	1.665	1.44	1.443
[O II]	7325	0.07:	0.108	0.049	0.145
O III]	1664	0.31	0.355	0.20	0.338
[O III]	4363	0.057	0.056	0.052	0.053
[O III]	5007	1.00	1.00	1.00	1.00
O IV]	1400	0.46	0.513	0.53	0.432
[Ne III]	3869	0.070	0.063	0.15	0.121
[Ne IV]	2425	0.12	0.180	0.23	0.279
[Ne V]	3425	0.056	0.058	0.06	0.183
C II]	2325	0.041	0.035	0.10	0.080
[C III]	1909	0.09	0.116	0.17	0.220
C IV	1549	0.17	0.595	0.44	1.076
Mg II	2795	0.056	0.057	0.17	0.175

^a The preshock density $n = 1 \text{ cm}^{-3}$ at shock velocity $V_{\text{sh}} = 100 \text{ km s}^{-1}$; $nV_{\text{sh}}^2 = \text{constant}$; $B/n^{1/2} = 0.1$ (weak field). Abundances: H = 12.00, O = 16.00, Ne = 15.25, C = 14.50, Mg = 13.50. Model N1 uses a power-law index of 0.40 and includes flux ratios from planar models with shock velocities in the range $V_{\text{min}} = 30 \text{ km s}^{-1}$ to $V_{\text{max}} = 160 \text{ km s}^{-1}$.

^b The preshock density $n = 16 \text{ cm}^{-3}$ at shock velocity $V_{\text{sh}} = 100 \text{ km s}^{-1}$; $nV_{\text{sh}}^2 = \text{constant}$, $B/n^{1/2} = 4.0$. Abundances: H = 12.00, O = 16.00, Ne = 15.50, C = 14.80, Mg = 13.90. Model E1 uses a power law index of 0.50, for shock velocities between $V_{\text{min}} = 30 \text{ km s}^{-1}$ and $V_{\text{max}} = 500 \text{ km s}^{-1}$.

low shock velocity cutoff of 160 km s^{-1} is consistent with the observation of little or no X-ray emission from the N132D ejecta.

We used a slightly different approach in E0102. Figure 2 shows how the brightest X-ray emission generally coincides with the UV/optical filaments in E0102. Hence, in our modeling, we assumed constant ram pressure in the reverse shock between those shocks that produce the X-ray emission and those responsible for the UV/optical emission. Hughes (1994) estimated an average density of $n \approx 3\text{--}6 \text{ cm}^{-3}$ in the (postshock) X-ray-emitting material of E0102. Assuming a compression factor of $\sim 4\text{--}10$ in this material and that the X-rays in the main emission shell are generated by shocks with velocities of order 500 km s^{-1} , we then scaled the preshock densities for the slower, optically emitting shocks in our grid keeping $nV^2 = \text{constant}$. We adopted a normalization for the preshock density of $n = 16 \text{ cm}^{-3}$ at a shock velocity of 100 km s^{-1} . The total velocity range in the models was $30\text{--}500 \text{ km s}^{-1}$ with a corresponding preshock density range of $178\text{--}0.6 \text{ cm}^{-3}$. Using these preshock densities, the high compression in the postshock region resulted in de-excitation of [O II] $\lambda 3727$ well below the observed flux ratio relative to [O III] $\lambda 5007$. In order to match the observed ratios, we used a magnetic parameter $B/n^{1/2} = 4 \mu\text{G cm}^{3/2}$ to restrict the postshock compression. While this fairly high magnetic field strength may be plausible, similar results may be obtained with a lower preshock density and lower magnetic parameter. Nevertheless, our match to the observed E0102 line ratios is quite good and gives us confidence in both the technique and in our derived abundances.

As a check on our abundance estimates derived from modeling the UV/optical filaments, we compared our E0102 shock model spectrum to the available X-ray data for E0102. Figure 9 shows the match of our shock modeling to *ASCA* and *ROSAT* spectroscopic data. We used the same *ASCA* Solidstate Imaging Spectrometer (SIS) data

and response functions as those published by Hayashi et al. (1994). The *ROSAT* PSPC spectrum was extracted from an observation (sequence number rp500250) taken in 1993 October for a duration of 20,240 s (live-time-corrected). E0102 was slightly off-axis (4'5) in this pointing. The source spectrum was extracted from within a circular region with radius $70''$. Background was taken from an annular region

FIG. 9.—X-ray spectra for E0102 from the *ROSAT* PSPC and *ASCA* SIS. The PSPC data and corresponding model are the upper points and histogram that extend down to roughly 0.1 keV. The SIS data and model are the lower points and histogram that display sharp spectral features from highly ionized O, Ne, Mg, and Si, as indicated.

centered on the remnant with inner and outer radii of 100" and 200", respectively. A weak point source in the annulus was excluded from the background spectrum. Only data in PSPC channels 3 through 31, corresponding to photon energies 0.1–2 keV, were included. The minimum number of counts in any spectral channel after background subtraction was 33, so rebinning of the spectrum was not necessary.

The same abundances and distribution of shock velocities derived from the optical/UV study were used to generate the X-ray spectral model. The only free parameters in the X-ray fit were (1) the overall intensity scaling of the model to the data and (2) the column density of absorbing material along the line of sight to the remnant. The best-fit value we derive for the column is $N_H = 1 \times 10^{21}$ atoms cm^{-2} , which corresponds to $E(B-V) = 0.18$ using the empirical relationship between these quantities from Predehl & Schmidt (1995). The fit of the oxygen and neon lines is remarkably good considering that their abundances and ionization states were not adjustable parameters. Nevertheless, we note the following areas in which the model falls short in describing the X-ray spectral data: (1) the oxygen emission in the model spectrum is slightly enhanced, (2) neon is slightly underionized, (3) magnesium and silicon K-shell line emission are grossly underpredicted, and (4) the implied value of $E(B-V)$ from the derived column density of absorbing material is higher than was used to correct the UV/optical line ratios.

Minor modifications of order 10%–20%, well within our uncertainties, to the O and Ne abundances could produce a more precise match to the O and Ne X-ray emission. In addition, extending our planar shock models to higher shock velocities would increase the Ne ionization. Altering the range and combination of shock velocities included in the X-ray model could adjust the spectral energy distribution, which may lead to a better agreement in the extinction correction with the UV/optical data. [We note that the UV/optical extinction curve for the SMC may alter the relation between N_H and $E(B-V)$ derived in Predehl & Schmidt 1995.] The abundances of Si and Mg are essentially unconstrained by our UV/optical spectra. It may be possible in the future to obtain higher resolution, higher signal-to-noise ratio UV spectra that could distinguish

Si II], Si III], or Si IV emission in order to measure the Si abundance. However, there are no additional significant Mg features in the UV/optical range that could constrain the Mg abundance. Ultimately, the Mg abundance in these and similar objects will need to be estimated through fits to spectra obtained at other wavelengths, such as in the X-rays or IR. Below we use abundances for Si and Mg derived from a new fit to the *ASCA* X-ray spectrum in order to compare to models of nucleosynthesis yields. Nevertheless, the results of the comparison in Figure 9 clearly indicate that the O and Ne X-ray line emission, at least, from E0102 can be quantitatively described by a superposition of spatially unresolved shocks with a broad range of temperatures in the enriched SN ejecta. The result is that our *single* power-law combination shock model of E0102 accounts for most of the major emission features all the way from near-IR to X-ray wavelengths.

3.3. Abundance Estimates and Comparison to Nucleosynthesis Models

By making detailed studies of supernova remnants throughout the Galaxy and the Local Group, we can investigate the role that supernovae play in the structural and chemical evolution of galaxies. Galaxies become chemically enriched when supernovae inject the by-products of nucleosynthesis occurring in the cores of massive stars into the ISM. Core-collapse supernovae play a major role in enriching the ISM in young galaxies and the surrounding intergalactic medium with heavy elements. Thus, understanding nearby core-collapse supernovae, their abundance yields and energy output, leads to a better understanding of these important processes in the early universe.

The ultimate goal of this study has been to derive a set of abundances for the enriched ejecta of E0102 and N132D and to compare these abundances to those predicted by nucleosynthesis models to see if we can determine the stellar types and masses of the progenitor stars. The relative abundances we have determined for the ejecta in E0102 and N132D are summarized in Table 10. The values are derived from a combination of models for the *HST* FOS UV/optical and *ASCA* X-ray data as detailed below. Also listed in Table 10 are predicted abundance ratios from nucleo-

TABLE 10
DERIVED EJECTA ABUNDANCES AND COMPARISON TO NUCLEOSYNTHESIS MODELS

Object	$N(\text{O})/N(\text{C})$	$N(\text{O})/N(\text{Ne})$	$N(\text{O})/N(\text{Mg})$	$N(\text{O})/N(\text{Si})$
E0102	16	3.2	10–20:	45–50:
N132D	32	5.6	20–40:	90–100:
Nomoto et al. Models ^a :				
13 $M_\odot$	50	8.3	22	3.8
15 $M_\odot$	3.2	13	15	7.9
18 $M_\odot$	3.7	5.3	24	15
20 $M_\odot$	10	7.1	12	25
25 $M_\odot$	15	5.9	19	45
40 $M_\odot$	45	16	26	136
70 $M_\odot$	34	13	27	39
Woosley et al. Model ^b :				
60 WRA (60 $M_\odot$)	2.0	12	61	14

^a Relative abundance ratios derived from the mass yields of the explosive nucleosynthesis models in Nomoto et al. 1997. The masses identifying each model are main sequence stellar masses of the progenitor stars.

^b Relative abundance ratios derived from the mass yields of the explosive nucleosynthesis model 60 WRA (main-sequence stellar mass 60 $M_\odot$) listed in Table 4 of Woosley et al. 1993.

synthesis models by Nomoto et al. (1997) and Woosley, Langer, & Weaver (1993).

In E0102, we adopt the abundance ratios of O/Ne and O/C used in our shock models of the UV/optical FOS data. We then estimated relative abundances of O/Mg and O/Si based on new model fits to the *ASCA* spectrum of E0102. In the new X-ray spectral model fits, we have imposed a specific O/Ne abundance ratio of ~ 3 found from the UV/optical models. One model fit used the same temperature, ionization timescale, and column density derived in Hayashi et al. (1994). The other fit used new values of these parameters, and was optimized for fitting the Mg and Si emission features. The O/Mg and O/Si estimates in Table 10 show a range of values obtained from the two models. It is interesting to note that when the O/Ne abundance ratio is held fixed, the derived values of O/Mg and O/Si are relatively insensitive to variations in the other parameters of the model fits.

In N132D, we again adopt the abundance ratios of O/Ne and O/C used in our shock models of the UV/optical FOS data. Since it appears that the strengths of all the UV/optical emission lines from Ne, C, and Mg are decreased roughly uniformly relative to the O emission lines in N132D as compared to E0102, we then assumed constant relative abundances of Ne/Mg and Ne/Si as estimated above for E0102. As a result of this tenuous bootstrapping procedure, we regard our values for O/Mg and O/Si in the N132D ejecta as extremely tentative. Comparing the O/Mg values in Table 10 to the ones used in our shock models of N132D and E0102 suggests that our UV/optical abundance estimates based on matching just the Mg II $\lambda 2800$ resonance doublet are about an order of magnitude below their true values. We hope to hone all of our abundance measurements in future studies by folding together new spectroscopic data from *FUSE* and *Chandra* with the *HST* FOS data.

For completeness, we again note that our FOS UV/optical data and previous ground-based spectra (e.g., Lasker & Golimowski 1991) of ejecta emission in N132D and E0102 imply an absence of H, He, N, S, Ca, Ar, Ni, and Fe to a level of $\sim 10^{-2}$ to 10^{-3} relative to O in the radiative filaments.

Before making detailed comparisons to models of nucleosynthesis yields, we make a few general comments. We identify emission only from O, Ne, C, and Mg in the UV/optical spectra and observe the presence of Si in the X-ray spectrum of E0102. Essentially all explosive nucleosynthesis models estimating the abundance yields of supernovae from progenitors of various masses predict significant mass fractions of Si-group and Fe-group elements in the ejecta. The absence of these elements in the radiative ejecta of N132D and E0102 leads us to consider two scenarios: (1) the progenitors of these SNRs were of fairly low mass and did not complete substantial O-burning in the core prior to exploding as Type II supernovae; or (2) the progenitors were very massive O stars that underwent substantial mass loss of their outer layers, became W/O stars with extensive O-rich layers, and then exploded as Type Ib supernovae. In this latter case, our idea is that the explosion did not thoroughly mix the outer atmospheric layers with the deep inner core layers, and the reverse shock has not yet penetrated deeply enough into these interior layers to expose the Si-group and Fe-group elements. Although both E0102 and N132D are substantially older than Cas A, the penetration of the

reverse shock into the inner ejecta layers may be limited by the relatively lower density circumstellar media of the Magellanic Cloud SNRs. The medium around E0102 is particularly low density, given the observation of background galaxies in the vicinity. Still, it is difficult to imagine how the O-burning products remain hidden in the E0102 and N132D ejecta if these species are as abundant as typical nucleosynthesis models predict.

We first compare our derived ejecta abundances in N132D and E0102 to the explosive nucleosynthesis models of Nomoto et al. (1997). We chose these models as being representative of the state-of-art yields from core-collapse Type II supernovae models. If we confine our attention to the elements detected in the SNR ejecta, Table 10 shows fair agreement between the model predictions and the observations. E0102 appears well approximated by the $25 M_{\odot}$ model. Although we estimate 2 times more Ne in E0102 than predicted by this model, the abundance ratios of C, Mg, and Si relative to O are close to the predictions. For N132D, the best model match may be in the range $30\text{--}35 M_{\odot}$, unfortunately not specifically represented in the Nomoto et al. grid. Again, the $N(\text{O})/N(\text{Ne})$ ratio may be a bit lower than the models predict, but taking all the measured ratios together suggests a mass $\geq 25 M_{\odot}$. We note the sensitivity of the $N(\text{O})/N(\text{Si})$ ratio to progenitor mass and that our tentative estimates for both remnants suggest high-mass progenitors.

The comparison to the predicted explosive nucleosynthesis yields of the 60 WRA model listed in Table 4 of Woosley et al. (1993) is not particularly favorable. Not only are the relative abundance ratios listed in Table 10 in disagreement with the models, but, as with the Type II nucleosynthesis models by Nomoto et al., the model also predicts significant mass fractions of S, Ca, Ar, and Ni (as well as He) that are not observed in the ejecta. In fact, the most favorable overall comparison appears to be with the extensive oxygen-rich layer (between 2.7 and $7 M_{\odot}$ interior mass) in the atmosphere of the Woosley et al. 85 WRB *presupernova* model shown in their Figure 4f. This layer contains approximately the same relative abundance ratios as observed in the E0102 and N132D ejecta and is strongly dominated by the four species (O, C, Ne, Mg) observed in the radiative filaments. We therefore suggest the possibility that the emission from the O-rich filaments in N132D and E0102 may represent the reverse shocks propagating through the ejected layers of Wolf-Rayet (probably W/O) stars that have *not* been mixed with other, deeper layers that contain the heavier nucleosynthesis products.

Models of supernova explosions suggest convective motions and Rayleigh-Taylor instabilities may mix or overturn the ejected layers (e.g., Arnett et al. 1989; Burrows, Hayes, & Fryxell 1995). In Cas A, the optical spectra of the ejecta are generally dominated by O and S emission, suggesting that the O-rich and O-burning layers mixed during the explosion. In the X-ray band, Hughes et al. (2000) see direct evidence for overturning of the Fe-rich and Si-rich ejecta layers in Cas A. Evidence for fractionation of chemically distinct bullets in the ejecta of Cas A has been observed by Hurford & Fesen (1996). These authors have observed several ejecta knots that do not appear mixed, some being dominated by almost pure O emission, and others by S, Ca, and Ar emission but with little O emission. With all these effects observed in Cas A, it is curious that there is *no* evidence in E0102 and N132D for O-burning

products, since O-burning must have occurred on the way to the cores exhausting their nuclear fuel prior to the explosion.

4. SUMMARY

We have presented *HST* FOS UV/optical spectra of three emission knots in the young, oxygen-rich SNR N132D in the LMC and one position in the O-rich debris of E0102 in the SMC. Full UV/optical coverage with the same aperture and instrument combined with the spatial resolution provided by *HST* has resulted in data sets far superior to previously available spectra. We also present *HST* WFPC2 imagery of E0102 in the light of [O III] λ 5007 emission and compare this image to a recently obtained *Chandra* ACIS-S image. Our principal results include the following:

1. The WFPC2 [O III] λ 5007 image of E0102 bears a striking resemblance to ground-based emission-line images of Cas A. Numerous compact, intersecting filaments and knots form a shell of emission. Many of these filaments coincide with X-ray emission detected by the *Chandra* ACIS-S. However, there are also regions along the northern and western rims where the X-ray peaks fill in gaps in the optical emission. This distribution is consistent with the ejecta dominating both the UV/optical and X-ray emission from this object, unlike N132D.

2. Using a power-law technique for combining the emission predicted by grids of planar shock models, we are able to reproduce the flux ratios of most of the major emission lines in the UV/optical range in a shocked ISM cloud and the ejecta of both young SNRs.

3. Abundances we have derived in the shocked ISM cloud in N132D are consistent with those previously found for LMC supernova remnants by Russell & Dopita (1990)

and Vancura et al. (1992), as well as X-ray-based abundances for N132D by Hughes et al. (1998). In particular, we find no evidence for nitrogen enhancement that might occur if the radiative, shocked filaments were part of a ring of circumstellar debris from CNO-processed mass loss from the progenitor star.

4. The only elements we detect in the UV/optical spectra of the ejecta in N132D and E0102 are O, C, Ne, and Mg. By combining our data with the *ASCA* SIS spectrum of E0102, we also identify Si in the ejecta. The relative abundances we derive for these elements compare favorably with those predicted by the core-collapse explosive nucleosynthesis models of Nomoto et al. (1997) for progenitor masses in the range 25–35 $M_{\odot}$. However, there is no evidence for O-burning products in these remnants that are also predicted by the nucleosynthesis models. We suggest that the progenitors of N132D and E0102 were W/O stars with extensive O-rich mantles that may have exploded as Type Ib supernovae. The agreement between our ejecta abundances and the overall yield predicted in the Woosley et al. (1993) 60 $M_{\odot}$ He star model is not very good. However, we see distinct similarities with the extensive O-rich interior layers of very massive star models such as these, leading to the idea that we are seeing the reverse shock penetrating ejecta from these layers in N132D and E0102.

We thank J. Eisenhamer for assistance with STSDAS reductions. Support for this work was provided by NASA grants GO-5365.01-93A to the Johns Hopkins University, GO-5365.02-93A to the Space Telescope Science Institute, GO-06052.03-94A to the University of Colorado, and GO-06052.04-94A to Rutgers University.

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