COSMIC ORIGINS SPECTROGRAPH OBSERVATIONS OF THE CHEMICAL COMPOSITION OF SNR LMC N132D

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ABSTRACT

We present new far-ultraviolet (far-UV) spectra of an oxygen-rich knot in the Large Magellanic Cloud supernova remnant N132D, obtained with the Hubble Space Telescope (HST)-Cosmic Origins Spectrograph (COS). Moderate-resolution (∆v ≈ 200 km s⁻¹) spectra in the HST far-UV bandpass (1150 Å ≤ λ ≤ 1750 Å) show emission from several ionization states of oxygen as well as trace amounts of other species. We use the improvements in sensitivity and resolving power offered by COS to separate contributions from different velocity components within the remnant, as well as emission from different species within the oxygen-rich knot itself. This is the first time that compositional and velocity structure in the ultraviolet emission lines from N132D have been resolved. No nitrogen is detected in N132D, and multiple carbon species are found at velocities inconsistent with the main oxygen component. We find helium and silicon to be associated with the oxygen-rich knot and use the reddening-corrected line strengths of O IV, O III, O V, and Si IV to constrain the composition and physical characteristics of this oxygen-rich knot. We find that models with a silicon-to-oxygen abundance ratio of N(Si)/N(O) = 10⁻² can reproduce the observed emission for a shock velocity of ∼130 km s⁻¹, implying a mass of ∼50 M☉ for the N132D progenitor star.

Key words: supernova remnants – supernovae: individual (LMC N132) – ultraviolet: ISM

1. INTRODUCTION

Oxygen-rich supernova remnants (SNRs) are a category of young remnants characterized by enhanced abundances of oxygen, neon, and other heavy elements, and are observed to have large outflow velocities (v ≥ 1000 km s⁻¹). O-rich remnants are thought to be the ejected stellar interiors from helium-burned layers of massive (>10 M☉) progenitor stars. These objects are ideal for studies of the evolution of massive stars and stellar nucleosynthesis. O-rich SNRs are found locally (e.g., Cassiopeia A; Chevalier & Kirshner, 1979) as well as in nearby galaxies (e.g., Blair et al. 2000).

Far-ultraviolet (far-UV) spectra of these objects provide a rich set of diagnostic lines for determining the composition and physical state of the stellar remnant. Far-UV observations probe excitation mechanisms and shock physics, providing a quantitative observational basis for studies of the interaction between supernovae and the interstellar medium. However, the accessibility of these objects varies widely depending on the foreground extinction to a given SNR. The majority of Galactic SNRs are strongly reddened, making studies of local O-rich ejecta challenging. O-rich SNRs beyond the Local Group of galaxies cannot be spatially resolved. The Magellanic Clouds offer the best compromise of low reddening and spatially resolvable targets suitable for far-UV investigations. Well studied O-rich remnants include N132D and SNR 0540 in the Large Magellanic Cloud (LMC), and E0102 in the Small Magellanic Cloud (SMC).

The young, oxygen-rich SNR N132D is located in the bar of the LMC and was first identified as a SNR by Westerlund & Mathewson (1966). Danziger & Dennefeld (1976) and Lasker (1978) confirmed its oxygen-rich nature. Spectroscopic studies (Danziger & Dennefeld 1976; Lasker 1980; Dopita & Tuohy 1984) revealed high-velocity filaments showing optical emission from only oxygen and neon, and spanning a total velocity range of ∼4400 km s⁻¹. The oxygen-rich filaments are concentrated near the middle of the remnant (Borkowski et al. 2007). Outside the fast-moving material is a bright X-ray shell (Long et al. 1981; Mathewson et al. 1983) that is associated with an optical emission line rim (Hughes 1994; Blair et al. 1994) of radius ∼1 arcmin (∼13 pc). Dickel & Milne (1995) observed 6 cm radio emission that coincides with the X-ray shell.

Blair et al. (2000) found that the abundances derived for the ejecta in N132D roughly match models of a star with an initial mass of 35 M☉ with the following condition: the O-rich mantle of the progenitor star did not mix with deeper O-burning layers. If there had been mixing between these layers, sulfur and silicon would have been added to the ejecta. They conclude that the ejecta is comprised of oxygen, neon, carbon, and magnesium, which may indicate that the progenitor was a WO Wolf–Rayet star, perhaps with a mass as high as 85 M☉ (Woosley et al. 1995).

In this Letter, we expand on previous observations of N132D. We present first results from the Cosmic Origins Spectrograph (COS), recently installed on the Hubble Space Telescope (HST). We use these data to resolve the composition of an O-rich knot in N132D, and estimate the mass of the progenitor star based on the elemental abundances of the stellar ejecta. We describe the COS observations and custom data reduction in Section 2. A quantitative analysis of the far-UV spectrum is presented in Section 3. In Section 4, we compare the measured line strengths to shock models to constrain the post-explosion abundances and the mass of the N132D progenitor star.
2. HST-COS OBSERVATIONS AND DATA REDUCTION

The COS is a slitless, modified Rowland Circle spectrograph designed for high-sensitivity observations of point sources in the vacuum-ultraviolet bandpass (1150–3200 Å). COS is optimized for deep, moderate-resolution spectroscopy (R ≈ 20,000; ∆λ ≈ 15 km s−1 for point-source observations) in the far-UV (1150 < λ < 1750 Å). The far-UV channel employs a single optical element for dispersion, focus, and correction of the spherical aberration of the HST primary mirror. A pre-flight review of COS can be found in Green et al. (2003) and a full instrument description and on-orbit performance characteristics are in preparation (J. C. Green et al. 2010, in preparation; S. Osterman et al. 2010, in preparation).

COS was installed on HST during STS-125/Servicing Mission 4 (SM4) in 2009 May. This O-rich knot in N132D was observed by COS on 2009 August 10 and 31 as part of the Early Release Observation program (HST proposal ID 11503; data sets lacc01 and lacc51). Spectroscopic data were obtained on N132D over five orbits, using both far-UV medium-resolution gratings (G130M and G160M) to provide continuous spectral coverage from ∼1150–1750 Å. The pointing (R.A. = 05h25m25s, decl. = −69°38’14”; J2000) of this three-color image (HST-ACS F658N (Hα); R), F475 (∼[O III]; G), F550M (stellar continuum; R)). The R and B filters are shown on a linear scale while the G filter is displayed with a square root stretch. The almost total lack of Hα emission at the COS pointing highlights the compositional difference of the oxygen-rich knot. The HST-FOS pointing (Blair et al. 2000) lies inside the circular COS aperture depicted here.

3. ANALYSIS AND RESULTS

3.1. Nebular Species and Velocity Separations

The narrowband WFC2 (Morse et al. 1996) and multi-band Advanced Camera for Surveys (ACS) images (Figure 1) clearly indicate that the O-rich knot targeted by COS has a substantially different composition than other regions of the remnant. This is attributable to the degree of mixing between the stellar ejecta and the ambient presupernova medium, both interstellar and from earlier mass loss episodes of the progenitor star. The sensitivity and spectral resolving power of COS enable us to separate the emission from individual species unambiguously and quantify the velocity offsets between these components. We find oxygen to dominate the emission from this knot, consistent with previous findings (Blair et al. 1994, 2000; Morse et al. 1996; Borkowski et al. 2007). We observe oxygen in four flight-qualified version of the COS calibration pipeline, CALCOS. Custom processing was performed to properly extract, calibrate, and co-add the N132D data set. The detector coordinates used by CALCOS for extracting one-dimensional (λ versus Fλ) spectra from the two-dimensional spectrogram are optimized for point sources, hence custom extraction windows were used to define proper target and background regions for this filled-aperture observation. A correction for spectral drift during the exposure was made by referencing an on-board calibration lamp. Finally, pulse height screening was performed in order to remove detector hot spots and other spurious events on the microchannel plates from the final spectrum. Spectra from individual exposures were then cross-correlated and co-added onto a common wavelength grid. The full far-UV spectrum of N132D is shown in Figure 2 with dominant nebular emission lines labeled. The minimum spectral resolution is observed to be ∆λ ≈ 200 km s−1, corresponding to the expected COS extended source resolving power for the medium-resolution grating modes (R ≈ 1500).

1 We refer the reader to the COS Data Handbook for more details: http://www.stsci.edu/hst/cos/documents/handbooks/datahandbook/ COS_longdhbcover.html.
ionization states (O\textsc{i}, O\textsc{iii}, O\textsc{iv}, and O\textsc{v}), as well as emission from C\textsc{ii} \lambda\lambda 1334, 1335, C\textsc{iv} \lambda\lambda 1548, 1550, smaller amounts of Si\textsc{iv} \lambda\lambda 1394, 1403, He\textsc{ii} \lambda 1640, and several unidentified lines (Table 1).

Line centers, widths, and integrated strengths are determined from Gaussian fits to the data. We employ a modified version of the MPFIT IDL routine that accommodates interactive fitting of multiple lines simultaneously. On-orbit flux calibration files were not available during SMOV, and we added 25% to the estimated to have a 1σ uncertainty of ±100 km s\textsuperscript{-1}.

Helio-centric velocity, $v_{\text{hel}} = (\lambda_{\text{obs}} - \lambda_{\text{rest}}) \times (c/\lambda_{\text{rest}})$.

Tentative identification.

### 3.2. Reddening Correction

In order to make a meaningful comparison to the ultraviolet emission lines predicted by SNR shock models (described in the following section), a correction must be made for the effects of differential extinction by interstellar dust. We performed an extinction correction by assuming that all of the relevant dust was associated with the LMC and can be represented by the average 30 Doradus reddening curve (Fitzpatrick 1986). Taking $E(B - V) = 0.12$ with a total-to-selective extinction ratio $R_V = 3.2$ (Blair et al. 2000), a continuous extinction curve is created for the COS bandpass. The line strengths are corrected by dividing this curve in transmission space.

### 4. DISCUSSION

#### 4.1. O-rich Shock Models and Physical Conditions in the Knot

We have compared the emission line strengths observed by COS with a grid of supernova shock models in order to constrain important physical quantities including the density of the pre-shock medium ($n$), the abundances of carbon and silicon relative to oxygen, and the shock velocity. We have used a modified version of the Raymond (1979) shock model code. This is the same code used to model the HST-FOS observations presented associated with C\textsc{iv}, O\textsc{iv}, and O\textsc{v}, all consistent with a velocity of 788 km s\textsuperscript{-1}. Interestingly, we do not observe a high-velocity component in O\textsc{iii}. We note that the unidentified feature at \lambda_{\text{rest}} = 1221.62 Å is approximately consistent with high velocity O\textsc{v} (\lambda_{\text{rest}} = 1218.34 Å), however, there is no detection of this O\textsc{v} line at the main oxygen knot velocity. Nitrogen is not detected in any ionization state in our data set. We place an upper limit on the line flux from N\textsc{v} \lambda\lambda 1238, 1242 of 2 × 10\textsuperscript{-6} erg cm\textsuperscript{-2} s\textsuperscript{-1}, a factor of ~30 lower than the upper limit presented by Blair et al. (2000).

We take these distinct velocity components as representative of the composition of the O-rich knot. The knot is predominantly oxygen, with trace abundances of helium and silicon. The carbon species and the emission associated with the high-velocity components are assumed to be spatially distinct from the O-rich knot and located in a different region of the remnant.
Comparison of the observed O iv, Si iv, O iv], and O iii λ1664 line strengths with those predicted by the modified Raymond et al. (1979) model described in Section 4. A single normalization that set the observed/O iv ratio to unity at $v_{\text{shock}} = 130$ km s$^{-1}$ was applied to all line ratios. The model confirms the pre-shock density of $n = 1$ cm$^{-3}$ and oxygen-to-silicon abundance ratio ($N(O)/N(Si) = 100$) used in Blair et al. (2000), and constrains the shock velocity in the highly ionized species. We use the $N(O)/N(Si)$ ratio in conjunction with an upper limit on $N(O)/N(C)$ to estimate the N132D progenitor mass to be $\sim 50 M_\odot$.

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by Blair et al. (2000), and we refer the reader to that paper for details of the model. We ran this model in the weakly magnetized limit (using magnetic parameter $B/n^{1/2} = 0.1 \mu G$ cm$^{3/2}$), with a pre-shock density of $n = 1$ cm$^{-3}$. The pre-shock density was chosen with a shock velocity of $v_{\text{shock}} = 100$ km s$^{-1}$ for a constant ram pressure ($n v_{\text{shock}}^2 = \text{constant}$) and a power-law index of $\alpha = 0.4$ (Blair et al. 2000). We used the elemental abundances from Blair et al. (2000) for silicon ($N(O)/N(Si) = 10^5$) and from our COS-derived upper limit for carbon ($N(O)/N(C) \gtrsim 10^5$). We ran a grid of models for values of $v_{\text{shock}} = 30$–200 km s$^{-1}$, and tabulated the predicted far-UV emission line strengths in three ionization states of oxygen (O iii, O iv, and O v) and Si iv.

The normalized ratios of observed/model line strengths are shown in Figure 4. We find relatively good agreement between the model and observed line strengths with a shock velocity of $v_{\text{shock}} = 130 \pm 20$ km s$^{-1}$ for O v, O iv, and Si iv. The fit for the O iii line is discrepant in both shock velocity and surface brightness. It is interesting to note that the $\sim 20\%$ offset for the O iii line strength is exactly the same difference in the dust attenuation curve between 1400 and 1664 Å. We suggest that the extinction curve to N132D is significantly flatter than the typical 30 Doradus or LMC extinction curves, perhaps reflecting a depleted population of small dust grains ($R_V > 4.0$) on the sight line to this remnant. O iii is more sensitive to slower shocks ($v_{\text{shock}} \sim 80$ km s$^{-1}$), while the higher ionization traced by O v cannot be produced in shocks slower than $\sim 100$ km s$^{-1}$. Taken as a whole, these findings agree with a physical scenario where shocks of different velocities are seen superposed (Vancura et al. 1992) in this O-rich knot, which has a pre-shock density and silicon abundance consistent with those presented in Blair et al. (2000), while ruling out a substantial carbon abundance in this region.

### 4.2. Mass of the Progenitor Star

The relative abundances of the O-rich knot in N132D can be compared to models of massive stars and supernova explosions to constrain the mass of the progenitor star. It should be stressed that we are presenting an analysis of one small knot of ejecta in a much larger remnant. While we can use this information to place bounds on the progenitor star, it would be inappropriate to make definitive statements regarding the nature of the presupernova star based on such a small sample of the stellar core. With that caveat in mind, we find relatively good agreement between our abundances and those of the 40 $M_\odot$ main-sequence model presented in Nomoto et al. (1997). Similar results are seen for the 70 $M_\odot$ star, but the lower $N(C)/N(Si)$ ratio in the model more closely reproduces our results. The 25 $M_\odot$ can be ruled out as it predicts too little silicon and $N(C)/N(Si)$ greater than unity. Blair et al. (2000) also comment on the 85 $M_\odot$ Wolf–Rayet B model (Woosley et al. 1993) with core masses from $2.7 < M_{\text{CORE}} < 7M_\odot$ being a reasonable fit to the observations. This model has a relatively high $N(C)/N(O)$ (>0.1). In light of the spatial separation between the carbon and oxygen components, which could not be resolved in the Faint Object Spectrograph (FOS) data, we consider this model to be ruled out. We note, however, that for a narrow range of core mass ($M_{\text{CORE}} = 2.6 \pm 0.1 M_\odot$), the 60 $M_\odot$ Wolf–Rayet A model (the distinction between “A” and “B” in Woosley et al. 1993 is the reaction rate for the conversion of carbon to oxygen in the stellar core) provides a reasonable fit to the abundances. In this model, the relative silicon and carbon abundances are of order $10^{-2}$, in agreement with the COS data. Additionally, more recent models by Umeda & Nomoto (2008) calculate abundances of oxygen and silicon in the post-explosion material for 50 and 100 $M_\odot$ main-sequence stars. Their 50 $M_\odot$ model, with an explosion energy of $3 \times 10^{52}$ erg matches the $N(Si)/N(O)$ ratio for the O-rich N132D knot, while the post-explosion yields for a 100 $M_\odot$ star overpredict the silicon abundance by an order of magnitude. Given the findings described above, we adopt a mass of $50_{-15}^{+25} M_\odot$ for the progenitor of the N132D supernova. In light of the uncertainties in the observational data and reddening correction, as well as the shock and supernova models, an error bar smaller than this conservative estimate is not supported. Constraints on the mass, structure, and composition of core-collapse supernova progenitors based on a relatively small subset of the ejecta are not uncommon (Blair et al. 2000; Morse et al. 2006; Fesen et al. 2006), and our results for N132D are best considered as one piece in a larger effort toward understanding the physical processes governing core-collapse supernovae.

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### REFERENCES

Blair, W. P., Raymond, J. C., & Long, K. S. 1994, ApJ, 423, 334
Blair, W. P., et al. 2000, ApJ, 537, 667
Borkowski, K. J., Hendrick, S. P., & Reynolds, S. P. 2007, ApJ, 671, L45
Chevalier, R. A., & Kirshner, R. P. 1979, ApJ, 233, 154
Danziger, I. J., & Dennefeld, M. 1976, ApJ, 207, 394
Dickel, J. R., & Milne, D. K. 1995, AJ, 109, 200
Dopita, M. A., & Tuohy, I. R. 1984, ApJ, 282, 135
Fesen, R. A., et al. 2006, ApJ, 636, 859
Fitzpatrick, E. L. 1986, AJ, 92, 1068
Green, J. C., Wilkinson, E., & Morse, J. A. 2003, Proc. SPIE, 5164, 17
Hughes, J. P. 1994, in AIP Conf. Ser. 313, The Soft X-ray Cosmos, ed. E. M. Schlegel & R. Petre (Melville, NY: AIP), 144
Lasker, B. M. 1978, ApJ, 223, 109
Lasker, B. M. 1980, ApJ, 237, 765
Long, K. S., Helfand, D. J., & Grabelsky, D. A. 1981, ApJ, 248, 925
Mathewson, D. S., Ford, V. L., Dopita, M. A., Tuohy, I. R., Long, K. S., & Helfand, D. J. 1983, ApJS, 51, 345
Morse, J. A., Smith, N., Blair, W. P., Kirshner, R. P., Winkler, P. F., & Hughes, J. P. 2006, ApJ, 644, 188
Morse, J. A., et al. 1996, AJ, 112, 509
Nomoto, K., Hashimoto, M., Tsujimoto, T., Thielemann, F.-K., Kishimoto, N., Kubo, Y., & Nakasato, N. 1997, Nucl. Phys. A, 616, 79
Raymond, J. C. 1979, ApJS, 39, 1
Umeda, H., & Nomoto, K. 2008, ApJ, 673, 1014
Vancura, O., Blair, W. P., Long, K. S., & Raymond, J. C. 1992, ApJ, 394, 158
Westerlund, B. E., & Mathewson, D. S. 1966, MNRAS, 131, 371
Woosley, S. E., Langer, N., & Weaver, T. A. 1993, ApJ, 411, 823
Woosley, S. E., et al. 1995, ApJ, 448, 315