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HST-COS OBSERVATIONS OF HYDROGEN, HELIUM, CARBON AND NITROGEN EMISSION FROM THE SN 1987A REVERSE SHOCK

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ABSTRACT

We present the most sensitive ultraviolet observations of Supernova 1987A to date. Imaging spectroscopy from the Hubble Space Telescope-Cosmic Origins Spectrograph shows many narrow ($\Delta v \sim 300$ km s$^{-1}$) emission lines from the circumstellar ring, broad ($\Delta v \sim 10 - 20 \times 10^3$ km s$^{-1}$) emission lines from the reverse shock, and ultraviolet continuum emission. The high signal-to-noise (> 40 per resolution element) broad Lyα emission is excited by soft X-ray and EUV heating of mostly neutral gas in the circumstellar ring and outer supernova debris. The Lyα signal-to-noise ($\lambda > 1350$ Å) can be explained by δ 12-photon ($2s^2S_{1/2} - 1s^2S_{1/2}$) emission from the same region. We confirm our earlier, tentative detection of N V λ1240 emission from the reverse shock and present the first detections of broad He II λ1640, C IV λ1550, and N IV λ1486 emission lines from the reverse shock. The helium abundance in the high-velocity material is He/H = 0.14 ± 0.06. The N V/Hα line ratio requires partial ion-electron equilibration ($T_e/T_p \approx 0.14 - 0.35$). We find that the N/C abundance ratio in the gas crossing the reverse shock is significantly higher than that in the circumstellar ring, a result that may be attributed to chemical stratification in the outer envelope of the supernova progenitor. The N/C abundance ratio may have been stratified prior to the ring expulsion, or this result may indicate continued CNO processing in the progenitor subsequent to the expulsion of the circumstellar ring.

Subject headings: supernovae: individual (SN 1987A) — shock waves — circumstellar matter

1. INTRODUCTION

Borkowski, Blondin, & McCray (1997) predicted that the spectrum of SN 1987A should display very broad ($\Delta v \sim 12,000$ km s$^{-1}$) emission lines of Lyα, Hα, N V λ1240, and He II λ1640, produced where the freely expanding supernova debris crosses a reverse shock located inside the equatorial circumstellar ring. In September 1997, using the Hubble Space Telescope Imaging Spectrograph (HST-STIS), Sonneborn et al. (1998) detected broad Lyα emission, and Michael et al. (1998) showed how observations of this emission can be used to map the shape of the reverse shock and the flux of H I atoms crossing it. Michael et al. (2003) and Heng et al. (2006) analyzed subsequent (February 1999 – October 2002) STIS observations of both Lyα and Hα to map the increasing flux of H I atoms across the reverse shock.

The evolution of the broad Hα emission can also be tracked with ground-based telescopes, notably in February 2005 with the Magellan telescope (Smith et al. 2005) and from December 2000 to January 2009 with the Very Large Telescope (Fransson et al. 2011). Smith et al. pointed out that the Hα emission from the reverse shock could be suppressed due to preionization of hydrogen in the supernova debris by soft X-rays and EUV radiation from the rapidly brightening shock interaction with the inner circumstellar ring. Extrapolating the X-ray light curve, they predicted that this preionization would cause the broad Hα emission to vanish by 2012. However, since 2005, the X-ray light curve has leveled off (Park et al. 2011), so the preionization effect should be less than that predicted by Smith et al.

France et al. (2010) analyzed the most recent (31 January 2010) STIS observations of SN 1987A. They pointed out that the observed ratio of Lyα/Hα photon fluxes was $> 30$ at large, negative velocities, much greater than the value $\approx 5$ that would be expected for hydrogen atoms excited as they cross the reverse shock. Moreover, the spatially resolved Lyα line profile differed dramatically from that of Hα. France et al. proposed that the broad Lyα emission is dominated by Lyα emission from the nearly stationary equatorial ring that has been resonantly scattered by hydrogen atoms in the expanding supernova debris. France et al. also noticed a faint glow at wavelengths ranging from about 1260 – 1290 Å, which they attributed to the N V λ1240 emission predicted by Borkowski et al. They suggested that a critical test of that hypothesis would be detection of broad emission from C IV λ1550.

Here we describe far-ultraviolet (1140 – 1780 Å) spectra of SN 1987A obtained with the Cosmic Origins Spectrograph (COS) that was installed on HST in May 2009. With COS, we have measured the profiles of Lyα and N V λ1240 with signal-to-noise ratios (S/N) far superior to the previous STIS spectra. We have also detected the broad He II λ1640 emission predicted by Borkowski et al. (1997) and the broad C IV λ1550 emission predicted by France et al. (2010). We find that while the He/H abundance ratio in the outer ejecta is consistent with that
SN 1987A was observed with the medium resolution far-UV modes of HST-COS (G130M and G160M) on 2011 February 11 and March 14 for a total of 7 spacecraft orbits (18555 s; Table 1) as part of the Supernova 1987A INTensive Study (SAINTS - GO12241; PI - R. Kirshner). A description of the COS instrument and on-orbit performance characteristics can be found in Osterman et al. [2011]. All observations were approximately centered on the SN 1987A circumstellar ring (R.A. = 05h 35m 28.07s, Dec. = -69°16′10.8″; J2000) and COS performed an offset imaging target acquisition from a reference star ≈ 8″ away. A NUV image was obtained with the MIRRORB imaging mode after the slew to the science pointing in order to verify that the circumstellar ring was in the primary science aperture (PSA). Figure 1 (top) shows the COS aperture location on an optical image of SN 1987A, The MIRRORB configuration introduces optical distortions into the image, but a first-order analysis indicates that the entire circumstellar ring was inside the 2.5″ diameter PSA (Figure 1, bottom).

The COS position angle was chosen to maximize the spatial separation on the COS detector between Star 3 and the supernova emission we aim to study. The G130M observations were made at a position angle of ≈ −75°, while the G160M observations were acquired with a position angle of ≈ −45°. Light from objects outside the nominal 1.25″ COS aperture radius can be recorded with the science spectrum in crowded fields. Star 3 is a far-UV-bright Be star (Gilmozzi et al. 1987; Walborn et al. 1993) separated from the center of the SN 1987A ring by ≈ 1.7″. Stellar contamination could compromise supernova data quality if the two objects overlapped on the spectroscopic detector. Thus, we used the imaging spectroscopic capability of COS to keep SN 1987A centered while placing Star 3 at the bottom of the microchannel plate (MCP) detector.

We complemented this observing strategy with post-processing techniques and custom spectral extractions to maximize the spatial resolution of the instrument in the cross-dispersion direction. Due to long-term exposure of the COS MCP to geocoronal Lyα and hot-star spectra, the number of electrons generated by each incident photon at a given detector location has been decreasing. This is manifest as lower pulse heights observed by the detector electronics 2. The exact form of the pulse-height evolution is a complicated function of the dispersion and cross-dispersion arrival location of the incident photon, but to first order we can approximate this as a pulse-height dependent mislocation of the photon y-location. The approximate form of this mislocation is -0.47 y pixels per pulse height bin drop. We have reprocessed the COS observations of SN 1987A, including a correction for the cross-dispersion misplacement, producing more accurate photon arrival positions. This additional data reduction step improves the far-UV angular resolution of the instrument by 20 – 30% across the bandpass.

Star 3 can be seen at the bottom of the two-dimensional spectrogram shown in Figure 2. Star 3 is well isolated at the bottom of the detector. The angular resolution in the reprocessed two-dimensional data

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2 We refer the reader to the cycle 19 COS Instrument Handbook for more details: http://www.stsci.edu/hst/cos/documents/handbooks/current/cos_cover.htm
is ≃ 0.8″. This imaging capability allows us to make custom spectral extractions at three spatially resolved locations: the “WNW” region at the top of the detector (approximately centered on the hotspots at: R.A. = 05h 35m 27.98s, Dec. = -69°16′10.5″; J2000), the “ESE” region towards Star 3 (approximately the telescope pointing coordinates), and a separate extraction of Star 3 itself. Star 3 contributes negligible flux to the one-dimensional WNW spectrum and less than 15% of the flux in the ESE extraction. The spatially resolved spectra will be analyzed in a future work, and we focus on the combined WNW + ESE spectra here.

The custom data extractions were then reprocessed with the COS calibration pipeline, CALcos v2.13.6, and combined with the custom IDL coaddition procedure described by Danforth et al. (2010) and Shull et al. (2010). The coaddition routine interpolates all detector segments and grating settings onto a common wavelength grid, and makes a correction for the detector QE-enhancement grid. No correction for the detector hex pattern is performed. Data were obtained in four central wavelength settings in each far-UV grating mode (λ1291, 1300, 1309, and 1318 with G130M and λ1577, 1589, 1600, and 1611 with G160M) at the default focal-plane split position. The instrumental configurations are summarized in Table 1. Observations at multiple wavelength settings provide continuous spectral coverage over the 1136 – 1782 Å bandpass and minimize the residual fixed pattern noise from the detector grid wires and the MCP pores. The point source resolving power of the medium resolution COS far-UV modes is $R \equiv \Delta \lambda / \lambda \approx 18,000 \ (\Delta v = 17 \ \text{km s}^{-1})$; however, the filled-aperture resolving power is $R \sim 1500 \ (\Delta v \sim 200 \ \text{km s}^{-1})$; France et al. 2009). Multiple point sources within the aperture (e.g., the multiple hotspots along the SN 1987A circumstellar ring) produce spectral resolution that is similar to the extended source response. The point source flux calibration of COS is accurate to better than ≃ 3%; however, the extended source and custom processing limit the absolute flux cal-

![Fig. 2.— Two-dimensional spectrogram of the G130M segment B data. Reverse shock emission is labeled in yellow, hotspot emission is labeled in blue, and interstellar absorption features are marked in green.](image)

![Fig. 3.— Full far-UV spectrum of the combined WNW and ESE regions. Broad emission from the SN 1987A reverse shock, narrow emission lines attributable to circumstellar hotspots, as well as underlying continuum emission are observed. Representative 1-σ error bars (a combination of photon statistics and flux calibration uncertainties) are shown in red.](image)

### 3. DATA ANALYSIS

#### 3.1. Emission Spectrum and Interstellar Corrections

The extracted emission spectrum of SN 1987A is shown in Figure 3. The spectra presented here are shown in photon units as these are the natural units for line flux comparisons. There is a wealth of narrow and broad emission and absorption features in the spectrum as well as a strong underlying continuum. The "narrow" (FWHM ≈ 200 – 300 km s$^{-1}$) resolved emission features are attributed to the circumstellar ring. The circumstellar ring spectrum is dominated by the hotspots which originate at shock interfaces where the forward blast wave encounters regions of high density in the circumstellar ring (Lawrence et al. 2000). A discussion of the ring-ejecta interaction is given by Larsson et al. (2011). Most of the circumstellar ring emission lines have been observed in previous HST-STIS (e.g., Pun et al. 2002) and IUE (Lundqvist & Fransson 1996) observations, including N V λ1239, 1243, C II λ1334, 1335, Si IV λ1394, 1403, the O IV] λ1400 multiplet, N IV] λ1483, 1486, C IV λ1548, 1550, [Ne IV] λ1602, He II λ1640, O III] λ1661, 1666, and the N III] λ1750 multiplet. Our deep COS observations enable first detections of O V λ1371 and Si II λ1526, 1533, although the ground state transition of Si II is blocked by the interstellar medium. We also tentatively detect the coronal [Si VIII] doublet λ1441, 1446. These features will be discussed in detail in a future work, though we will make use of the circumstellar ring line fluxes where relevant.

The broad emission features observed in the spectrum of SN 1987A arise as atoms and ions cross the reverse shock front (Michael et al. 1998), located just interior to the circumstellar ring. H I Lyα (and the corresponding Hα) emission from the reverse shock has been well studied (Michael et al. 2003; Smith et al. 2003; Heng et al. 2006; France et al. 2010), and we display the
the most likely formation site for high-velocity UV line opaque to UV radiation. Therefore, the reverse shock is enshrouded in dust (Matsuura et al. 2011) and is mostly the debris in the core (Jerkstrand et al. 2011), the core is UV line emission from SN 1987A has been attributed to data (Figure 5). While at earlier times, low-ionization V\(^\alpha\) set from the observed Ly\(\beta\) § with those predicted by Borkowski et al. (1997); see also α\(\alpha\) in Figure 3 is presented by Gordon et al. (2003) for the far-UV line ratios (§4.1.1) or the extinction towards Star 2, and the use of this curve would result in fluxes \(\sim 20 – 30\%\) larger than those derived below. None of the possible extinction curves significantly alters the shape of the continuum (§4.1.1) or the far-UV line ratios (§4.3.3).

There are several estimates of the interstellar reddening towards the region of the LMC in which SN 1987A resides (Walker & Suntzeff 1990; Fitzpatrick & Walborn 1990; Scuderi et al. 1996; Michael et al. 2003). We adopt a Milky Way \((R_V = 3.1)\) extinction curve (Cardelli et al. 1989) with \(E(B-V) = 0.19\) as this curve approximates the average extinction correction favored by the studies cited above. This curve also closely approximates the far-UV properties of the average LMC curve presented by Gordon et al. (2003) for \(A_V = 0.6\). Assuming \(E(B-V) = 0.17\) (Michael et al. 2003), would lower the fluxes derived in subsequent sections by \(\sim 15\%\). Scuderi et al. (1996) present a comprehensive study of the extinction towards Star 2, and the use of this curve would result in fluxes \(\sim 20 – 30\%\) larger than those derived below. None of the possible extinction curves significantly alters the shape of the continuum (§4.1.1) or the far-UV line ratios (§4.3.3).

The bright continuum \((F_\lambda(\text{observed}) \sim 1 \times 10^{-4} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1})\) underlying the hotspot and reverse shock emission was suggested in coadded STIS G140L spectra from 2010, cospatial with the circumstellar ring. However, the significance of the detection was low. We propose that this continuum is mostly H I 2-photon emission (§4.1.1).

3.2. Binned Spectrum for Broad Line & Continuum Analysis

Narrow emission lines, as well as the narrow interstellar absorption components, complicate measurements of the continuum and broad emission from the reverse shock. In order to remove confusion from these narrow lines during the analysis of the broad spectral features, we created binned spectra of the WNW and ENE extractions. These binned spectra were centered on hand-chosen regions of the data at \(1 – 5\) \(^\Delta A\) intervals and were free of narrow features. The flux and error of these binned data points were taken to be the average flux and standard deviation of a 0.8 \(^\Delta A\) region centered on the selected wavelength. These binned data are shown as diamonds overplotted on the spectra in Figures 5 – 8.

We quantify the total reverse shock flux by integrating the binned spectra over wavelength intervals corresponding to the velocity ranges of interest for a given feature. The velocity ranges were chosen to cover the maximum extent of a given line without significantly overlapping with other reverse shock emission features. The inner approximately 3000 \(\text{km s}^{-1}\) were not included to avoid strong hotspot emission lines located at \(\approx 0 \text{ km s}^{-1}\). In most cases the hot spot lines are doublets, therefore a velocity interval larger than the nominal 300 \(\text{km s}^{-1}\) nar-

![Fig. 4.— RS Ly\(\alpha\) and hotspot N V in the WNW extraction. Hotspot emission lines are marked in blue and interstellar absorption components are labeled in green. The purple line shows a fit to the Ly\(\alpha\) line core for log\(_10\)(N(H)) = 2.143 \(\pm\) 0.02 cm\(^{-2}\). Dashed orange lines are plotted as velocity references. Representative 1-s error bars (a combination of photon statistics and flux calibration uncertainties) are shown in red.](image)

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row line-width was excluded. We were unable to measure two reverse shock components due to velocity blending. The blue component of the N V line is lost under the Lyα line, and the weak red wing of the N IV emission is overwhelmed by the stronger blue C IV emission. The velocity and wavelength intervals are given in Table 2 with the summed line fluxes.

4. RESULTS

4.1. Hydrogen: 2-photon Emission and Broad Lyα

4.1.1. H I Continuum

Figure 3 shows that the emission and absorption lines are superposed upon a far-UV continuum with $F_\lambda > 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$. This continuum was marginally detected in previous STIS G140L spectra, with the emission being concentrated in the ring plane. It is detected in our COS observations at high significance, $(\text{Flux} / \text{Error}) \gtrsim 8$ per spectral resolution element from 1360 – 1540 Å.

We can rule out the possibility that this emission is uncorrected scattered light from Star 3. As described in Section 2, care was taken to isolate the emission from Star 3 at the bottom of the MCP detector (Figure 2). At the observed continuum levels, the scattered light from Star 3 would have to be over twice as bright outside of the stellar extraction region as within it, and relatively constant with angular separation from the stellar spectrum. Additionally, the observed continuum of Star 3 has a different spectral shape than the supernova continuum and there is no evidence for stellar features in the supernova spectrum (such as photospheric and wind absorption lines of C III λ1175 and Si IV λ1394, 1403; Pellerin et al. 2002). Therefore, we consider it unlikely that Star 3 contributes more than 10% to the supernova continuum at $\lambda > 1350$ Å.

We propose that this continuum is predominantly H I 2-photon ($2s \, ^2S_{1/2} - 1s \, ^2S_{1/2}$) emission. We fit the $1350 \leq \lambda \leq 1720$ Å spectrum with the analytic formula of Nussbaumer & Schmutz [1984],

$$J_\lambda = \frac{1}{4\pi} \frac{hc}{\lambda^3} A(\lambda) N_{2s^2S}$$  

where $J_\lambda$ is the emissivity and $N_{2s^2S}$ is the H I column density in the $2s^2S$ state. This function rises sharply from 1216 Å to a maximum at $\lambda \approx 1420$ Å, and then declines slowly to the red. The 2-photon spectral model is shown in orange in Figure 6. Based on our near-UV images, we estimate that the circumstellar ring fills approximately $30 \pm 20\%$ of the inner 2° of the COS aperture where the transmission is $> 0.6$. Assuming this filling fraction, the continuum level determines the column density, and we find $\log_{10}(N_{2s^2S}(H)) = 21.34^{+0.50}_{-0.26}$ cm$^{-2}$.

The total integrated (1216 Å – 6 μm) H I 2-photon flux is $9.1 \pm 0.6 \times 10^{-1}$ photons cm$^{-2}$ s$^{-1}$, and the observed ratio of Lyα line emission to 2-photon is $F(\text{Lyα})/F(2s) = 1.96 \pm 0.23$. Since this ratio is consistent with the 2p/2s ratio of 2.1 (observed as $F(\text{Lyα})/F(2s)$) expected for recombination at $T \approx 10^4$ K (Spitzer 1978) and the $\lambda(1s \rightarrow 2p) / (\lambda(1s \rightarrow 2s)$ ratio of 2.05 – 2.10 expected for excitation by electron collisions (Callaway 1988), we infer that it is likely that the Lyα and the 2-photon emission come from the same source.

An important constraint on the origin of the far-UV continuum is the density of the emitting region. H I 2-photon emission can be suppressed by a factor $[1 + n_p/n_{cr}]^{-1}$ due to collisional depopulation of the 2s state, where the critical density is given by $n_{cr} = A_{2s}/C_{sp}$ and $n_p$ is the density of protons. The $(2s \rightarrow 2p)$ collision rate coefficient is $C_{sp} = 5.31 \times 10^{-4}$ cm$^{3}$ s$^{-1}$ (Seaton 1955; see also Dennison et al. 2005 for a discussion of 2s and 2p level populations in H II regions) and $A_{2s} \approx 8.23$ s$^{-1}$ for the 2-photon decay (Klarstfeld 1963), therefore $n_{cr} = 1.5 \times 10^4$ cm$^{-3}$.

Based on the observed 2-photon flux, we can predict the total amount of associated Hα if this emission is predominantly recombination. In Case B recombination, the rate of population of the 2s state is 3.3 times the rate of emission of Hα (Osterbrock & Ferland 2006). The expected Hα in this scenario is $\approx 2.8 \times 10^{-1}$ photons cm$^{-2}$ s$^{-1}$. We have made an estimate of the total Hα flux from the circumstellar ring by analyzing STIS G750M spectra obtained in 2009 October ($HST$ exposure IDs OB7I200A0 – OB7I200D0), making a correction for differential reddening between Hα and the 2-photon emission. The total Hα emission from the ring is $\approx 2.5 \times 10^{-1}$ photons cm$^{-2}$ s$^{-1}$, very close to the value expected if the 2-photon emission was produced by recombination. However, Gröningson et al. [2008H] find that the Hα flux from the ring is dominated by high-density ($> 4 \times 10^6$ cm$^{-3}$) shocked material around 5700 days after the explosion (October 2002). 2-photon emission could be highly suppressed from such gas, which has $n_p/n_{cr} \gtrsim 300$. 2-photon emission from lower density ($\lesssim 5 \times 10^3$ cm$^{-3}$; Matilla et al. 2010) gas in the unshocked ring would not be suppressed, but such gas can only account for $\approx 20\%$ of the observed 2-photon emission.

Because we observe no comparable source of Hα emission, we conclude that the majority of the 2-photon emission is produced not by recombination, but by thermal
(T ≈ 10^4 K) electron impact excitation of the 2s^2S state of neutral hydrogen atoms in the outer ejecta, near the reverse shock front. This low-density gas (n_H ≈ 100 cm\(^{-3}\); Smith et al. 2005; Heng et al. 2006) is heated by X-rays emitted from the shocked gas near the hotspots. In particular, the energy deposition of the soft X-ray/EUV photons from the shocked hotspots will be concentrated in a layer near the reverse shock (Fransson et al. 2011). When the ionization fraction is \( \gtrsim 3 \times 10^{-2} \), the majority of the X-ray energy heats the gas through Coulomb stopping of fast photoelectrons (Xu et al. 1992; Kozma & Fransson 1992). The primary coolants for this gas are Ly\( \alpha \) and 2-photon emission.

Is it reasonable to expect this level of X-ray heating of gas near the reverse shock? We calculate the total X-ray flux from the circumstellar ring using the two-component model spectrum of Zhekov et al. (2004), scaled to the total 0.5 – 2.0 keV luminosity observed by Chandra near day 8000 (\( L(0.5 – 2.0 \text{ keV}) \approx 1.5 \times 10^{36} \text{ erg s}^{-1} \); Racusin et al. 2009). The total 2-photon luminosity is \( L(2s) \approx 2.2 \times 10^{36} \text{ erg s}^{-1} \), therefore the 0.5 – 2.0 keV X-ray flux is insufficient to power the far-UV continuum. However, the total shock luminosity is most likely dominated by emission in the soft X-ray/EUV band (0.01 – 0.5 keV) that is attenuated by the neutral hydrogen in the interstellar media of the Milky Way and LMC (Fransson et al. 2011). The luminosity in this band inferred from the model by Zhekov et al. is \( L(0.01 – 0.5 \text{ keV}) \approx 3 \times 10^{36} \text{ erg s}^{-1} \). Assuming that roughly half of this emission intersects the outer ejecta, we find that approximately 1.4% of the soft X-ray/EUV luminosity from the shocked ring must be reprocessed into H I 2-photon emission.

### 4.1.2. H I Line Emission

Figures 4 and 5 show the broad emission from H I Ly\( \alpha \). This emission was first observed in HST-STIS spectra 10.25 years after the SN 1987A explosion (Sonneborn et al. 1998). Subsequent studies have explored the reverse shock Ly\( \alpha \) and H\( \alpha \) emission in more detail (Michael et al. 1998, 2003; Fransson et al. 2011 for discussion of the H\( \alpha \) evolution). The combination of increased sensitivity and spectral resolution and low instrumental background of COS enable us to produce the highest-quality ultraviolet velocity profiles of the reverse shock emission to date. The velocity distribution of the neutral hydrogen emission extends from \(-13000 \leq +8000 \text{ km s}^{-1} \) (Figure 5). The velocity maxima are much smaller than the initial observations by Sonneborn et al. (1998; \( \pm 20000 \text{ km s}^{-1} \)) and are consistent with the decrease in maximum projected velocity observed from 2004 to 2010 (France et al. 2010). Using the limited angular resolution of COS, we confirm that emission at negative velocities is concentrated towards the northern side of the circumstellar ring while positive velocities are concentrated on the southern side of the ring. The total integrated (\(-12000 \leq +8000 \text{ km s}^{-1} \)) Ly\( \alpha \) flux inferred from Figure 5 is 1.78 ± 0.18 photons cm\(^{-2} \) s\(^{-1} \).

Previous work noted that the Ly\( \alpha / H\alpha \) ratios from the reverse shock exceed the 5:1 photon production ratio expected for a Balmer-dominated shock (Heng et al. 2006; France et al. 2010) found Ly\( \alpha / H\alpha \) ratios \( \geq 30 \) from \(-8000 \leq +2500 \text{ km s}^{-1} \) and \( \geq 20 \) from \(+3000 \leq +7000 \text{ km s}^{-1} \) for isolated cuts across the northern and southern sides of the reverse shock, respectively. They attributed the enhanced Ly\( \alpha \) emission to a second source of Ly\( \alpha \) photons. They argued that Ly\( \alpha \) photons from the hotspots are resonantly scattered by onrushing hydrogen with a distribution of velocities spanning a width \( \Delta v_H \sim 3000 – 9000 \text{ km s}^{-1} \) (unlike Ly\( \alpha \), H\( \alpha \) is not a resonance line and therefore hotspot H\( \alpha \) photons pass through the debris freely).

While the Ly\( \alpha \) enhancement at the largest negative velocities can likely be explained by this mechanism, our preceding discussion of the 2-photon continuum suggests that the majority of the lower velocity (\( \pm 7000 \text{ km s}^{-1} \)) Ly\( \alpha \) excess is attributable to the X-ray heating of the outer supernova debris. As described above, Ly\( \alpha \) is the primary coolant for mostly neutral hydrogen-rich gas excited by soft X-ray/EUV photoelectrons, and the agreement between the observed and theoretical \( F(\text{Ly}\alpha)/F(2s) \) ratio therefore argues that thermal electron collisions dominate the production of Ly\( \alpha \) photons in the outer ejecta near the reverse shock front. Resonant scattering will cause the newly produced Ly\( \alpha \) photons to emerge preferentially in the outward direction, substantially favoring the blue-shifted wing as observed.

### 4.2. He II \( \lambda \)1640 Emission

The broad emission feature that we attribute to He II \( \lambda \)1640 from the reverse shock is easily visible above the 1600 – 1700 Å continuum in Figure 6. In Figure 7, we compare the He II velocity profile with the red side of the N\( V \) \( \lambda \)1240 (§4.3.1) profile. As neutral or singly ionized helium crosses the reverse shock, collisions with thermal electrons (Laming et al. 1996) cause the helium to emit...
the analog to Hα. The velocity distribution of the ionized helium is expected to be quite different from that of neutral hydrogen because the He$^+$ ions that have crossed the reverse shock will be deflected by turbulent magnetic fields in the shock isotropization zone (Michael et al. 1998). The broad He II displays a somewhat asymmetric line shape, spanning approximately $-9000 - +11000$ km s$^{-1}$.

Interpolating the integrated red and blue reverse shock He II $\lambda1640$ photon fluxes given in Table 2 through the narrow emission line, we measure a total flux of $1.9 \times 10^{-2}$ photons cm$^{-2}$ s$^{-1}$. Because this line is the hydrogenic analog to Hα, the $F(1640)/F($Hα$)$ ratio should give a direct measure of the relative abundance of helium (by number), assuming full hydrogen and helium ionization and that our line identification and continuum subtraction are correct. We compare our He II measurement with the Hα flux from the day $\sim 8000$ VLT-UVES observations presented by Fransson et al. 2011, $F_{\text{obs}}($Hα$) \approx 1.4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. We convert this value into a total reverse shock Hα by applying a factor of 1.86 slit correction, a factor of 1.45 reddening correction at Hα (Gröningsson et al. 2008a), and a factor of 24/22 to account for the relative time of observation after the explosion. The integrated Hα photon flux in 2011 is $\approx 0.14$ photons cm$^{-2}$ s$^{-1}$. The He/H abundance ratio in the reverse shock is 0.14 $\pm$ 0.06, in agreement with the He/H abundance ratio derived by Mattila et al. (2010) for the circumstellar ring. The fact that the He II $\lambda1640$/Hα ratio reproduces the circumstellar ring He/H abundance ratio suggests that the neutral hydrogen pre-ionization predicted by Smith et al. (2003) is negligible 22 years after the explosion.

Borkowski et al. (1997) predicted the time evolution of the observable (accounting for attenuation due to interstellar reddening) reverse shock flux in several abundant ions, including He II. Their predictions only extend to 2007, but we can extrapolate their curves to 24 years after the explosion for comparison with the COS data.

![2-photon continuum-subtracted N V and He II in the combined WNW + ESE spectra. The blue side of the N V distribution is lost under the RS Lyα emission. The He II velocity profile appears qualitatively similar to that of N V.](image)

**FIG. 7.** 2-photon continuum-subtracted N V and He II in the combined WNW + ESE spectra. The blue side of the N V distribution is lost under the RS Lyα emission. The He II velocity profile appears qualitatively similar to that of N V.

We estimate their prediction for the observed He II flux in 2011 to be $\sim 1 - 3 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ from Figure 4 of Borkowski et al. (1997). Correcting these values by a factor of 4 to account for interstellar reddening, their prediction for the He II flux is $0.4 - 1.2 \times 10^{-2}$ photons cm$^{-2}$ s$^{-1}$, only a factor of $\sim 2$ below the He II flux observed by COS. Differences between the predicted and observed He II fluxes are likely due to assumed electron temperatures that are lower than suggested by the observations (see the next subsection).

4.3. Carbon and Nitrogen Emission Lines

4.3.1. N V $\lambda1240$

Prior to the first STIS observations of SN 1987A, Borkowski et al. (1997) predicted that strong reverse shock emission from Li-like N V $\lambda1240$ would be detectable. This emission was not apparent, however, in the first deep far-UV STIS spectra presented by Sonneborn et al. (1998) and Michael et al. (1998). In recent (January 2010) STIS observations, we tentatively

<table>
<thead>
<tr>
<th>Species</th>
<th>$\Delta \lambda_{\text{obs}}$ (Å)</th>
<th>$\Delta v^a$ (km s$^{-1}$)</th>
<th>Line Flux (photons cm$^{-2}$ s$^{-1}$)</th>
<th>Flux Uncertainty (photons cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H I$^b$</td>
<td>1169.6 – 1208.0</td>
<td>-12000 – -1500</td>
<td>$1.1 \times 10^9$</td>
<td>$5.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>H I</td>
<td>1222.8 – 1247.1</td>
<td>1500 – 8000</td>
<td>$4.5 \times 10^{-1}$</td>
<td>$4.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>N V$^c$</td>
<td>1197.9 – 1233.9</td>
<td>-10000 – -10000</td>
<td>$5.7 \times 10^{-2}$</td>
<td>$6.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>N V</td>
<td>1247.1 – 1285.5</td>
<td>2000 – 12000</td>
<td>$8.0 \times 10^{-2}$</td>
<td>$8.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>N IV$^d$</td>
<td>1428.3 – 1478.8</td>
<td>-12000 – -1500</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$4.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>N IV$^d$</td>
<td>1497.0 – 1523.8</td>
<td>1500 – 8000</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C IV</td>
<td>1491.9 – 1539.4</td>
<td>-12000 – -1500</td>
<td>$4.6 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>C IV</td>
<td>1558.9 – 1584.6</td>
<td>1500 – 8000</td>
<td>$2.1 \times 10^{-3}$</td>
<td>$4.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>He II</td>
<td>1590.4 – 1633.7</td>
<td>-10000 – -10000</td>
<td>$6.8 \times 10^{-4}$</td>
<td>$7.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>He II</td>
<td>1658.0 – 1705.0</td>
<td>2000 – 12000</td>
<td>$9.6 \times 10^{-3}$</td>
<td>$8.1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$^a v = 0$ assumed to be the rest wavelength of the stronger lines of the N V and C IV doublets.

$^b$ Corrected for interstellar neutral hydrogen absorption of log N(H) = 21.43, however the inner $\pm 6$ Å (± 1500 km s$^{-1}$) cannot be reconstructed. All reverse shock fluxes have been corrected for interstellar dust extinction, assuming $E(B - V) = 0.19$ and $R_V = 3.1$.

$^c$ Blue N V flux is overwhelmed by reverse shock Lyα emission and interstellar H I absorption. We assume the N V Blue/Red ratio is the same as the He II reverse shock emission ($\approx 0.7$).

$^d$ Red N IV flux is obscured by the stronger blue emission from C IV.
detected broad, redshifted N V emission (Figure 3 of France et al. 2010), but low S/N precluded a detailed analysis. Now, in our COS observations, we unambiguously detect this emission. While the blue wing of the line is lost under the bright Lyα emission, we observe the complete red wing of the N V λ1240 velocity profile. In Figure 7, we compare the line profile of N V with that of He II, observing that the red wings of the two profiles are qualitatively similar. Both ions present a boxy line profile, with a flat top and fall off between +9000 – +10000 km s\(^{-1}\). The N V profile extends to at least +14000 km s\(^{-1}\), where the data are contaminated by the geocoronal O I triplet.

At the relevant energy scales of nonradiative supernova shocks, \(v_\text{s} \gtrsim 10^4\) km s\(^{-1}\), the excitation cross sections for Li-like species (e.g., C\(^{4+}\), N\(^{4+}\), O\(^{5+}\)) by collisions with protons and heavier ions are considerably larger than the cross-section for ionization to their He-like stage (Laming et al. 1996; Borkowski et al. 1997). Therefore, these species may emit many (several hundred) line photons (predominantly C IV λ 1550, N V λ 1240, O VI λ 1032 for the ions listed above) for every atom that crosses the reverse shock front before becoming ionized. The total ratio of N V λ1240 photons emitted to Hα is given by

\[
\frac{F(\text{N} \, \text{V})}{F(\text{H} \alpha)} = \frac{1}{0.2} \frac{x_N}{x_H} \frac{R(1240)}{R(N^{4+} \rightarrow N^{5+})} \tag{2}
\]

where 0.2 is the number of Hα photons emitted per neutral hydrogen atom crossing the shock (Michael et al. 2003), \(x_N/x_H\) is the nitrogen abundance ratio, \(R(1240)\) is the rate of electron and ion impacts that result in N V emission, and \(R(N^{4+} \rightarrow N^{5+})\) is the rate of ionization to N\(^{5+}\). The relative nitrogen abundance in the circumstellar ring is 2.8 (± 1.1) \(\times 10^{-4}\) (Mattila et al. 2010). Given the similarity of the red side of the He II and N V profiles, we compute the total N V reverse shock photon flux by assuming that the relative red/blue contribution is the same as He II (Table 2) and interpolating through the narrow emission lines, as described above. Under these assumptions, the observed \(F(\text{N} \, \text{V})/F(\text{H} \alpha)\) ratio is \(\approx 1.15\). Folding in the nitrogen abundance, we can therefore make a rough estimate of the ratio \(R(1240)/R(N^{4+} \rightarrow N^{5+}) \sim 850^{+550}_{-350}\) required to explain the observed line ratio.

\[R(1240)\] can be evaluated analytically,

\[
R(1240) = n_e \langle \sigma_{e} v_s \rangle + n_H \langle \sigma_{p} v_s \rangle + n_{He} \langle \sigma_{He} v_s \rangle \tag{3}
\]

where the cross-sections, \(\sigma_{e,p,\alpha}\), are for excitation of N V λ1240 by electrons, protons, and alpha particles, respectively. We simplify the averages over velocity distribution by evaluating the expression at a single shock velocity, \(v_s = 10^4\) km s\(^{-1}\). Cross-sections for the proton and alpha particle collisions are taken from Table 2 of Laming et al. (1996) for proton energies (\(E_p = 1/2 m_p v_s^2\)) of 522 keV (we assume the 544 keV values) and alpha particle energies (\(E_\alpha = 1/2 (4m_p)v_s^2\)) of 2088 keV (we assume 1.2 times the 2720 keV values). The electron impact excitation cross-sections are not as well determined, but we expect them to be similar to those of the protons at high shock velocity. Therefore, we estimate \(\sigma_{e,p,\alpha} = [4.31, 4.31, 14.4] \times 10^{-17}\) cm\(^2\), respectively. Taking \(n_e = 450\) cm\(^{-3}\) (Borkowski et al. 1997), \(n_H \approx 100\) cm\(^{-3}\) (Smith et al. 2005; Heng et al. 2006), and \(n_{He} = 0.17 n_H\) (Mattila et al. 2010), we compute a total N V excitation rate for \(v_s = 10^4\) km s\(^{-1}\); \(R(1240) = 2.6 \times 10^{-5}\) s\(^{-1}\).

Ionization rates by baryons are expected to be small compared to those by electrons due to the high energy of post-shock protons and heavier species (Laming et al. 1996), therefore we neglect their contribution to the N\(^{4+}\) ionization rates. Cross-sections for the direct ionization to N\(^{5+}\) by thermal electrons can be calculated as a function of electron energy from Equation 1 of Arnaud & Rothenflug (1983). Using coefficients for the Li-sequence (their Table 1), we calculate an electron ionization cross-section of \(\sigma_{ion}^{NV} = 1.5 \times 10^{-18}\) cm\(^2\) at \(E_e = 107\) eV. The direct ionization rate, \(R(N^{4+} \rightarrow N^{5+}) = n_e \langle \sigma_{ion}^{NV} v_s \rangle = 1.5 \times 10^{-7}\) s\(^{-1}\). This gives \(R(1240)/R(N^{4+} \rightarrow N^{5+}) \approx 170\), which is outside the range allowed by the observations.

If, on the other hand, there is partial equilibration between the electron and proton distributions (Cargill & Papadopoulos 1988; Laming et al. 1996; Heng 2010), then \(T_e = \beta_{eq} T_p\), where

\[
T_p = \frac{3}{16} \frac{\mu m_p v_s^2}{k_B} \tag{4}
\]

and \(\beta_{eq}\) is the equilibration factor, which has a maximum value of 1. \(\mu\) is the mean particle weight, \(\mu \approx 0.55\) (for \(x_H = 0.85\), \(x_{He} = 0.14\), and \(x_Z = 0.01\)). In this case \(E_e = 1/2 m_e (2kBT_e / m_e) = k_BT_e\). Using this energy to calculate the ionization cross-sections, we find that for \(\beta_{eq} = 0.14 - 0.35\) (\(T_e = 1.7 - 4.4 \times 10^8\) K), the electron ionization cross-sections \(\sigma_{ion}^{NV} = 9.7 - 4.2 \times 10^{-20}\) cm\(^2\), and the ionization rates of \(R(N^{4+} \rightarrow N^{5+}) = 4.3 - 1.9 \times 10^{-8}\) s\(^{-1}\). This gives \(R(1240)/R(N^{4+} \rightarrow N^{5+}) \sim 610 - 1380\), approximately the range required to account for the observed \(F(\text{N} \, \text{V})/F(\text{H} \alpha)\) ratio\(^4\). \(v_s = 10^4\) km s\(^{-1}\) is used as the fiducial velocity in our calculations, but the general conclusions hold for a range of possible shock velocities. Computing \(R(1240)/R(N^{4+} \rightarrow N^{5+})\) for velocities (5 – 12) \(\times 10^3\) km s\(^{-1}\) we find that \(\beta_{eq}\) decreases by \(\sim 50%\) across this range, but \(\beta_{eq} > 0.1\) is required to explain the data for all velocities considered.

It seems clear that partial ion-electron equilibration is required to explain the observation of strong reverse shock N V emission from SN 1987A. However, values of \(\beta_{eq} = 0.14 - 0.35\) are greater than those favored by Laming et al. (1996) from their non-radiative shock modeling of SN1006. Moreover, equilibration values of \(\beta_{eq} \geq 0.1\) for the high shock velocity (\(v_s \sim 10^4\) km s\(^{-1}\)) in SN 1987A are inconsistent with some recent results on electron-ion equilibrium in collisionless shocks. Glavanian et al. (2007) discuss a sample of older (\(\sim 10^3\) yr) supernova remnants whose electron-to-proton temperature ratio is inversely proportional to the square of the shock velocity, \(\beta_{eq} \propto v_s^{-2}\); however, this relation

\(4\) Eq. 3

\(5\) We note that if we assume that the ionization cross-sections scale as \(\sigma_{ion}^{NV} \propto T_e^{-0.5}\) in the high-\(T_e\) limit, then the ion-electron equilibration factor could be a factor of 2 – 3 higher, approaching the limit of complete equilibration.
has not been confirmed in subsequent work [Helder et al. 2011]. Additionally, van Adelsberg et al. (2008) present evidence suggesting an increasing β_{eq} for v_σ > 2000 km s^{-1}. Finally, we note that very high electron temperatures (T_e ∼ 10^9 K) were inferred for the high velocity ejecta in SN 1993J [Fransson et al. 1996], suggesting that electron heating may be efficient in high velocity environments (see §5.3).

We also compare the observed N V flux with that predicted by Borkowski et al. (1997). Extrapolating their prediction to the time of our observations, we would have expected (1.5 – 2.0) × 10^{-13} erg cm^{-2} s^{-1} in 2011, or 0.06 – 0.08 photons cm^{-2} s^{-1} after including a factor of 6.3 to account for interstellar reddening. We see that, similar to the prediction for He II, these values are a factor of ∼ 2 below their observed 2011 values (F(N V) = 0.16 photons cm^{-2} s^{-1}). Overall, we consider the prediction made 14 years prior to the observation to be remarkably good. The slight differences between the predicted and observed N V flux can most likely be attributed to their choice of a value for β_{eq} that is lower than we determine from the data. Lower electron energies increase the ionization cross-section and hence R(N^+ \rightarrow N^{5+}) thereby reducing the total number of N V photons emitted.

4.3.2. N IV λ1486

Figure 6 shows that there is considerable substructure on the continuum in addition to the strong reverse shock emission from H I, He II, and N V. The weakest of these features spans ∼ 1430 – 1500 Å. We attribute this emission to N IV λ1486 from the reverse shock. The N IV emission is highly asymmetric about the rest velocity. The blue-shifted component extends to roughly −8000 km s^{-1}, while the red side of the profile is at the noise level by +3000 km s^{-1}. Additionally, the blue wing of the reverse shock C IV profile, discussed in the next section, overwhelms any additional red flux. Again making the assumption that the red/blue N V ratio is the same as that for He II, and assuming that the red side of the N IV profile contributes an additional 20% to the total flux, we find that the total F(N V)/F(N IV) ratio is ∼ 72 ± 17.

4.3.3. C IV λ1550

Figure 6 also shows C IV λ1550 from the reverse shock covering ∼ 1500 – 1580 Å, with emission from −12000 – −1500 km s^{-1} having 2.2 times the total integrated photon flux as the +1500 – +8000 km s^{-1} interval (Table 2). The red side of the velocity profile is only marginally above the noise level at v_{CIV} > +3000 km s^{-1}. We consider the relative fluxes of C IV and N V here, and in the next section we will discuss the relative velocity distributions of the reverse shock species.

Interpolating the spectrum through the narrow emission lines, we measure an integrated broad line photon flux (−12000 – +8000 km s^{-1}) of F(C IV) = 7.7 × 10^{-3} photons cm^{-2} s^{-1}. With the previously-noted assumptions about the N V flux in mind, we find a flux ratio of F(N V)/F(C IV) ≈ 20 ± 3. The ratio of N V λ1240/C IV λ1550 is given by an expression similar to equation (2):

\[
\frac{F(NV)}{F(CIV)} = \frac{x_N}{x_C} \left( \frac{R(1240)}{R(N^+ \rightarrow N^{5+})} \right) \left( \frac{R(1550)}{R(C^{3+} \rightarrow C^{4+})} \right)^{-1}
\]

The ratio of the quantities in square brackets is very close to 0.9 for v_σ = (5 – 12) × 10^3 km s^{-1} (the ratio is near unity because both are Li-like ions). That implies that the abundance ratio of nitrogen/carbon atoms crossing the reverse shock is x_N/x_C ≈ 22 ± 3, greater than the ratio x_N/x_C ≈ 8.5 ± 3 inferred from spectroscopic observations of the equatorial ring (Lundqvist & Fransson 1996; Mattila et al. 2010).

We note that while our estimate of the flux ratio N V λ1240/C IV λ1550 is somewhat uncertain because our choice of the blue side of the N V profile is speculative, the integrated flux in the red side of the N V profile alone is more than 10 times greater than the total C IV flux. Therefore, we are confident that the N V/C IV ratio is enhanced well beyond what can be attributed to the circumstellar ring abundances of the two species. We return to this point in Section 5.4.

5. DISCUSSION

5.1. Relative Velocity Distributions

In Sections 4.2 and 4.3, we describe the velocity distributions of He II, N V, N IV], and C IV. The red side of the N V velocity profile is compared with He II in Figure 7 and a comparison of the He II, N IV], and C IV velocity profiles is shown in Figure 8. We observe qualitatively different velocity profiles from He II, N IV], and C IV. He II displays a mildly asymmetric profile spanning ∼ −9000 – +11000 km s^{-1}, while N IV] and C IV are strongly weighted towards the blue, spanning ∼ (9000 – 8000) – +3000 km s^{-1}. Peculiar geometric projection of the velocity can be ruled out because all three ions were observed with the G160M instrument mode, with a constant spacecraft roll orientation.

In nonradiative shocks, He II is thought to be excited...
by collisions with electrons, while the Li-like species (N V and C IV) are excited by ion-collisions (Laming et al. 1996). As we have shown above, the electron and ion distributions have likely not equilibrated in the SN 1987A debris, therefore it may be that the relative distributions of the impacting species is reflected in the velocity profiles of the excited ions. One might also speculate that if ion collisions dominate the emission from metals, the preferentially blue N IV and C IV profiles would reflect an asymmetric spatial distribution of the protons and ions. The N IV and C IV profiles also show spatial variations between the WNE and ENE spectra. In contrast, the He II profile, which is primarily excited by electrons, is more spatially and spectrally symmetric. This may indicate a more uniform distribution of electrons. With these possibilities in mind, one is tempted to separate the metals from the helium, however we observe N V extending to red velocities as high as +10000 km s\(^{-1}\) before declining. Modeling of both the fluxes and velocity distributions of ions in the SN 1987A reverse shock would be very useful for our understanding of the observed velocity profiles.

5.2. Excess Emission at \(\lambda < 1350\) Å

The high throughput and low instrumental background of COS have allowed us to study the ultraviolet continuum of SN 1987A for the first time. Similarly, we have presented the first conclusive observation of elements heavier than hydrogen in the reverse shock. Figures 3 and 6 show that there is additional ultraviolet continuum at \(\lambda < 1350\) Å, above which we propose that hydrogen 2-photon emission can adequately explain the data. As we discuss in §4.1.2, the spectral contamination from Star 3 is inversely proportional to wavelength, as the cross-dispersion astigmatism height is largest at the shortest wavelengths. This could account for some, but probably not all, of the bluest continuum emission. Instead, we propose four speculative possibilities for this emission. He\(^+\) has a 2\(p\) → 1s Ly\(\alpha\) line at 304 Å, and will emit a 2\(s\) → 1s 2-photon continuum which peaks at \(\lambda \approx 355\) Å, and declines to the red. We estimate that this emission contributes \(\approx 10\%\) of the 1150 Å continuum.

There may be an additional Ly\(\alpha\) component at very high velocities, although this would require \(v_{Ly\alpha} \gtrsim 30 \times 10^3\) km s\(^{-1}\) (\(\gtrsim 0.1\ c\)) to account for the reddest observed emission. Another possibility is that low-ionization emission line from the core, as opposed to higher-ionization emission from atoms crossing the reverse shock, contributes to the \(\lambda \leq 1350\) Å emission. Jerkstrand et al. (2011) describe 2-photon emission, scattered by low-ionization, high-opacity metal lines in the core, contributing to the observed spectrum at \(\sim 8\) years following the explosion. The observed excess begins at roughly the wavelength of the O I \(\lambda 1356\) Å emission line. If an appreciable amount of low-ionization metal emission escapes from the near side of the core, it may be responsible for a portion of the observed flux.

Perhaps the most likely scenario is one in which several minor reverse shock species contribute to the observed continuum between 1140 – 1350 Å. We have seen that reverse shock emission from Be-like ions (e.g. N IV \(\lambda 1486\)) are present. Therefore, emission from lines of C III \(\lambda 1175\) and O V \(\lambda 1371\) may also contribute\(^6\).


In Section 4.3.1, we found that large ion-electron temperature equilibration ratios (\(\beta_{eq} \approx 0.14 – 0.35\)) are required to explain the high N V \(\lambda 1240\) flux observed in the spectrum of SN 1987A. Ghavamian et al. (2007) predict equilibration ratios several times less than this for shock velocities observed in SN 1987A (\(v_s \sim 10^4\) km s\(^{-1}\)). Therefore, we consider additional electron heating mechanisms that could explain the observed N V emission. One mechanism that has been proposed for collisionless shocks (usually assumed to be quasi-perpendicular) at low Alfvén mach numbers (\(M_A\)) is the cross-shock potential (e.g Balikhin et al. 1993). But the cross-shock potential is expected to become less important as \(M_A\) increases because the plasma resistivity causes insufficient dissipation and the shock becomes unsteady (Edmiston & Kennel 1984). Electrons undergoing \(E \times B\) drift across the shock front are not guaranteed to see the same cross-shock potential. They may lose energy as well as gain it, and this limits the electron heating.

However, it has also been suggested that at Alfvén Mach numbers appropriate to shocks in supernova remnants, the shock transition becomes thin. The shock transition can develop a length scale less than the electron convective gyroradius, thus eliminating any \(E \times B\) drift within the shock. This onsets at \(M_A = \sqrt{m_i/m_e}\), and electron heating by the cross shock potential again becomes viable (Balikhin et al. 1993; Gedalin et al. 2008). Typical SNR shocks have \(M_A\) much higher than this, neglecting any modification of the preshock medium. Yet the predicted heating is not observed. Most likely, \(M_A\) at these shocks is much lower than expected due to amplification of the magnetic field by cosmic rays streaming ahead of the shock (Bell 2004, 2005). Electron heating in these systems occurs via plasma waves excited upstream by shock reflected ions or cosmic rays. At higher velocity shocks, or for those likely to have weak upstream magnetic field due to their environment and/or insignificant cosmic ray populations, \(M_A > \sqrt{m_i/m_e}\) and the cross-shock potential may be capable of heating electrons to the required energy. Therefore the energetic environment of SN 1987A, especially at its reverse shock, may enable additional electron heating mechanisms that do not contribute in lower \(M_A\) systems.

5.4. The N V/C IV Ratio

The final unresolved issue is the large N V/C IV ratio in the reverse shock emission. Carbon and nitrogen abundance ratios in the circumstellar ring suggest this number should be \(\approx 8\) (Lundqvist & Fransson 1996; Mattila et al. 2010), however the observed flux ratios indicate N/C \(\approx 22\). It may be that the N/C abundance ratio in the outer envelope of the progenitor was stratified prior to the ejection of the circumstellar rings, and that we are now seeing the first observational evidence of that stratification. A second possibility to
account for this discrepancy is that ongoing thermonuclear processing continued to convert C to N in the supernova progenitor following the circumstellar ring ejection. The CNO bi-cycle will enrich the $^{14}$N abundance at the expense of the abundances of $^{12}$C and $^{16}$O and, in equilibrium, will convert almost all of the primordial C and O into N (Caughlan & Fowler 1962). CNO processing has been invoked to explain the fact that the observed nitrogen abundance in the circumstellar ring is elevated by a factor $\sim 10$ over its value in the LMC (Fransson et al. 1989). Our observation that the He abundance does not change between the ring and reverse shock is qualitatively consistent with the 14E1 model presented by Shigeyama & Nomoto (1990). They show that the high-velocity material we observe crossing the reverse shock front is only a small fraction of the total ejected mass, and does not probe deep enough into the interior of the ejecta to observe significantly elevated He abundances.

If CNO processing continued near the stellar surface following the ejection of the circumstellar rings, it could have in principle converted most of the remaining C and O abundances seen in the equatorial ring into N. Heng et al. (2008) note reduced oxygen abundances, possibly related to the high N V/C IV ratio observed in our observations. For this explanation to be viable, the timescale to reach equilibrium in the CNO cycle must be $\lesssim 20,000$ years, the interval since the ejection of the equatorial ring. This condition will be met if the temperature of the shell where CNO burning takes place is $T \gtrsim 3.5 \times 10^7$ K (Caughlan and Fowler 1962, Table 4). This effect could not only account for the high N/C ratio in the gas crossing the reverse shock, it could also increase the N/H ratio by an additional factor of $\sim 2$. This would lower the required $\beta_{eq}$ derived in §4.3.1.

6. CONCLUSIONS

We have presented an analysis of deep HST-COS spectroscopy of SN 1987A. Below, we summarize our primary results.

1. We observe narrow lines from shocked gas in the circumstellar ring, broad emission lines from the reverse shock, and a strong detection of ultraviolet continuum emission. Several of the emission line species and the far-UV continuum are conclusively detected for the first time.

2. The asymmetry in Ly$\alpha$ profile and its enhancement relative to H$\alpha$ suggests that most of the Ly$\alpha$ emission is a result of the illumination of the outer supernova debris by soft ($E \leq 0.5$ keV) X-rays emitted by the shocked circumstellar ring.

3. The $\lambda \gtrsim 1350$ Å continuum may be described by hydrogen 2-photon emission originating in the outer ejecta, near the reverse shock front.

4. We present resolved velocity profiles of He II, C IV, N IV, and N V from the reverse shock. A comparison of the velocity integrated He II and H$\alpha$ velocity profile indicates a He/H abundance ratio of $0.14 \pm 0.06$. In order to reproduce the observed $F$(N V)/$F$(H$\alpha$) line ratio, partial ion-electron equilibration is required, $T_{eq} = \beta_{eq} T_p$, with $\beta_{eq} \approx 0.14 - 0.35$. Large values of $\beta_{eq}$ may be explained by additional electron heating by the cross-shock potential.

5. The velocity profiles of C IV and N IV are significantly different from that of He II, which may be related to the different excitation processes (ion vs. electron collisions) for the different species.

6. We observe additional continuum emission at $\lambda < 1350$ Å that is not readily explained. We favor a scenario where several weaker emission lines contribute, but spectral overlap with the much stronger Ly$\alpha$ and N V emission profiles prevents an unambiguous interpretation.

7. Finally, we observe that the C IV reverse shock emission is weaker than would be expected assuming circumstellar ring abundances. This may be explained by chemical stratification in the outer envelope of the progenitor, and may indicate additional CNO processing between the period of circumstellar ring ejection and the supernova explosion.

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