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HST OBSERVATIONS OF OXYGEN-RICH SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS[1]

Jon A. Morse

Center for Astrophysics and Space Astronomy, University of Colorado, Campus Box 389, Boulder, CO 80309, USA; morsey@casa.colorado.edu

William P. Blair

Department of Physics and Astronomy, Johns Hopkins University, Charles and 34th Streets, Baltimore, MD 21218, USA; wpb@jhufos.pha.jhu.edu

and

John C. Raymond

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; raymond@cfa.harvard.edu

RESUMEN

Presentamos imágenes del *HST* y espectros ópticos UV de dos remanentes jóvenes de supernova en las Nubes de Magallanes N132D y E0102.2–7219. Hemos aislado nudos específicos y filamentos que contienen residuos rápidos de material nuclear procesado que está desprovisto de hidrógeno y que aparenta haber sido originado de los núcleos de las estrellas progenitoras. Identificamos solamentos los elementos O, Ne, C y Mg en los residuos de ambas remanentes. No encontramos evidencia de productos de la combustión de oxígeno tales como S, Ca, Ar, etc., los cuales son detectados en Cas A y se esperan de modelos de supernovas de Tipo II. Sugerimos que las estrellas progenitoras de N132D y E0102.2–7219 contienen grandes mantos, ricos en oxígeno (quizás estrellas W-R) y que pueden ser el producto de supernovas de Tipo Ib.

ABSTRACT

We present *HST* images and UV/optical spectra of two young supernova remnants in the Magellanic Clouds, N132D and E0102.2–7219. We isolate 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. We identify only the elements O, Ne, C, and Mg in the debris from both remnants. 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 E0102.2–7219 had large, oxygen-rich mantles (perhaps Wolf-Rayet stars), and may be the products of Type Ib supernovae.

Key words: **ISM: INDIVIDUAL (N132D, E0102.2–7219) — ISM: SUPERNOVA REMNANTS — ULTRAVIOLET: ISM**

1. INTRODUCTION

Young supernova remnants (SNRs) with uncontaminated ejecta expose stellar interiors to direct investigation and provide stringent observational tests for theories of stellar evolution, nucleosynthesis, and chemical enrichment of the interstellar medium. Several SNRs have been identified over the last 20 years with fast-moving ($V > 1000$ km s^{-1}) debris. Their highly elevated abundances of oxygen, neon, carbon, magnesium, and other elements, are consistent with their origin within the helium-burnt layers of massive ($> 10\ M_{\odot}$) progenitor stars. Cas A in our Galaxy is the prototype of this class, and other members include the Galactic

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objects G292+1.8 and Puppis A, N132D and SN0540–69.3 in the LMC, E0102.2–7219 in the SMC, and two unresolved objects in the more distant galaxies M83 and NGC 4449.

Observations with the *Hubble Space Telescope* (*HST*) are advancing our understanding of the structure, composition, and physical processes in O-rich SNRs by providing unprecedented spatial resolution and UV/optical spectrophotometry of the enriched debris. The high spatial resolution allows us to study the fine-scale structure of the debris and to isolate stellar ejecta from shocked circumstellar material. UV/optical spectrophotometry of individual knots is needed to determine the excitation mechanisms operating in young SNRs, which in turn allows us to measure 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. The UV also provides abundance information for C, Mg, and Si, that cannot be obtained from optical spectra (e.g., Blair et al. 1989; Blair, Raymond, & Long 1994).

The O-rich SNRs in the Magellanic Clouds are particularly valuable for study because they are the only objects near enough to show spatially resolved structure (uncontaminated ejecta are resolved from shocked interstellar clouds; Morse et al. 1996) while having low enough foreground extinction to be observable in the UV. 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, & Muller 1989). The ejecta reflect nucleosynthesis in a low-metallicity regime of initial abundances, applicable to high-z galaxies.

2. OBSERVATIONS

We have observed the O-rich remnants N132D in the LMC and E0102.2–7219 (hereafter E0102) in the SMC with *HST*. Emission-line images were obtained with the Wide Field and Planetary Camera 2 (WFPC2) and UV/optical spectra of knots of supernova ejecta were obtained with the Faint Object Spectrograph (FOS). The diameter of the X-ray outer shell of N132D subtends over 2 arcminutes ($\sim$ 24 pc, assuming a distance of 50 kpc), while the optically emitting filaments of enriched debris are distributed at the center of the shell over a diameter of about 1 arcminute ($\sim$ 12 pc). N132D was placed on the WF3 chip of WFPC2 so that most of the O-rich debris fell onto a single chip (in order to measure accurate offsets for the spectroscopy aperture positions). Subsequently, some of the outer regions of the remnant at the northern and eastern edges were excluded from the field of view. E0102 subtends a diameter of about 25 arcseconds ($\sim$ 7 pc, assuming a distance of 59 kpc) and was placed on the PC1 chip to obtain maximum resolution. Both SNRs were imaged through the F502N ([O III]λ5007) filter (see Figures 1 and 2). N132D was also imaged through the F375N ([O II]$\lambda\lambda$3727) and F673N ([S II]$\lambda\lambda$6724) filters. Due to the narrowness of the filter widths, some high-velocity debris were excluded from the images as their Doppler velocities shifted the emission outside the filter bandpasses. Knots labeled in Figs. 1 and 2 show the positions in each remnant where we obtained UV/optical spectroscopy with the FOS. In N132D, spectra were acquired in two filaments of O-rich debris and one shocked interstellar cloud (called "quasi-stationary flocculi" or QSF). In E0102, we obtained spectra at one position in the SN debris. The FOS gratings G160L, G270H, G400H, G570H, and G780H were used to cover the full UV/optical spectrum from $\sim 1200 - 7500$Å. An 0.86-arcsecond aperture was used in all the FOS observations.

Our WFPC2 data reduction and analysis techniques are described in Morse et al. (1996). We discuss the WFPC2 images of N132D in considerably more detail in that paper; here we concentrate more on the UV/optical spectra of the SN debris. We followed standard procedures for reducing the FOS spectra, extracting wavelength and flux calibrated spectra from the *HST* "pipeline" files. The reduced spectra (corrected for reddening) are shown in Figures 3 and 4. The spectra from the two SN debris filaments in N132D were very similar, so we shifted the spectra to a common velocity and co-added them to increase the signal-to-noise ratios. Important emission lines in the SN debris are identified in Figs. 3 and 4.

3. DISCUSSION

The WFPC2 images in Figs. 1 and 2 allow us to study the morphology and fine-scale structure of N132D and E0102 with a spatial resolution comparable to $\sim 1''$ ground-based images of Cas A. Indeed, the morphology of E0102 bears a striking resemblance to Cas A; there is even a suggestion that the radial filaments in the southwest corner of E0102 outline the walls of a jet-like outflow, similar to the northeast jet in Cas A (e.g., see Fesen & Gundersen 1996). The O-rich filaments show complicated internal structure, ranging from compact knots at the limit of our resolution to finger-like protrusions that appear to be "swept back" along the direction of expansion in some filaments. In E0102, there are a number of "swirls" of diffuse emission in addition to the compact filaments.

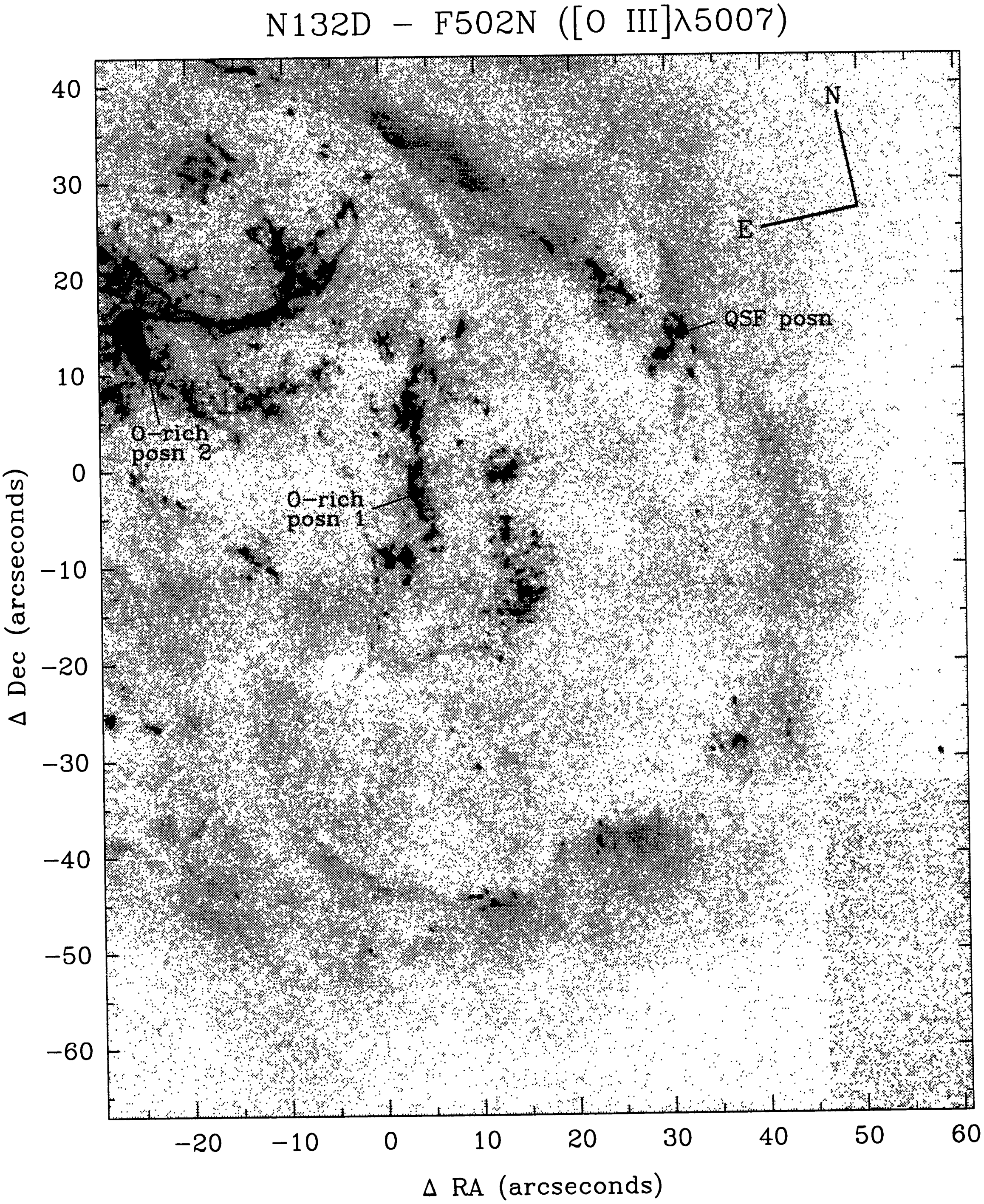

Fig. 1. WFPC2 image of N132D in [O III]λ5007. Roughly 10^4 stars have been subtracted from the image. The FOS aperture positions are marked: 2 positions in the O-rich ejecta and 1 position in a QSF knot. The large Doppler shifts of some O-rich filaments shifted the emission out of the filter bandpass (see Morse et al. 1996 for details). The position (0,0) is at coordinates 5:25:01.4, -69:38:31 (2000), roughly the center of the outer X-ray shell. The orientation is indicated in the upper right corner.

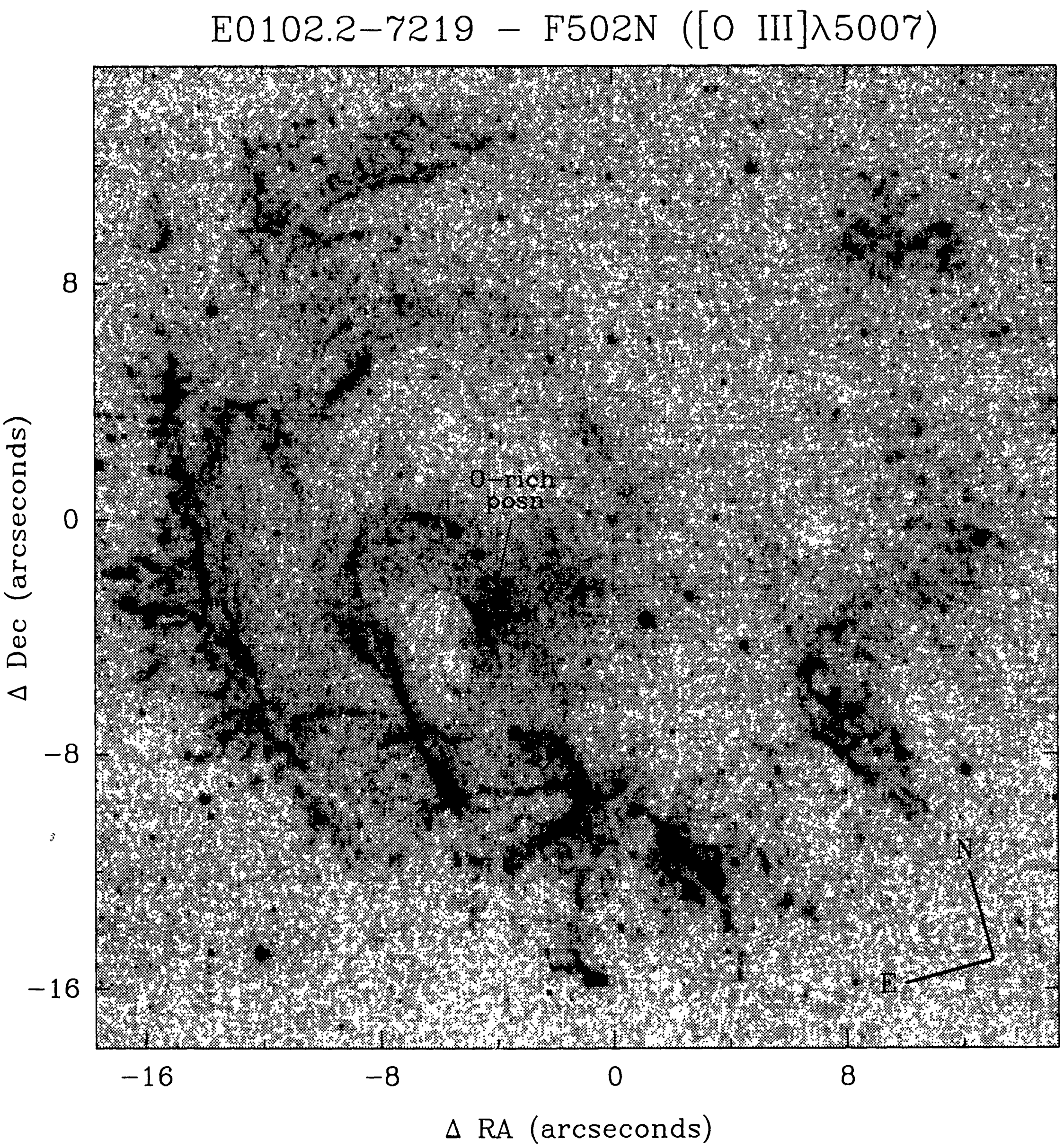

Fig. 2. WFPC2 image of E0102.2–7219 in [O III]λ5007. The position of the FOS aperture in the O-rich debris is marked. Due to the large velocity range in the ejecta, a substantial number of filaments in the center of the remnant are excluded from the filter bandpass. Overall, however, the morphology of this remnant bears a striking resemblance to Cas A. The position (0,0) is at coordinates 1:04:01.4, −72:01:54 (2000), and the orientation is indicated in the lower right corner.

When comparing the stucture and morphology of N132D and E0102 to each other and to other remnants, it is important to consider the evolutionary state of each remnant. The morphology and emission properties are expected to change as each SNR expands and interacts with its surroundings. The ages of N132D and E0102 have been estimated by assuming the O-rich debris have not been decelerated by interactions with the circumstellar environment. (Neither remnant has a synchrotron nebula that might accelerate the debris, as in the Crab.) By measuring the spatial extent of the O-rich debris, which appear to have roughly shell-like

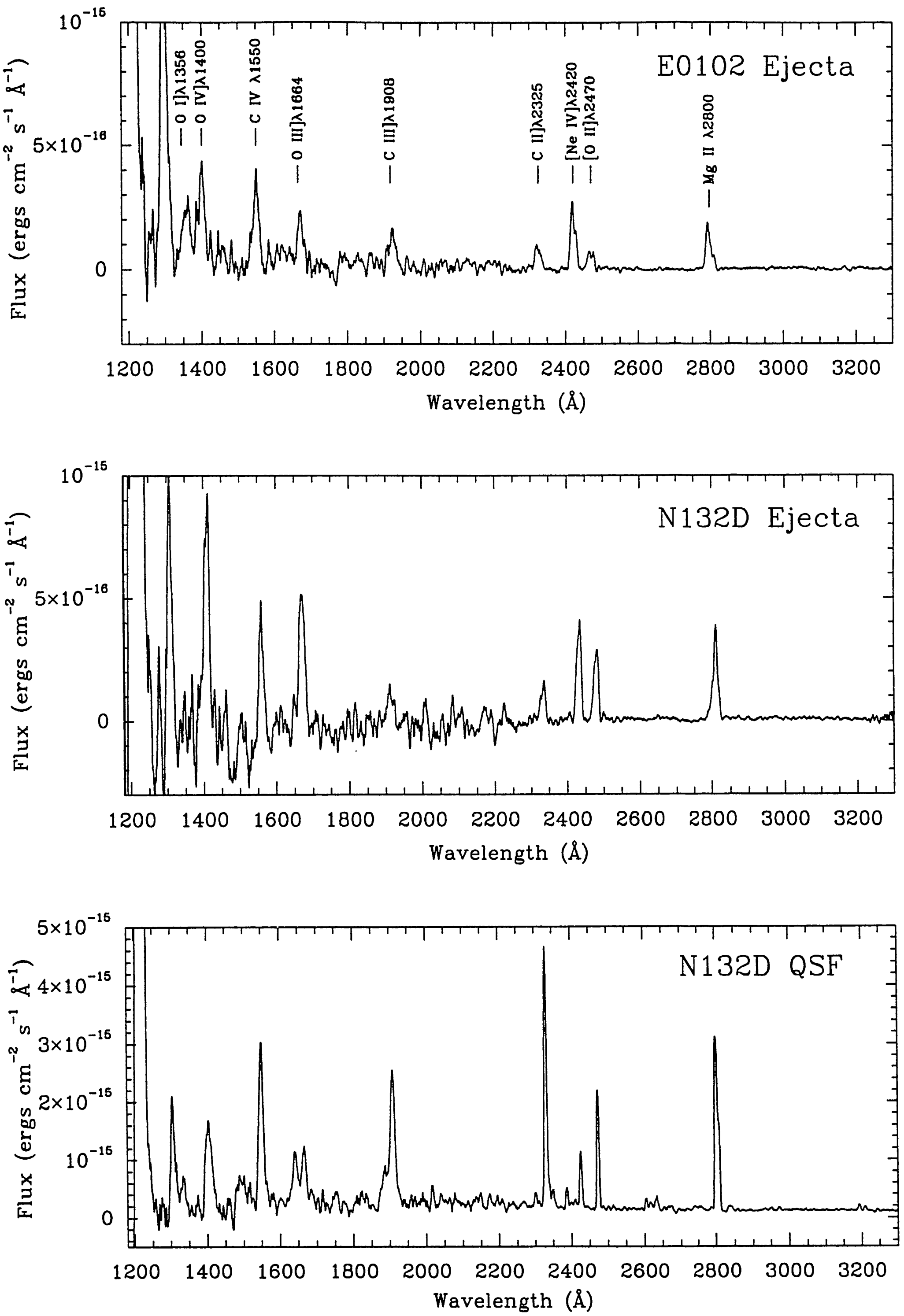

Fig. 3. UV spectra of N132D and E0102.2–7219 obtained with the FOS aboard *HST*. The aperture positions are marked in Figs. 1 and 2. For N132D, the two O-rich positions were shifted to a common velocity and co-added to increase the S/N. Major emission lines in the O-rich ejecta are labeled in the top panel. The spectra of the ejecta in E0102 and N132D are similar, but the QSF spectrum shows He II λ1640 and Si III]λ1885 emission, plus a number of lines near 2600Å, that are not present in the ejecta. The E0102 spectrum was corrected for extinction using $E(B-V)=0.1$, and the N132D spectra were corrected using $E(B-V)=0.2$.

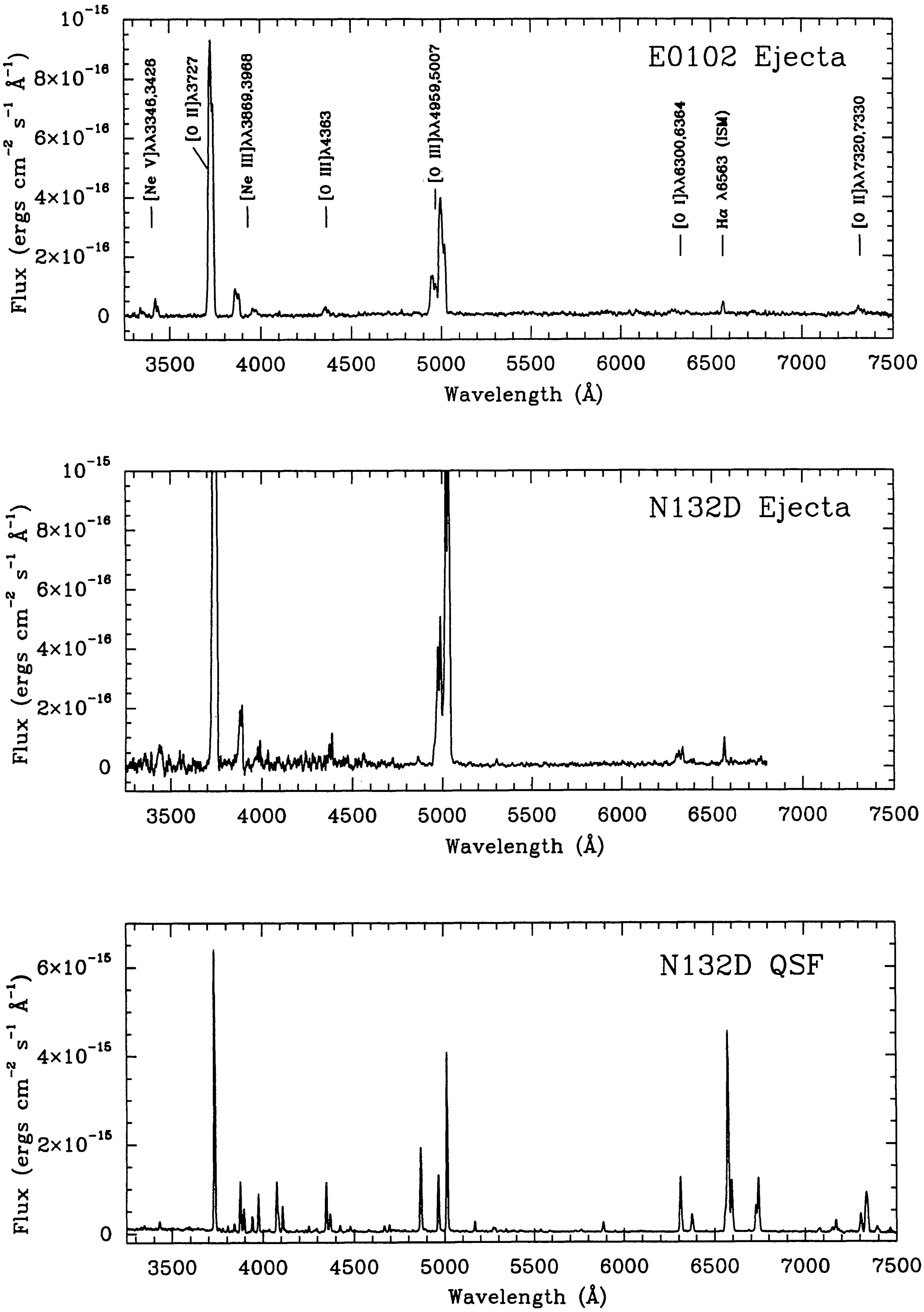

Fig. 4. Optical spectra of N132D and E0102.2–7219 obtained with the FOS aboard *HST*. See the caption to Fig. 3 for further notes. The spectrum of N132D stops at 6800Å because, due to time constraints, we did not use the G780H grating when observing the N132D ejecta. Foreground Hα emission is present in the ejecta spectra because the SNRs are surrounded by H II regions. The Hα emission lines in the ejecta spectra are narrow and lie at rest velocities, unlike the ejecta emission. The N132D QSF spectrum has numerous metal lines and a normal Balmer decrement.

distributions, and then determining the kinematics, the dynamical age estimates are $\sim 2500 - 3000$ yr for N132D (Sutherland & Dopita 1995a; Morse, Winkler, & Kirshner 1995) and $\sim$ 1000 yr for E0102 (Dopita & Tuohy 1983).

This factor of $\sim$ 3 difference in age has observational consequences. The N132D blast wave has had more time to expand and interact with its surroundings, and this is reflected in the large number of shocked, normal-abundance, moderate-velocity circumstellar clouds (QSFs) scattered across the remnant (see Morse et al. 1996). No QSFs have been identified in E0102 as yet; all of the optically emitting knots and filaments appear to be oxygen-rich ejecta. Additionally, in N132D there is a large offset ($\sim$ 6 pc in radius) between the outer X-ray shell and the inner ring of optically emitting O-rich filaments. The offset may signify a forward/reverse shock structure, with the separation growing in time as the reverse shock propagates back into the high-velocity SN debris. The X-ray spectrum of N132D contains strong oxygen emission, but the inferred abundances are not inconsistent with shocked ISM gas (Hwang et al. 1993). There appears to be little or no soft X-ray emission emanating from the optically emitting O-rich debris (Morse et al. 1996). On the other hand, the ASCA spectrum of E0102 shows emission lines from oxygen, neon, and magnesium (Hayashi et al. 1994), consistent with the line species identified in our UV/optical *HST* spectra discussed below. Overlaying the *HST* image of E0102 from Fig. 2 on the *ROSAT* HRI image of Hughes (1994) shows that the X-rays are spatially coincident with the shell of optically emitting filaments.

Our analysis of the *HST*/FOS spectra of N132D and E0102 shown in Figs. 3 and 4 is not complete, nor are our models for predicting the emission-line ratios from the O-rich debris. Ultimately, we would like to determine reliable relative abundances in the SN debris and compare these results with the predictions of models for nucleosynthesis yields from massive stars (e.g., Woosley, Langer, & Weaver 1995; Thielemann, Nomoto, & Hashimoto 1996) and mixing in the SN ejecta (e.g., Arnett et al. 1989). However, at this point we are able to draw several important conclusions from the data.

- 1. The UV/optical spectra of the enriched debris in N132D and E0102 are similar to each other, but are qualitatively different from spectra of knots in Cas A. The only elements identified in the N132D and E0102 spectra are oxygen, neon, carbon, and magnesium —i.e., He-burning and C-burning products. There is no evidence, either from our *HST* spectra or from ground-based observations (e.g., Lasker & Golimowski 1991), for O-burning or Si-burning products, such as sulfur, argon, calcium, nickel or iron, in the ejecta of N132D and E0102, but which *are* seen in Cas A and SN0540–69.3 in the LMC (Hurford & Fesen 1996; Kirshner et al. 1989). The composition of the SN debris in N132D and E0102 suggests the progenitor stars had large oxygen-rich mantles, perhaps WC/WO stars, and may be the products of Type Ib supernovae, e.g., as modelled by Woosley et al. (1993, 1995). It is interesting to note that the Wolf-Rayet nebula N76A lies adjacent to E0102.

- 2. Recent models of supernova explosions (e.g., Burrows, Hayes, & Fryxell 1995) predict strong convective mixing of the SN debris. Even if there were well-defined nucleosynthesis layers in the presupernova star, the ejecta are expected to be mixed by convective fingers during the SN explosion. In Cas A, most knots contain oxygen and the O-burning products sulfur, argon, and calcium. However, some knots are of almost pure oxygen, while others contain little oxygen and are dominated by Si-group metals. Hurford & Fesen (1996) have commented that the chemical fractionation of knots in the SN debris of Cas A suggests incomplete mixing during the supernova explosion and that knots representing distinct layers in the progenitor core may be preserved. In the debris of N132D and E0102, there are only four elemental species detected that, according to many models, would have originated in an outer extended mantle above a central Fe-rich or Ni-rich core. With *HST* spectra obtained at so few positions in these SNRs, we are not able to say whether there are abundance inhomogeneities among the four constituent species. However, we view it as unlikely that there may be substantial Si-group or heavier debris that have not been detected. One could argue that perhaps the lack of O-burning products is a result of the evolutionary state of the remnants —that the reverse shocks have not penetrated into the deepest ejected layers at the centers of the remnants. The level of mixing between distinct nucleosynthesis layers in Cas A (and SN0540–69.3), though not complete, suggests that if the O-burning products existed in N132D and E0102 in any significant abundance, we would see them. The factor of three difference in age between N132D and E0102 makes it difficult to hide the Si-group and heavier elements by invoking remnant evolution. E0102 is older than Cas A and comparable in age to SN0540–69.3, and yet E0102 has no O-burning products while the latter two remnants contain ample evidence for O-burning. In addition, the N132D and E0102 O-rich filaments contain neon, whereas neon is essentially absent in Cas A and SN0540–69.3. We conclude that N132D and E0102 belong to a different sub-class of remnants, probably distinuished by progenitor mass and mass-loss history, than Cas A and SN0540–69.3.

- 3. The QSF knots in N132D are easily distinguished from the enriched SN ejecta (see Morse et al. 1996). The QSFs are chemically and kinematically distinct. The QSF spectrum in Figs. 3 and 4 shows strong emission from hydrogen, helium and metals, and has line ratios of "normal" abundance radiative shocks, like those found in the Cygnus Loop. QSF knots also have narrower line widths than the SN debris and only low-to-moderate radial velocities, consistent with the clouds being accelerated in radiative shocks with velocities of a few hundred km s^{-1} (see Morse et al. 1995). Note that the *IUE* spectra of N132D of Blair et al. (1994) included contributions from both O-rich ejecta *and* QSF filaments, due to the large aperture size. The new *HST* spectra of separate O-rich and QSF knots clearly show that, e.g., He II λ1640, is found only in the QSF spectrum; there is no He in the O-rich debris.

Modelling the emission from the O-rich debris is difficult. In particular, it is difficult to ascertain whether the excitation mechanism in the metal-rich debris is predominantly shock heating or photoionization. The strongest emission lines in the *HST* spectra are low-to-intermediate ionization species, such as Mg II, [O II], and [O III]. The relative importance of high ionization coolants, such as O VI, is not known. Possible future FUV spectra with FUSE could indicate whether a substantial fraction of the line emission comes from highly ionized atoms, which may indicate that the debris are shock heated in the reverse shock. ASCA spectra indicate there are highly ionized species emitting in the debris of E0102 (Hayashi et al. 1994); however, the strongest UV/optical emission line is [O II].

Shock models have a difficult time reproducing the emission spectra from the O-rich filaments (Blair et al. 1989, 1994). The models tend to over-produce [O III] and higher ionization emission, and vastly under-produce low ionization emission, especially [O II]$\lambda\lambda$3727. Sutherland & Dopita (1995b) attempted to account for the large range of ionization in the spectra of the O-rich debris by including the emission from an ionization front that precedes the shock moving through the O-rich plasma. In particular, the ionization front produces substantial low-to-intermediate ionization line emission, while the shock produces high ionization line emission. In our *HST* images of N132D, where we have both [O II]$\lambda\lambda$3727 and [O III]λ5007 images, the emission is clumpy though the ionization appears fairly uniform across the O-rich filaments, suggesting that the [O II] and [O III] emissions originate from regions in close proximity. The spatial resolution in the *HST* images of N132D constrains the extent of the photoionized region producing the [O II] emission to $\sim 2\times10^{17}$ cm. This observation may exclude low-density ($n_0 < 100$ cm^{-3}) shock + photoionized precursor models for N132D which require very extended ($> 10^{18}$ cm) precursors to produce the low ionization emission (see Sutherland & Dopita 1995b). The combination of compact knots and diffuse emission in E0102 may indicate that both shock excitation and photoionization are important. In E0102, the emission comes from a combination of clumpy (possibly shock-compressed) filaments and extended, diffuse "swirls" in the [O III] image. It would be interesting to compare a similar *HST* image in [O II] to test whether the [O II] arises predominantly from the more diffuse (possibly photoionized) regions. The models ultimately adopted for the O-rich filaments in N132D and E0102 will need to account for the lack of X-rays observed from the N132D filaments but the prodigious amount of X-rays coming from the E0102 filaments. Also, O I recombination emission at λ1356 and λ7774 is seen in E0102 but not N132D. Future shock models of the O-rich plasmas may also need to relax the ion-electron equilibration assumption, since the ions carry most of the energy for a considerable distance behind the shock.

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The SOC: Manuel Peimbert, Silvia Torres-Peimbert, Evan Skillman, Greg Shields, and Reggie Dufour.