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FUSE Observations of an X-Ray Bright Region in the Vela Supernova Remnant

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ABSTRACT

We present the results of a Far Ultraviolet Spectroscopic Explorer observation of an X-ray selected knot in the Vela supernova remnant. Spectra were obtained through the $30'' \times 30''$ low resolution aperture and the $4'' \times 20''$ medium resolution aperture. O VI $\lambda\lambda1032,1038$ and C III $\lambda977$ are detected strongly in both spectra, and S VI $\lambda\lambda933,944$ is detected weakly only in the larger aperture spectrum. We also report the first detection of C II $\lambda1037$ emission in a supernova remnant. The spectra show the presence of two kinematic components along the line of sight - one with both low and high excitation emission centered at a velocity of $-50$ km s$^{-1}$ and another with only low excitation emission centered at a velocity of $+100$ km s$^{-1}$. We associate the $-50$ km s$^{-1}$ component with the observed X-ray knot, and find a dynamical pressure of $3.7 \times 10^{-10}$ dyne cm$^{-2}$ driving the shock. We compare our results with data obtained using the Hopkins Ultraviolet Telescope at nearby locations and find that differences in the spectra imply the existence of two emitting components in the X-ray knot. Based on the X-ray morphology seen in a ROSAT HRI image, we identify two distinct regions which can be associated with these two components whose ultraviolet emission differs dramatically. These observations demonstrate the importance of high spectral resolution in understanding the proper physical relationships between the various emitting components in supernova remnants.

Subject headings: ISM: individual (Vela) — ISM: supernova remnants

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1. Introduction

The Vela supernova remnant (SNR) is a nearby Galactic SNR that is visible in all passbands from radio to X-ray. Its age, based on the spin down age of the central Vela pulsar, is about 11,400 years (Reichley, Downs & Morris 1970) and it is at a distance of about 250 pc (Cha, Sembach & Danks 1999). In the optical it is characterized by long arc-shaped filaments with arbitrary centers of curvature and has been classified as having a “smoke-ring” morphology by van den Bergh 1978. In the X-ray (Kahn et al. 1985; Aschenbach, Egger & Trümper 1995), the overall shape and extent of the remnant is more easily discerned - it is roughly circular with an angular diameter of about 8°. However, the detailed structure of the X-ray emitting gas is very complex, with a plerion around the central pulsar (Harnden et al. 1985), and several knots and filaments having a range of temperatures between one million and a few million degrees (Kahn et al. 1985). To add to the complexity, another SNR (RXJ0852.0-4622) lying within the boundaries of Vela in projection has been discovered in ROSAT X-ray maps (Aschenbach 1998; Slane et al. 2000). The overall extent of the radio emission in Vela is similar to the extent of the X-ray emission (Duncan et al. 1996), but when considered in detail the radio filaments only occasionally correlate well with the X-ray emission and the optical filaments (Bock, Turtle & Green 1998). The velocity structure of the SNR is also very complex. Absorption line studies towards several stars in the region have shown that high velocity components are distributed more or less randomly across the face of the remnant (Jenkins, Silk & Wallerstein 1976; Cha & Sembach 2000).

Vela, as a “middle-aged” remnant whose emission is dominated by the interaction of the supernova blast wave with the surrounding interstellar medium (ISM), has often been compared and contrasted with the Cygnus Loop, another nearby remnant at a similar stage of evolution. The Cygnus Loop has a classical limb-brightened shell morphology at radio, optical and X-ray wavelengths, and there is evidence to show that the SN explosion happened in a cavity cleared out by the progenitor star (Levenson et al. 1998). Vela, in contrast, seems to be the result of an explosion in a highly inhomogeneous medium. However, the optical and ultraviolet emission from individual filaments in both these remnants is due to shock excitation of the ambient medium (e.g. Raymond et al. 1981). The source of the energy for these shocks is the supernova explosion, and therefore, understanding the properties of individual filaments is an important part of addressing the broader problem of SNR evolution in the ISM.

Ultraviolet spectra of filaments in Vela have revealed the presence of lines from species covering a wide range of ionization states, from C II to O VI (Raymond et al. 1981; Blair Vancura & Long 1995; Raymond et al. 1997; henceforth R97). These data have been used to infer that the emission is due to shocks with velocities between about 100 km s^{-1} and 200 km s^{-1}. In this paper we present far-ultraviolet spectra of an X-ray knot in Vela obtained with the Far Ultraviolet Spectroscopic Explorer (FUSE). The X-ray knot is near the projected center of Vela and it has bright optical filaments running along part of its
eastern edge. Spectra of the knot obtained with the *Hopkins Ultraviolet Telescope* (HUT) were presented by R97. HUT apertures were placed on the bright optical filament and a region to the west within the X-ray knot in an attempt to view edge-on and face-on portions of the same shock. We have observed a region adjacent to the HUT “face-on” position selected to have less optical emission and more uniformly bright X-ray emission. The two datasets can therefore be compared; they are complementary - HUT spectra do not have the high spectral resolution of the FUSE spectra, but they span a wider wavelength region and include many more diagnostic emission lines. We also present archival ROSAT images of the X-ray knot to guide our understanding of the local morphology and the relationship between the X-ray and the ultraviolet emission. The aperture positions for both HUT and FUSE observations are shown in Figure 1. From left to right (east to west), these are (and we will use the following nomenclature in this paper) - HUT “edge-on”, HUT “face-on”, FUSE low resolution (LWRS) and FUSE medium resolution (MDRS) apertures. (The location of the optical filaments can be seen in Figure 1 of R97.)

2. Observations

The FUSE observations (ID P1141202) were obtained on 25 January 2000 as part of the Guaranteed Time Team project on SNRs. Five exposures with a total integration time of 11023 s were obtained with the low resolution (LWRS) 30″ × 30″ aperture centered at RA(J2000) = 08h 41m 02s 43, DEC(J2000) = -44° 44′ 01″ 8. Data were obtained simultaneously through the medium resolution (MDRS) 20″ × 4″ aperture, which was located about 3.5′ westward from the LWRS aperture (Figure 1d). The FUSE instrument and its performance have been described in detail by Moos et al. 2000 and Sahnow et al. 2000. Briefly, there are four independent channels – SiC1, SiC2, LiF1 and LiF2, each having two segments – “A” and “B”. Therefore each observation may be considered as having eight separate spectral segments. We will refer to these segments by names – “SiC1A” and so on. The overall wavelength coverage is 905Å - 1187Å. The shorter wavelengths (∼ 905Å - 1000Å) are covered by segments SiC1B and SiC2A, the intermediate wavelengths (∼ 1000Å - 1100Å) by segments LiF1A, SiC1A, LiF2B, SiC2B and the longer wavelengths (∼ 1100Å - 1187Å) by segments LiF1B and LiF2A. We will discuss spectra taken through the LWRS and MDRS apertures. Since the source is extended and thus fills the apertures, the effective spectral resolution is ∼ 0.34Å for the LWRS data and ∼ 0.045Å for the MDRS data.

To reduce the data, we first extracted one-dimensional spectra from the raw data for each segment in each of the five exposures. The five exposures were then added segment by segment. The count rate is simply the total counts divided by the total exposure time (11023 s). The flux calibration was done using the standard files used by the CALFUSE calibration pipeline software (version 1.6.9), which gives the count rate to flux conversion as a function of pixel number for each segment and aperture. We used the same wavelength solutions as the calibration pipeline, but found we needed to apply a zero point offset for
each segment. The offsets were determined using the airglow lines - Ly$\beta$ for LiF1A, SiC1A, LiF2B and SiC2B and Ly$\gamma$ for SiC1B and SiC2A. (Only these segments will be considered in this paper, since no lines were detected in the long wavelength segments - LiF1B and LiF2A.) Finally all the segments contributing to a wavelength region were co-added, weighted appropriately by their effective areas. (In the case of the short wavelength MDRS spectrum, however, only the SiC1A data were used.) Thus our final data products consist of LWRS and MDRS spectra in the 905Å - 1000Å and 1000Å - 1100Å bands.

Images of the X-ray knot (on which the FUSE apertures are located) were obtained by ROSAT with the PSPC (sequence ID rp500013n00) in 1991 and with the HRI (sequence ID rh500135n00) in 1992. Both PSPC and HRI pointings were centered at RA(J2000) = 08$^h$ 40$^m$ 45$^s$ 0, DEC(J2000) = -44$^\circ$ 38$'$ 24$''$ 0, placing the X-ray knot in the center of the field. These data are now available to the public and we have obtained them from the archive maintained by HEASARC. In the case of the PSPC images, we obtained the raw data from each energy channel and processed them according to the method described by Snowden & Kuntz 1998. For the HRI data, we obtained the 5$''$ resolution image directly from the archive. These X-ray images are shown in Figure 1. The PSPC images in the R1R2 band (0.11 keV - 0.28 keV) and the R4R5 band (0.44 keV - 1.21 keV) are shown in Figures 1a and 1b respectively. The field of view for the PSPC images is 2$^\circ$. The HRI image of the knot is shown in Figure 1c, and a blowup of the HRI image, with overlaid contours and the location of the HUT and FUSE apertures is shown in Figure 1d. We discuss the X-ray morphology in more detail in §4.

3. Results

The lines detected in the FUSE LWRS spectrum are S VI $\lambda\lambda$933,944, C III $\lambda$977 and O VI $\lambda\lambda$1032,1038. The spectral regions near these lines are shown in Figure 2. The O VI lines are very strong and each line has a FWHM of about 0.45Å ($\sim$130 km s$^{-1}$). These lines are broader than the terrestrial airglow lines (e.g. Ly$\beta$, Ly$\gamma$), which have filled slit widths of about 0.34Å. The C III line is double peaked. The shorter wavelength component is about the width of the airglow line, and the longer wavelength component is broader, having a FWHM of about 150 km s$^{-1}$. The component centroids are separated by about 0.5Å. The S VI lines are very weak and the widths cannot be measured as accurately. In Figure 3 the regions around the C III and O VI lines from the MDRS spectra are shown (S VI is too weak to be detected). The O VI lines, as in the LWRS spectrum, are broader than the airglow. Each has a FWHM of about 0.2Å ($\sim$60 km s$^{-1}$), compared to about 0.045Å for the filled slit width. The O VI line widths imply that the gas temperature, $T \lesssim 1.2 \times 10^6$ K. If the properties of the gas sampled by the LWRS and MDRS spectra are the same, then the width of the O VI lines in the LWRS spectrum is the result of the

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instrument line profile convolved with their intrinsic width, which is at most about 0.2Å. The C III emission in the MDRS is also double peaked, with the two components separated by the same amount as in the LWRS spectrum. As in the LWRS spectrum, the shorter wavelength component is about the width of the slit, and the longer wavelength component is broader, consistent with the FWHM of about 150 km s\(^{-1}\) seen in the LWRS spectrum.

In Figure 4 we show an overlay of O VI \(\lambda 1032\) flux and 2 times the O VI \(\lambda 1038\) flux plotted as a function of velocity. This is shown for the LWRS (top panel) and MDRS (bottom panel) spectra. The lower state for each of these transitions is the ground state, and the upper states have statistical weights in a 2:1 ratio. Therefore, in the case of optically thin emission, the 1032Å line is expected to be twice as strong as the 1038Å line. As the O VI optical depth increases, the shorter wavelength line is preferentially scattered out of the line of sight and this ratio becomes smaller. The overlay in Figure 4 shows that for the region we have observed, the emission is close to being optically thin. The lines are centered at about \(-50\) km s\(^{-1}\) with FWHM of about 130 km s\(^{-1}\) in the LWRS and 60 km s\(^{-1}\) in the MDRS.

The line profiles of the two O VI lines match up well at velocities around the emission peak and in the red wing, but the O VI 1038Å line has excess emission on its blue wing, between \(-200\) km s\(^{-1}\) and \(-300\) km s\(^{-1}\) (Figure 4, top panel). This excess is seen clearly in each of the individual LWRS segments covering the O VI wavelength region and it is therefore highly unlikely to be an instrumental artifact. We have identified this feature as C II \(\lambda 1037.02\) emission. It is at the correct wavelength for this line blue shifted by the same amount as the O VI lines. A corresponding excess of emission at the same velocities is seen also in the MDRS spectrum. (By itself, the MDRS spectrum is noisy as seen in Figure 4 and we would not have claimed a detection based on that alone. However, the coincidence with the LWRS result makes the identification plausible in the MDRS data.) The C II 1037.02Å line is one of a pair of lines that have a common upper state. This line has a lower state which is 63 cm\(^{-1}\) above the ground state, while the companion 1036.34Å line is a ground state transition (see Morton 1991). We do not see the 1036.34Å line in our spectra, but this is not surprising. This line is only half as strong as the 1037.02Å line in the recombination spectrum and furthermore, being a ground state transition, it could quite easily be absorbed by intervening gas. The existence of C II is expected in a fully recombined shock. For instance, R97 detected C II \(\lambda 1335\) (albeit weakly) in their HUT spectra of nearby regions in Vela.

In Figure 5 we show an overlay of C III \(\lambda 977\) and O VI \(\lambda 1032\) fluxes plotted in velocity space. The C III flux has been multiplied by 2 for the display. The two components of C III are seen in both the LWRS (top panel) and MDRS (bottom panel) spectra. The shorter wavelength component of C III lines up with the O VI line, though it is clearly narrower. (The offset of about 20 km s\(^{-1}\) between their peaks is not significant. The lines are from two different detector segments, and the offset is within the relative errors in the absolute wavelength scale.) The second component of C III is wider (FWHM \(\sim\) 150 km s\(^{-1}\)) and
is centered at about +100 km s\(^{-1}\). We estimate that this red-shifted component contains about 45% of the total C III flux.

C III \(\lambda 977\) is a strong resonance line and therefore the observed line profile is likely to be affected by self absorption (see Blair et al. 2000a for an example of this effect in the LMC SNR N49). Having observed no other low ionization lines in the FUSE spectrum we cannot make a detailed assessment of the effect of self absorption. However, the fact that the width of the red-shifted component is the same in both LWRS and MDRS spectra while the blue-shifted component is narrower in the MDRS (reflecting filled slit emission) is evidence that the two emission peaks are from two physically distinct components. (This interpretation is also supported by the O VI line profiles which show no sign of a tail towards the red-shifted wing). We have examined FUSE spectra of a few stars behind Vela and found that the C III absorption is typically centered near zero velocity, has a FWHM of about 60 km s\(^{-1}\) and a peak absorption of about 50%. Absorption by such a component would change the C III flux by about 8%. Also, taking this absorption into account would leave unchanged our conclusion that there are two distinct components. We note that the C III fluxes presented in this paper have not been corrected for any self absorption.

In Table 1 we list line fluxes and the C III and O VI surface brightnesses for our FUSE spectra and for the HUT spectra of adjacent regions presented in R97. The FUSE line fluxes were obtained by simple trapezoidal integration over the lines. The error in each of the fluxes for the stronger lines is dominated by the absolute flux calibration which is accurate to about 10% (Sahnow et al. 2000). For the MDRS C III and LWRS S VI fluxes, which have higher random errors, we estimate the accuracy to be 15% and 30% respectively. In the table, the total C III flux is presented for the FUSE observations, to allow direct comparison with the HUT data, for which the kinematic components were unresolved. (In the FUSE spectra, the blue-shifted component contains \(\sim 55\)% of the flux, and the red-shifted component contains the remaining \(\sim 45\)%). Also, the C II \(\lambda 1037.02\) flux, estimated to be \(7 \times 10^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) in the LWRS spectrum (Figure 4), was subtracted from the O VI \(\lambda 1038\) flux. (The exact value of the C II flux will not affect our discussion below, since it is so much weaker than the O VI.)

The flux ratio of O VI \(\lambda 1032\) to O VI \(\lambda 1038\) in the FUSE spectra (LWRS and MDRS) is about 2:1, indicating that the emission is optically thin. (We note that the two lines were not resolved with HUT and so only the total flux was presented.) The S VI \(\lambda 933\) and S VI \(\lambda 944\) line strengths are also consistent with a 2:1 ratio as expected for optically thin emission. The O VI surface brightnesses in the LWRS and MDRS spectra differ by less than 5%. However, the C III surface brightness in the MDRS spectrum is about 30% higher than in the LWRS spectrum. It is not clear how significant this difference is - the MDRS short wavelength spectrum is noisy and the C III line is weak, so its measured flux is sensitive to the background value chosen and the real difference may not be as high as 30%. In any case, because the similarity in the line profiles, we will assume that the LWRS and MDRS apertures sample gas having more or less the same emission properties and use
mainly the LWRS data below.

The C III to O VI surface brightness ratio is 0.24 for the FUSE LWRS spectrum, 0.10 for the HUT face-on shock position and 0.39 for the HUT edge-on shock position. Differences in the C III surface brightness contribute more to this range of values than do differences in the O VI surface brightness. The C III in the FUSE LWRS spectrum is 3.1 times as bright as in the HUT face-on spectrum, while the O VI is only 1.3 times as bright. Similarly, the C III in the HUT edge-on spectrum is 5.5 times as bright as in the FUSE LWRS spectrum, while the O VI is 3.4 times as bright. The probable cause of these differences is discussed below in §4.2.

The fluxes presented in Table 1 have not been corrected for interstellar reddening. While this is useful in comparing different observations, the correction needs to be done to obtain intrinsic line fluxes that reflect conditions in the emitting gas. Even the moderate color excess, \( E_{B-V} = 0.1 \), towards Vela (Wallerstein & Balick 1990, Blair et al. 2000b) results in significant extinction at far-ultraviolet wavelengths. R97 corrected their HUT spectra of Vela using the Cardelli, Clayton & Mathis 1989 extinction curve and, following previous studies of the Cygnus Loop SNR (Blair et al. 1991, Long et al. 1992), used the Longo et al. 1989 extinction curve at the shortest wavelengths. They obtained correction factors of 3.8 and 3.7 for the C III and O VI fluxes, respectively. The Longo et al. 1989 extinction curve, which is based on Voyager observations, flattens out at about 1000 Å and falls below the extrapolation of the Savage & Mathis 1979 extinction curve (see their Figure 3). As Longo et al. 1989 themselves discuss, it is unclear which of these extinction curves is more accurate, especially since the data used to derive them had very low spectral resolution. For this paper, we use the more recent extinction curve presented by Fitzpatrick 1999 and follow his suggestion that extrapolation to far-ultraviolet wavelengths is the best dereddening strategy. For \( E_{B-V} = 0.1 \) and total to selective visual extinction, \( R = 3.1 \) (the standard value for diffuse ISM gas), we obtain correction factors of 4.5 and 3.7 for the C III and O VI fluxes, respectively. (The calculations were done using the IDL Astronomy Library implementation of the Fitzpatrick reddening correction routine.)

4. Discussion

4.1. Shock Components Observed by FUSE

The FUSE data show the existence of two components contributing to the ultraviolet emission along the line of sight. One component, blue shifted by about 50 km s\(^{-1}\) has strong O VI and C III emission. Weaker S VI and C II emission is also detected from this component. The C III emission can be explained by a shock that has cooled and recombined. Assuming that 55% of the total C III emission (Table 1) is from this component and correcting for reddening using the factors given above, the intrinsic O VI to C III flux ratio of this component is 6.3, implying a shock velocity of about 180 km s\(^{-1}\). The shock
front would have to be moving \( \sim 15^\circ \) out of the plane of the sky, towards us, for the emission peak to be at \(-50 \text{ km s}^{-1}\). The presence of S VI emission is consistent with a shock velocity of 180 km s\(^{-1}\) as it is a comparable but slightly lower ionization species than O VI. The second component, red-shifted by about 100 km s\(^{-1}\), has strong C III emission but no O VI emission (Figure 5). The emission is thus due to a shock with velocity less than about 140 km s\(^{-1}\), which produces negligible O VI. The location of this shock along the line of sight is uncertain - it could, for instance, be a shock driven into a cloud on the back face of the remnant. It is worth noting that Voyager UVS spectra of Vela presented by Blair, Vancura & Long 1995 showed C III to O VI ratios ranging from 0.6 to 2.8 in 300 square arcminute fields of view, indicating that the production of ultraviolet lines was dominated by slower shocks.

For the component with an observed Doppler shift \( v_{\text{obs}} = -50 \text{ km s}^{-1} \), we can invoke a procedure described by Raymond et al. 1988 to determine the shock’s dynamical pressure from an emission line, regardless of the projection factor \( \cos \theta \) of the front’s normal vector onto the line of sight. (See also equations 1-3 of R97.) Calculations of emission line intensities from planar shocks (Hartigan, Raymond & Hartmann 1987) indicate that for shocks with velocities over the range \( 160 < v_s < 400 \text{ km s}^{-1} \), the production rate \( Y \) for C III \( \lambda 977 \) radiation is nearly constant at 0.28 photons emitted in 4\( \pi \) steradians for each atom that passes through the shock front. The yield is much higher for shocks with \( v_s < 160 \text{ km s}^{-1} \), but the presence of O VI emission indicates that \( v_s \) is above this value. The production rate assumes a carbon abundance of 8.52 on a logarithmic scale where the abundance of hydrogen equals 12.0. It also assumes that the shock is radiative, the C III zone is complete and the emission is optically thin. The observed C III flux relative to the O VI flux requires that the shock we are considering is radiative. In a non-radiative shock that is fast enough to produce O VI, the C III flux would be over an order of magnitude weaker. We have run shock models (using an updated version of the code described in Raymond 1979), and found that at the point the O VI flux reaches half its maximum value for a radiative shock, the C III flux is less than 2% of its maximum value. The measured flux ratio of C II \( \lambda 1037 \) to C III \( \lambda 977 \) is about 0.1. We find from our shock models that such a high ratio is possible only in the case when the C III zone is complete and most of the carbon has recombined to C II. Since the blue-shifted component is radiative and complete, we are justified in using the value of \( Y \) from Hartigan, Raymond & Hartmann 1987 given above.

From Table 4, we find that the average of the two FUSE surface brightness measurements of this blue-shifted component (which accounts for 55\% of the total observed C III emission) is \( 0.83 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \). The energy of a C III \( \lambda 977 \) photon is \( 2.03 \times 10^{-11} \) ergs and 1 steradian equals \( 4.26 \times 10^{10} \) square arcseconds. Therefore, the blue-shifted C III surface brightness corresponds to a specific intensity, \( I_{\text{obs}} = 1.7 \times 10^5 \) photons cm\(^{-2}\) s\(^{-1}\) str\(^{-1}\). If we correct this observed intensity for extinction (multiplying by 4.5) and then divide by \( Y/4\pi \), we obtain a measure of \( n_0 v_s/ \cos \theta \), where \( n_0 \) is the number density of atoms and ions entering the shock on the upstream side.
Multiplying this quantity by the mean atomic mass $1.3m_{\text{H}}$ and $v_{\text{obs}} = v_s \cos \theta$ gives the dynamical pressure $pv_s^2 = 3.7 \times 10^{-10}$ dyne cm$^{-2}$, or $p/k_B = 2.7 \times 10^6$ cm$^{-3}$ K (where $k_B$ is the Boltzmann constant). For a shock velocity of 180 km s$^{-1}$, this implies a pre-shock hydrogen number density of $\sim 0.5$ cm$^{-3}$.

Our value for the dynamical pressure is more than a factor of 4 smaller than the $1.6 \times 10^{-9}$ dyne cm$^{-2}$ ($p/k_B = 1.2 \times 10^7$ cm$^{-3}$ K) found by R97 for a region immediately behind the HUT edge-on shock position. It is a factor of 8 smaller than the $2 - 4 \times 10^{-9}$ dyne cm$^{-2}$ ($p/k_B = 1.4 - 2.8 \times 10^7$ cm$^{-3}$ K) found by Jenkins & Wallerstein in another location within the Vela remnant. These other values were found using the method described above, applied to [O III] $\lambda\lambda 4959,5007$ emission. In sharp contrast, our value for the dynamical pressure is larger, by a factor of about 4, than the pressure for the diffuse emission in Vela found by Kahn et al. 1985. The pressure scales with the diameter of the remnant and Kahn assumed a distance of 500 pc to Vela. For the revised distance of 250 pc, his results imply a pressure of $\sim 1 \times 10^{-10}$ dyne cm$^{-2}$ ($p/k_B \sim 7 \times 10^5$ cm$^{-3}$ K) in the bulk of the remnant.

These differences in pressure have important implications for the properties of Vela, and for models of SNRs. For example the assumption sometimes made that the interior of an SNR is isobaric is not tenable in this case. The most straightforward explanation for a region of significantly higher pressure is the existence of a reverse shock driven back into the SNR interior when the forward blast wave encounters a dense cloud (e.g. Spitzer 1982). The region between the forward and reverse shocks is expected to be overpressured relative to the interior of the remnant. Since the pressures driving the shocks observed by FUSE and HUT are several times higher than the pressure in the interior, we infer the existence of reverse shocks. The density is also higher in this doubly shocked region which results in the X-ray emission being enhanced. We conclude that the X-ray knot consists of regions between forward and reverse shocks.

Craig 1994 studied the X-ray emission from this knot as well as two others in Vela and found that the X-ray brightness of the knots was about 20 times higher than neighbouring regions. Based on these measurements, he also came to the conclusion that these knots were overpressured compared to other locations in the remnant due to reverse shocks. In this scenario, the correlation between the X-ray emission and the radiative shocks (seen in HUT and FUSE ultraviolet spectra and in the case of the HUT edge-on shock also as optical filaments) favours a model where, in this region, the blast wave has encountered a cloud but has not yet engulfed it (Graham et al. 1995). The alternative model that the emission is from thermally evaporating material from smaller clouds engulfed by the blast wave cannot explain the observed pressure contrasts (Hester & Cox 1986; Graham et al. 1995).
4.2. Structure in the X-ray Knot

The difference in the C III to O VI ratio among the FUSE LWRS spectrum, the HUT face-on spectrum and the HUT edge-on spectrum is empirical evidence that the properties of the emitting gas vary on arcminute scales in the plane of the sky. We use the ROSAT images of the X-ray knot (Figure [1]) to correlate the ultraviolet emission with the X-ray morphology of the region.

The X-ray knot has dimensions of about $30' \times 12'$ and lies close to the projected center of Vela. Spectral analysis of Einstein data have constrained the temperature of this knot to lie between about $1 \times 10^6$ K and $2 \times 10^6$ K (Kahn et al. 1985). The ROSAT PSPC images in the R1R2 and R4R5 bands (Figures 1a, b) show that the emission within the knot is patchy on scales of a few arcminutes. On this spatial scale, the ratio of the R4R5 emission to the R1R2 emission is approximately constant over the knot. We have chosen specific arcminute-size regions within the knot and fitted the spectra obtained from individual ROSAT PSPC bands with Raymond-Smith models (Raymond & Smith 1977). We find that the emission from each of these regions can be fitted with a temperature $T \sim 1.2 \times 10^6$ K and a hydrogen column density $N_H \sim 4 \times 10^{20}$ cm. (The equilibrium calculation is presented to show the consistency between the ROSAT data and the Einstein data presented by Kahn et al. 1985. Further analysis of the x-ray emission, such as nonequilibrium ionization modelling, is beyond the scope of this paper.) The ROSAT HRI image (Figure 1c) shows that the eastern edge of the southern part of the knot is very well defined. Figure 1d is a blow-up of the HRI image, overlaid with contours derived from the image convolved with a 2D gaussian having a FWHM of 3 pixels ($15''$). The contour labels are count rates proportional to the X-ray flux. The contours clearly define the eastern edge, and show that the HUT edge-on aperture, which includes a bright [O III] filament (Figure 1 of R97), lies right at the boundary of the knot. We note that this morphological relationship of the X-ray and optical emission seen at a spatial resolution of $5''$ also favours the large cloud model over the thermal evaporation model (Hester & Cox 1986) discussed in §4.1, above.

The X-ray knot shows significant substructure. Of particular interest to the current study is the presence of a fainter band separating two bright regions in Figure 1d, demarcated by the level 8 contours. The contours have been chosen to highlight the morphology seen - the feature is clear in the higher contrast image, Figure 1c, within the white box. There is also a hint that the feature shows up in the PSPC images, especially the R1R2 band (Figure 1a). The FUSE LWRS aperture lies within the brighter region to the north of this band, while the HUT face-on aperture crosses into the fainter band. We will call these the “bright” and “faint” regions (based on the ROSAT HRI image) in the rest of the paper and discuss the spectral data based on this spatial separation.

If we define the level 8 contour to be the boundary between the bright and faint regions, then approximately one quarter of the area of the HUT face-on aperture (931
square arcseconds) lies on the bright region and the remaining three quarters (2793 square arcseconds) on the faint region (Figure 1d). We assume that the surface brightness of the lines in the upper quarter of the aperture is the same as in the adjacent FUSE LWRS aperture. (Note that we are assuming the same two kinematic components along the line of sight and are not concerned with separating the contributions of each.) Using these FUSE LWRS values for the C III and O VI surface brightness given in Table 1 and multiplying by 931 arcsec$^2$ (the area of the HUT face-on aperture lying on the bright region), we find the C III and O VI fluxes from this bright region within the HUT face-on aperture to be $1.19 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $4.99 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, respectively. We subtract these fluxes from the total HUT face-on spectrum fluxes (Table 1) and then divide by 2793 arcsec$^2$ (the area of the aperture lying on the faint region) to obtain a C III surface brightness of $0.13 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ and an O VI surface brightness of $3.95 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ for the faint region. The C III surface brightness of the faint region is thus only about 10% that of the bright region. The O VI emission is relatively uniform, as the surface brightness of the faint region is 75% that of the bright region. The C III to O VI ratio for the bright region is 0.24 (by definition equal to the ratio in the FUSE LWRS spectrum) and for the faint region the ratio is 0.03.

Based on their analysis of the HUT data, R97 concluded that the shock conditions in the edge-on shock and face-on shock are quite similar. They pointed out that the observed C III in the face-on shock spectrum is weaker than predicted by the best fit models; however, they did not address the question of why the C III to O VI ratio in the two locations is different. The picture we have presented requires a more extreme difference in this ratio between the edge-on shock and the faint region sampled by the HUT face-on aperture. A straightforward explanation of the very weak C III emission in the faint region is that the emission is dominated by “incomplete” radiative shocks - where the post shock gas has not yet fully recombined to C III. Note that this is consistent with the absence of [O III] emission from this faint region (Figure 1 of R97). This means that for a shock velocity of about 180 km s$^{-1}$, the swept up column is less than $1.5 \times 10^{18}$ cm$^{-2}$. If this is the case, conditions in the edge-on shock region and the faint region need not be drastically different. A small contrast in pre-shock density could result in different degrees of completeness in the recombination zone. The edge-on shock position was chosen to be on the bright [O III] filaments, and since C III and O III trace each other in recombining post shock gas, the strong C III emission in that position is a selection effect. A systematic study of the spatial distribution of both high and low ionization emission is required to address this issue in detail.

5. Concluding Remarks

We have presented FUSE spectra of an X-ray knot in the Vela SNR. Spectra taken through the LWRS and MDRS apertures show strong O VI and C III emission. The two
lines of the O VI doublet are well separated from each other and from the Lyβ airglow in these spectra. We have detected C II λ1037.02 emission as an excess of flux on the red wing of the O VI 1038Å line. This is the first detection of this emission line in an SNR. The high spectral resolution also allows us to examine the kinematic structure of the emitting gas in much more detail than has so far been possible. We detect two kinematic components, one of which has a central velocity of -50 km s\(^{-1}\) and a shock velocity of about 180 km s\(^{-1}\) (strong O VI emission) and the other which has a central velocity of about +100 km s\(^{-1}\) and a shock velocity < 140 km s\(^{-1}\) (no O VI emission). We identify the former with the observed X-ray knot and the latter with a separate component, possibly the back side of the SNR shell. The properties of the emitting gas (including the two component structure) are very similar in both the LWRS and MDRS aperture locations, which are separated by a few arcminutes.

We have obtained the dynamic pressure driving the shock responsible for the blue-shifted component observed in the FUSE spectra and found it to be a factor of about 4.5 smaller than the pressure found by R97 in an adjacent region near the bright optical filaments tracing the edge-on shock. The pressure we find is a factor of about 4 larger than the pressure in the regions of diffuse X-ray emission within Vela found by Kahn et al. 1988. We suggest that the presence of reverse shocks create these localized regions of high pressure within the remnant. These regions are associated with bright X-ray emission and with the observed radiative shocks and suggest that the emitting regions are part of a large cloud that the supernova blast wave has encountered relatively recently.

We have compared the FUSE spectra with HUT spectra taken at nearby locations and found that the emission characteristics, in particular the ratio of low excitation to high excitation lines, change on arcminute scales within the X-ray knot. We have presented ROSAT images and discussed a possible relationship between the X-ray morphology and the ultraviolet spectra. Specifically, we suggest that there are two distinct regions within the X-ray knot, separated by a rather sharp boundary, running approximately east-west. In this picture, the FUSE apertures are completely contained in the northern X-ray bright region while the large HUT aperture on the “face-on” shock position cuts across the boundary, sampling emission from both regions. We infer C III to O VI ratios for the X-ray bright and faint regions and suggest that variations in shock completeness can account for the observations. This is also consistent with the recently shocked cloud scenario.

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Fig. 1.— X-ray images of the knot in Vela. North is up and east is to the left in all these images. The coordinate labels are right ascension and declination in J2000 coordinates. (a) ROSAT PSPC image in the R1R2 (0.11 keV - 0.28 keV) band. The circular field of view is about 2° in diameter. (b) ROSAT PSPC image of the same region as (a) in the R4R5 (0.44 keV - 1.21 keV) band (c) The ROSAT HRI image of the knot. The white box corresponds to the region shown in panel (d). (d) A blow-up of the HRI image, 500″ on the side, displayed with a logarithmic stretch overlaid with contours. The contours were derived from the same HRI image, convolved with a gaussian with FWHM of 3 pixels. The contour levels are 3, 5 and 8 HRI counts per 5″×5″ pixel in a 61 ks exposure. The black boxes show aperture locations; from east to west (left to right), they correspond to the HUT edge-on, HUT face-on, FUSE LWRS and FUSE MDRS positions. Note that the MDRS aperture lies due west of the LWRS aperture. Arrowheads at the top of the plot are placed to help locate these boxes on the image.

Fig. 2.— Spectra taken through the 30″×30″ LWRS aperture showing the detected lines. The short wavelength spectra including S VI emission (top panel) and C III emission (middle panel) are the sum of two channels and the long wavelength spectrum including O VI emission (bottom panel) is the sum of four channels. In all plots, the spectra have been binned by 4 pixels. Airglow lines (all from the Lyman series) have been marked.

Fig. 3.— Spectra taken through the 4″×20″ MDRS aperture showing the detected lines. (S VI is very faint, and is not seen in the MDRS spectrum). The short wavelength spectrum is a single channel spectrum binned by 8 pixels. The long wavelength spectrum is the sum of four channels and binned by 4 pixels. Airglow lines have been marked. The center of this aperture lies about 3.5′ west of the LWRS aperture center, well within the X-ray knot (Figure 1).

Fig. 4.— Overlay of the O VI λ1038 and λ1032 lines. Both lines are centered at about −50 km s\(^{-1}\) and have FWHM equal to about 115 km s\(^{-1}\). The flux in the 1038Å line profile has an excess between −300 and −200 km s\(^{-1}\). This is clearly seen in the LWRS spectrum (top panel) and, though noisy, in the MDRS spectrum as well (bottom panel). The spectra shown here are each the sum of 4 channels; since the excess is seen in each of the individual channels, it is highly unlikely to be instrumental. We identify the feature as C II λ1037 emission.

Fig. 5.— Overlay of C III λ977 and O VI λ1032 for the LWRS (top panel) and MDRS (bottom panel) data. The C III line has two components. One component centered at about −50 km s\(^{-1}\) is associated with the O VI emission, while the other component is centered at about +100 km s\(^{-1}\) and has no corresponding O VI emission. The red shifted component of C III contains ∼45% of the total C III flux.
Table 1. Observed Line Strengths in FUSE and HUT Spectra

| Aperture  | FUSE LWRS | FUSE MDRS | HUT Face-on<sup>a</sup> | HUT Edge-on<sup>a</sup> |
|-----------|-----------|-----------|-------------------------|-------------------------|
| Aperture  | 30″ × 30″ | 4″ × 20″   | 19″ × 196″               | 10″ × 56″               |
| Flux (10<sup>−13</sup> erg s<sup>−1</sup> cm<sup>−2</sup>) |
| S VI 933  | 0.18      | ...       | ...                     | ...                     |
| S VI 944  | 0.09      | ...       | ...                     | ...                     |
| C III 977<sup>b</sup> | 1.15 | 0.14      | 1.55                    | 3.97                    |
| O VI 1032<sup>c</sup> | 3.17 | 0.28      | 16.03<sup>d</sup>      | 10.09<sup>d</sup>      |
| O VI 1038<sup>c</sup> | 1.65<sup>e</sup> | 0.13 | ...                     | ...                     |
| Observed Surface Brightness<sup>f</sup> (10<sup>−16</sup> erg s<sup>−1</sup> cm<sup>−2</sup> arcsec<sup>−2</sup>) |
| C III 977<sup>b</sup> | 1.28 | 1.75      | 0.41                    | 7.09                    |
| O VI 1032,1038<sup>c</sup> | 5.36 | 5.13 | 4.28 | 18.02 |

<sup>a</sup>Data from Raymond et al. 1997.

<sup>b</sup>Total of both kinematic components observed by FUSE. 55% is from the component at −50 km s<sup>−1</sup> and the rest from the component at +100 km s<sup>−1</sup>.

<sup>c</sup>O VI is seen only in the −50 km s<sup>−1</sup> component; see text and Figure 5.

<sup>d</sup>Total of both lines in the doublet, which was unresolved in the HUT spectra.

<sup>e</sup>Corrected for C II λ1037.02 emission; see text.

<sup>f</sup>Not corrected for foreground extinction.
The diagram shows the flux ($10^{-13}$ erg/(s cm $^2$ Å)) of C II 1037 (dashed lines) and 2 x O VI 1038 (solid lines) as a function of velocity (km/s) for LWRS and MDRS.

**For LWRS:**
- O VI 1032
- 2 x O VI 1038

**For MDRS:**
- O VI 1032
- 2 x O VI 1038

The flux values range from 0.0 to 8.0 on the y-axis.
