Far Ultraviolet Spectroscopic Explorer Survey of Magellanic Cloud Supernova Remnants

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ABSTRACT

We report the progress to date from an ongoing unbiased ultraviolet survey of supernova remnants in the Magellanic Clouds using the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. Earlier work with FUSE and other instruments has indicated that optical and/or X-ray characteristics of supernova remnants are not always good predictors of their brightness in the ultraviolet. This survey is obtaining spectra of a random large sample of Magellanic Cloud supernova remnants with a broad range of radio, optical, and X-ray properties. We proposed 39 objects in the Large Magellanic Cloud and 11 objects from the Small Magellanic Cloud, with a standard request of 10 ks per object using the FUSE 30\textdegree square aperture. To date, 39 objects have been observed in the survey (38 in the LMC and 1 in the SMC) and 15 have been detected, a detection rate of nearly 40%. Our survey has nearly tripled the number of UV-detected SNRs in the Magellanic Clouds (from 8 to 22). Because of the diffuse source sensitivity of FUSE, upper limits on nondetected objects are quite sensitive in many cases, dependent on night observing fraction and whether stellar light contamination plays a role for a given object. Estimated total luminosities in O vi, based simply on scaling the flux at the observed positions to an entire object, span a broad range from considerably brighter to many times fainter than the inferred soft X-ray luminosities, indicating that O vi can be an important and largely unrecognized coolant in certain objects. We compare the optical and X-ray properties of the detected and nondetected objects but do not find a simple indicator for ultraviolet detectability. Nondetections may be due to clumpiness of the emission, high foreground extinction, slow shocks whose emission gets attenuated by the Magellanic interstellar medium, or a combination of these effects. The characteristics of individual detected supernova remnants are summarized in an Appendix.

Subject headings: Magellanic Clouds — shock waves — supernova remnants — ultraviolet: general

1. INTRODUCTION

Supernova remnants (SNRs) as a class are important constituents of the interstellar medium (ISM). They are responsible for much of the enrichment of the ISM of a galaxy, and they are a significant energy source for stirring and mixing the ISM. They may also be important in some regions for triggering star formation in molecular clouds. SNRs typically emit over nearly the entire electromagnetic spectrum, and multwavelength observations have become an important source of physical information about the ejecta (in young objects), and the circumstellar medium and ISM into which the shock wave propagates.

Ultraviolet spectroscopy of SNRs has proven to be an important tool for providing physical information and insight into this important class of objects (Blair 2001; Raymond 2001 and references therein). Emission lines in the UV tend to come from material at temperatures that are intermediate between the X-ray emitting gas and the optical filaments. Information on shock velocities, preshock densities, and abundances of important elements such as carbon that have no bright optical lines can all be derived from UV observations of shocks. FUSE observations have the added bonus of high spectral resolution, which provides kinematic and line profile information. Thus, the importance of overlying absorption and in some cases the shock geometry can be assessed directly (Blair et al. 2002; Sankrit et al. 2003).

Primarily because of interstellar extinction, however, there are remarkably few objects available for study in the UV. In our Galaxy, the Cygnus Loop and Vela SNRs are the objects that have been studied extensively; both are nearby and have low foreground extinction. Notable but difficult observations of the Crab Nebula (Blair et al. 1992), SN 1006 (Raymond et al. 1995; Korreck et al. 2004), and Puppis A (Blair et al. 1995a) have also been performed.

The foreground Galactic extinction toward the Magellanic Clouds is relatively low, but the number of SNRs observed in the far-ultraviolet (FUV) is still very modest (see Table 1). The young “core-collapse” SNRs N132D (LMC) and 1E 0102–7219 (SMC) are very bright in soft X-rays and have been studied in the UV as well (Morse et al. 1996; Blair et al. 2000a). The X-ray and optically bright SNR N49 has received considerable attention (Vancura et al. 1992; Blair et al. 2000b; Sankrit et al. 2004). However, the next brightest optical SNR in the LMC, N63A, has not been observed in the ultraviolet since the early days of the International Ultraviolet Explorer (IUE) satellite (Benvenuti et al. 1980) even though it should be readily detectable by modern instrumentation. Three out of four of the Balmer-dominated SNRs identified by Tuohy et al. (1982) have only recently been detected with FUSE (P. Ghavamian et al. 2006, in preparation). Not only is this a small sample, but the objects observed have tended to have specific characteristics that attracted attention to them, and with very bright optical and/or X-ray emission in particular. They are not “typical” SNRs, and so the picture we derive for the global impact of SNRs on their host galaxy is seriously biased.

Positions for FUV spectral observations have often been selected based on the optical appearances or characteristics of the region or object being observed, including not only the surface brightness but also particular line ratios or signatures (e.g.,
Raymond et al. 1988; Blair et al. 2002; and references therein). More recently, a few FUV observation positions have been selected based on the appearance in soft X-rays rather than optical (Raymond et al. 1997; Sankrit et al. 2001). With very few FUV images available for guidance, observers have had little else to go by.

However, there have been a growing number of indications that selection criteria for FUV observations of SNRs have been too narrow. FUV spectro-imaging of the Cygnus Loop and Vela SNRs from the Voyager Ultraviolet Spectrometers (Blair et al. 1991, 1995b) and of Vela recently by the SPEAR experiment (Nishikida et al. 2006) show patchy, spatial distributions in key FUV emission lines, albeit at modest spatial resolutions. Higher spatial resolution FUV images of selected regions in the Cygnus Loop are available from the Ultraviolet Imaging Telescope (UIT). Danforth et al. (2000) show comparisons of UIT images to both X-ray and optical images, indicating all wavelengths are patchy and show relative spatial variations. Even though the UIT bandpass did not isolate individual emission lines, spatial variations of the FUV emission are clearly present. Some of the spectroscopic positions observed in the Cygnus Loop and Vela SNRs also correspond to very faint optical filaments and yet the UV emission is bright (Sankrit et al. 2001; Blair et al. 2002; Sankrit & Blair 2002; Raymond et al. 2003).

A serendipitous FUSE observation of a SNR in the SMC H ii region NGC 346 (N66) has provided another important example of potential observational bias (Danforth et al. 2003). With the FUSE MDRS aperture placed on a star in the NGC 346 star cluster, strong O vi and C iv λ977 emission lines were detected in the LWRS aperture a couple of arcminutes away. Reconstructing the LWRS aperture location showed that it was projected onto the limb of a known radio SNR 0057–7226 (Ye et al. 1991). The SNR had been observed previously in FUV absorption with FUSE, using the luminous blue variable HD 5980 as a background source (Koenigsberger et al. 2001; Hoopes et al. 2001), but no FUV emission had been detected. Indeed, no optical shell or emission from the SNR is evident in images of the region, and only extremely faint optical emission from the SNR can be detected in Hα echelle data (Chu & Kennicutt 1988; Danforth et al. 2003). The SNR is an X-ray source (Wang & Wu 1992; Yugokawa et al. 2000; Nazé et al. 2002), but with a luminosity of only Lx(0.3–10 keV) ≈ 1.4 × 10^{35} ergs s^{-1} (Nazé et al. 2002) is certainly not in the class that would make it a priority FUV target. It is unlikely that an FUV observation of this SNR would have ever been attempted had the serendipitous spectrum not been obtained, and yet this is a bright FUV emission source.

To understand the systematics of ultraviolet emission from a wider sample of SNRs, and in particular to investigate the properties of more typical SNRs, we are conducting an FUV survey of Magellanic Cloud SNRs that is not biased by optical, radio, or X-ray characteristics of the selected objects. While the survey is ongoing, we have a significant subset of the proposed observations in hand that allows us to address some of the primary questions about FUV detectability. Section 2 addresses the target selection criteria and describes the survey strategy and observational details. Section 3 describes a general analysis of the detected objects and compares to optical and X-ray data. Details about the individual objects detected are described in the Appendix.

2. TARGET SELECTION AND OBSERVATIONS

The FUSE Survey program category allows one to propose a set of targets for potential observation, with no guarantees that any particular target will be observed. Targets are selected and inserted into observation timelines in ways that provide scheduling flexibility to the observatory, while accomplishing the scientific objectives of the proposed program. We thus compiled a list of potential targets from the optical SNR catalogs of Mathewson et al. (1983, 1984, 1985) and from the X-ray SNR catalog of Williams et al. (1999a). We supplemented this list with a number of individual objects reported in the literature (Smith et al. 1994; Chu et al. 1995, 1997, 2000; Dickel et al. 2001; Smith et al. 2004) and a handful of objects where optical long-slit echelle data from CTIO (Danforth 2003) indicated high-velocity emission in Hα but for which no previous SNR identification had been suggested. Such objects may represent SNRs “buried” in H ii regions that have not heretofore called attention to themselves, similar to the SMC SNR 0057–7226 mentioned earlier. We culled this list by removing objects previously observed with FUSE (see Table 1) and a small subset for which optical extinction measurements or X-ray derived neutral hydrogen column densities indicated severe attenuation of any potential FUV emission. Finally, a selection of six SNRs newly identified in the Magellanic Cloud Emission Line Survey (MCELS) team (Smith et al. 2004) were added in the second year of the survey. Our final list contained 39 objects in the LMC and 11 objects in the SMC. The observations reported below took place over two observing cycles, using FUSE program identifiers D904 (44 LMC and SMC remnants) and E900 (six new MCELS objects in the LMC).

The FUSE instrument covers the wavelength range 905–1187 Å, with a nominal point source resolution R = 2/Δλ ≥ 20,000. For diffuse sources of interest to this program, the spectral resolution is driven instead by the spectrograph aperture size and filling factor. We are primarily interested in the LWRS (30′′ square) apertures.

In general, radio observations of Magellanic Cloud SNRs have had insufficient resolution for detailed comparisons with optical or X-ray imagery, but this is changing. See Dickel et al. (2005).

### Table 1: Previous FUSE Observations of Magellanic Cloud SNRs

| Object | R.A. (J2000.0) | Decl. (J2000.0) | Prog. ID | Detection? | Reference |
|--------|---------------|----------------|----------|------------|-----------|
| SNR 0057–7226 | 00 59 27 | −72 10 05 | P103, P203 | Yes | 1 |
| SNR 0102–7219 | 01 04 04 | −72 01 50 | A075, C083 | Yes | 2 |
| SNR 0505–679 (DEM L71) | 05 05 43 | −67 52 38 | P214, C072 | Yes | 3 |
| SNR 0509–675 | 05 09 32 | −67 31 17 | P214 | Yes | 3 |
| SNR 0519–690 | 05 19 34 | −69 02 10 | P214 | Yes | 3 |
| SNR 0525–696 (N132D) | 05 25 01 | −69 38 34 | A075, B095 | Yes | 4 |
| SNR 0525–661 (N49) | 05 26 04 | −66 05 18 | X005, C055 | Yes | 5, 6 |
| SNR 0548–704 | 05 47 50 | −70 24 52 | P214 | No | 3 |

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References:—(1) Danforth et al. 2003; (2) Sasaki et al. 2006; (3) P. Ghavamian et al. 2006, in preparation; (4) Beasley et al. 2006; (5) Blair et al. 2000b; (6) Sankrit et al. 2004.
for this paper. A filled LWRS aperture produces a roughly square-topped instrumental profile of width 106 km s\(^{-1}\) near 1035 Å. \textit{FUSE} contains four optical channels, each with its own focal plane and spectrograph aperture plate.\(^5\)

\(^5\) Note: Channels are referred to as LiF1, LiF2, SiC1, and SiC2, where LiF and SiC refer to the optical coatings on each channel and the numbers refer to one of two microchannel plate detectors. Furthermore, each detector is subdivided into two segments, A and B, whose boundaries in wavelength space are offset slightly so that full wavelength coverage is maintained. See sect 3 of Moos et al. (2000) for full details.

Small, thermally induced distortions in the \textit{FUSE} optical bench discovered after launch do not allow rigid coalignement of the apertures from each channel over time. Typical misalignments correspond to a few to as much as 10' and can vary even during the course of a given orbit or integration. For reference, the LiF1 LWRS aperture positions are shown in this paper. The LiF1 channel was used for guiding, and so its position on the sky was held fixed while the other channels drifted relative to it. In cases where the object is large in comparison to the \textit{FUSE} apertures, all of the apertures should be sampling similar SNR emission. However, apertures from each channel over time. Typical misalignments discovered after launch do not allow rigid coalignement of the small, thermally induced distortions in the \textit{FUSE} optical bench discovered after launch do not allow rigid coalignement of the apertures from each channel over time. Typical misalignments correspond to a few to as much as 10' and can vary even during the course of a given orbit or integration. For reference, the LiF1 LWRS aperture positions are shown in this paper. The LiF1 channel was used for guiding, and so its position on the sky was held fixed while the other channels drifted relative to it. In cases where the object is large in comparison to the \textit{FUSE} apertures, all of the apertures should be sampling similar SNR emission. However,
on the smaller objects, channel misalignments can cause different sampling and impact the assessments of relative O\textit{vi} and C\textit{iii} line strengths. Further details about the \textit{FUSE} instrument and on-orbit performance information are provided by Moos et al. (2000, 2002) and Sahnow et al. (2000).

The \textit{FUSE} survey strategy involved a standard 10 ks request on each object. These faint emission line sources could all be observed in time-tagged mode. The size of the LWRS apertures plus the sensitivity of the \textit{FUSE} detectors combine to provide exceptional diffuse source sensitivity compared with other FUV spectrographs that have been flown. For instance, a nominal 10 ks observation would detect emission in O\textit{vi} \lambda 1032 that is 100 times fainter than the bright LMC SNR N49 (Blair et al. 2000b; Sankrit et al. 2004), with limiting flux levels near $5 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$. Actual observation times ranged above and below the nominal 10 ks request, at the convenience of the \textit{FUSE} schedulers. (See discussion below and Table 2.)

The intent of the survey was to place the LiF1A LWRS aperture at or near the projected center of each SNR. This strategy had two primary motivations. First of all, to do anything other than this would apply a bias to our survey that was not desirable. We did not want to point at features selected from optical or X-ray images of the objects. Second, it may be advantageous to point through the centers, where typical Doppler shifting of $\pm 30$–150 km s$^{-1}$ would move any SNR emissions out from under potential overlying absorptions by the host galaxy. This is an important factor for strong resonance lines such as C\textit{iii} \λ 977 and O\textit{vi}, the strongest lines seen in most SNR spectra.

In practice, since published catalog coordinates were used for many of the objects, the \textit{FUSE} apertures did not always lie on the exact central positions. In objects with spotty optical emission, for instance, some of the Mathewson et al. (1983, 1984, 1985) coordinates are off center with respect to newer X-ray data, which tends to show the full extent of more objects. Also, in retrospect, some of the MCELS-supplied coordinates did not correspond to the object centers. In all of the SNR figures that follow, we show the actual LiF1A LWRS aperture location observed (i.e., coordinates shown in Table 2), so any miscenterings will be obvious. Since most of the objects in our survey were from 1$^\circ$ to 5$^\circ$ in extent, the LWRS apertures were usually filled with potential emission, even if modest channel misalignments or miscenterings were present. A number of the spectra are impacted to some degree by stellar emission, which affects our ability to sense the presence of potential faint emission features. Strong emission, if present, is still visible even if modest stellar contamination is present.

To date, 39 objects out of the 50 potential targets have been observed, all but one (SNR 0104–723) in the LMC. The distribution of these objects across the face of the LMC is shown in Figure 1, where detections and nondetections are indicated with
Fig. 2.—Summary figure for SNR 0450–709. The top panel shows optical and X-ray images of the SNR with the FUSE LWRS aperture (30′′ square) overlaid for the location and position angle at the time of the observation. Top left, Hα; top middle, [S ii]; top right, soft X-ray (from the source indicated by the label). The FUSE aperture (30′′ square) provides the scale. The middle and bottom panels show FUSE data sections centered on C iii λ977, and O vi λλ1032, 1038, respectively. Each spectral panel contains two horizontal bars with tick marks, indicating the positions of potential overlying absorption features, one at zero velocity for Galactic absorption (labeled “MW”), and one shifted to the mean velocity of the host Magellanic Cloud (+275 km s⁻¹ for LMC; +165 km s⁻¹ for SMC). The long, bold tick marks are at the expected positions of the C iii and O vi resonance lines, which are in emission from the SNR, but potentially in absorption by overlying gas. Medium tick marks indicate positions of H₂ transitions, and short tick marks indicate positions of interstellar O i lines. Very short tick marks in the bottom panel indicate the position of C ii λ1036.3, another very strong ISM absorption line. The Earth symbol indicates terrestrial H airglow emissions from Lyγ (C iii panel) and Lyβ (O vi panel).
separate symbols. Table 2 summarizes the targets observed and the results in terms of detections and nondetections. The details of the spectral analysis and search for SNR emission lines are described in the next section.

3. ANALYSIS AND DISCUSSION

Each FUSE data set has been reprocessed with the most current version of the CalFUSE pipeline publicly available at the time of our analysis, CalFUSE 3.0.7. The output from this version of CalFUSE makes it trivial to inspect both the total data sets and the orbital-night only time periods. The total data sets were inspected first. However, scattered light and backscattered solar line emission can cause confusion in the total data sets, especially for the SiC channels (which include the C\textsc{iii} λ977 line). The redshift of each Magellanic Cloud is enough to separate the SNR C\textsc{iii} emission (when present) from the backscattered solar emission, but potential faint emission can still be lost in the higher background. For those objects with detected C\textsc{iii} and/or O\textsc{vi} line emission, we have chosen to extract, plot, and measure the night-only fractions to avoid contamination problems when

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**Fig. 3.**—Same as Fig. 2, but for SNR 0448–669. In this case, no X-ray data are available, and the coordinate provided was apparently off-center and on the northern limb of the shell.
possible. (Two detected objects had no orbital night integration, however. See Table 2.)

The search for emission centered on the brightest transitions normally seen in the FUV—$\text{O}^{\text{vi}} \lambda 1031.9138, 1037.6154$ and $\text{C}^{\text{iii}} \lambda 977.020$. The $\text{O}^{\text{vi}} \lambda 1032$ line in the LiF1 channel was the primary feature searched for because the LiF1 channel has the highest effective area and the LWRS aperture position was known accurately. For most detected objects, the LiF2B channel also showed $\text{O}^{\text{vi}}$ emission, but at lower signal levels (due to the smaller effective area of this channel). $\text{O}^{\text{vi}} \lambda 1038$ was an important secondary indicator, although it is nearly always impacted severely by overlying absorption. Comparison with published grids of shock models (e.g., Hartigan et al. 1987) indicate that

6 For convenience, we will sometimes refer to these lines in the text with abbreviated wavelength notation, viz., $\lambda 1032, 1038$.

7 An exception is SNR 0509$–$687 (N103B), for which a strong $\text{O}^{\text{vi}}$ signal was seen in LiF1A but no signal was seen in LiF2B. Apparently, the channel misalignment was significant enough on this small diameter SNR to cause the LiF2B channel to miss the SNR entirely. In a similar manner, we cannot be certain whether the absence of $\text{C}^{\text{iii}}$ for this object’s spectrum is intrinsic or due to channel misalignments.
strong C\textsc{iii} emission occurs for shocks with velocities above about 100 km s\(^{-1}\), while O\textsc{vi} emission “turns on” above \(\sim 160\) km s\(^{-1}\), when the shock becomes effective at ionizing O\textsuperscript{4} to O\textsuperscript{5}. Hence, we also searched for C\textsc{iii}, which in principle could be seen even if no O\textsc{vi} was detectable. The SiC channels both cover the C\textsc{iii} line region, but the SiC2A channel has higher effective area, so this channel was searched for SNR emission. Of course, channel misalignment makes the exact location of the SiC2 LWRS aperture uncertain relative to the LiF1 LWRS aperture, as described in §2.

Out of the 39 objects observed to date, 15 detections have been obtained, as indicated in Table 2, a detection rate of 38.5%.

Summary figures showing images of each of these objects and \textit{FUSE} data sections are shown in Figures 2–16. Optical H\alpha and [S\textsc{ii}] CCD images in these figures were provided to us by the MCELS team (Smith et al. 1999), headed by R. Chris Smith of NOAO. The X-ray images have been obtained from the public HEASARC data archive for \textit{Chandra}, \textit{ROSAT}, \textit{XMM-Newton}, and \textit{Einstein}. Squares in the image panels show the nominal LiF1A LWRS aperture position and orientation for each observation. Since the LWRS aperture is 30\arcsec in size, this also provides the spatial scale for each image. \textit{FUSE} data segments near the O\textsc{vi} and C\textsc{iii} regions are shown in separate panels of each figure. Because we are searching for faint emission lines, we found it
beneficial to bin most data sets over 8 CalFUSE 3.0.7 pixels (∼30 km s$^{-1}$) for display in the figures. A brief discussion of each detected SNR is presented in the Appendix.

As can be seen in Figures 2–16, the line profiles exhibit a wide range of shapes. Some are broad (several hundred km s$^{-1}$), some narrow (only slightly above the filled aperture resolution), and some are multipeaked. The O\textsubscript{vi} k\textsubscript{1032} profile is most instructive, as it is often the strongest line seen and has relatively good signal-to-noise ratio. These figures each contain horizontal bars with tick marks that indicate the positions of potential ISM absorption features, primarily H\textsubscript{2} and O I lines. The bar marked “MW” (for Milky Way) shows the Galactic rest frame, and the other bar is shifted to the rest frame of the appropriate Magellanic Cloud (+275 km s$^{-1}$ for LMC; +165 km s$^{-1}$ for SMC). The longest tick marks indicate the expected positions of C\textsc{iii} and O\textsc{vi} lines. Of course, the same transitions that we expect from the SNRs in emission are strong resonance lines that can also be in absorption from the intervening ISM at both Galactic and MC velocities.

Many objects detected in our survey show both O\textsc{vi} and C\textsc{iii} emission at detectable levels. Interestingly, some objects show O\textsc{vi} but no C\textsc{iii} (e.g., SNR 0509–687), but there is only one
detection in C IV only (SNR 0527–658), and this detection is marginal. The presence of O VI emission in most of the detected objects indicates that each of them has some shocks with velocities in excess of 160 km s\(^{-1}\). In SNR 0527–658, at least at the observed location, such shocks are apparently absent. Additional observations at other locations within SNR 0527–658 would be needed to understand whether the absence of O VI is intrinsic to the object or due to the clumpiness of the O VI spatial distribution.

We have measured the observed line widths, approximate centroid velocities, and integrated total line fluxes for all SNRs with detections, and list these values in Table 3. These measurements have been made with IDL tools that permit user interaction in the measurements. Each spectrum is displayed and a cursor is used to set limits around each line for integrating the flux above the background for each feature. Since most of the line profiles are distinctly non-Gaussian, the fluxes derived in this way are simply integrated flux above background, not the equivalent flux for a Gaussian fit. These measurements are only lower limits to the actual fluxes since unknown but potentially significant amounts of emission are apparently absorbed by foreground ISM. (See discussion below.) The full width at zero intensity (FWZI) values listed in Table 3 indicate the full range over which the integration was made. The values listed in Table 3...
are all significantly above the value expected for a filled LWRS aperture, indicating that intrinsic line broadening is detected in all cases. The central velocities listed are not the centroid of measured flux, but rather the center of the FWZI velocity range used.

Two things are immediately obvious from inspection of Table 3. For all objects with both O\textsc{vi} and C\textsc{iii} lines, the central velocities for C\textsc{iii} are more redshifted than for O\textsc{vi}, and the FWZI line widths are significantly higher for O\textsc{vi} than for C\textsc{iii}. Both of these facts are consistent with significant impacts from overlying absorption. Inspection of any of Figures 3–59 from the Danforth et al. (2002) FUSE ISM atlas of sight lines in the Magellanic Clouds shows that the C\textsc{iii} ISM absorption at LMC velocities is typically very saturated and broader than the ISM absorption from O\textsc{vi}. Hence, the portion of the C\textsc{iii} SNR emission that is visible from under this ISM absorption is narrower and appears more redshifted. While O\textsc{vi} ISM absorption is also usually present, it is not usually saturated and varies in strength between sight lines. In the SNRs, often a broad base of emission is seen in O\textsc{vi} \(\lambda 1032\) (e.g., SNR 0454–665, Fig. 5), and thus a larger FWZI is measured and the central velocity is less shifted than for C\textsc{iii}.

Overlying absorption is also obviously present in many cases from inspection of the line profiles themselves. There are some cases where an apparently broad O\textsc{vi} emission line has been
partially but not totally absorbed on the blue side by LMC and/or Galactic ISM (e.g., SNR 0506–680, Fig. 6). In general, the line widths for C III are equal to or narrower than widths for O VI, consistent with a saturated C III ISM absorption (even stronger than in O VI) impacting the observed profile. The line profiles often give the impression of being cut off on the blue side, as if they are peeking out from under the overlying LMC absorption. We see only one example where substantial emission is seen blue-ward of the rest LMC (or SMC) wavelength, that being SNR 0536–706 (Fig. 15), and in this case the blue wing of the line appears to be truncated by Milky Way O VI absorption. Since we are looking through the middle of each SNR, we are preferentially seeing redshifted emission from the back side of each SNR, while the front-side shell emission is typically absorbed or partially absorbed by MC and Milky Way ISM absorptions.

We now address the one object with detected C III and no O VI emission, SNR 0527–658 (Fig. 9). It is conceivable that O VI emission is present in this object but just not at the location of the LWRS aperture, or that this object is dominated by shocks slower than \( \sim 160 \text{ km s}^{-1} \). We have no independent way of checking which of these possibilities may apply in this case. If the former suggestion is correct, it would imply a rather clumpy distribution of O VI, at least in some objects. If the latter situation is true, it may provide a reason why few (only one to date) C III–only objects are observed. Assuming we are systematically seeing the redshifted sides of the shells, objects with slower
shocks (and hence lower bulk motions) will tend to be buried (or mostly buried) underneath the strongly saturated MC C III ISM absorption line. We note that the observed C III profile in the spectrum of SNR 0527–658 appears to be cut off sharply on the blue side. Apparently in this case, the relative motions are such that the C III line is partially seen in spite of the overlying absorption.

In general, however, a combination of effects tend to complicate the situation with C III. The uncertainty in position of the SiC channels with respect to LiF1, the lower effective area, and the propensity for significant spectral contamination by solar-backscattered C III all work against C III detection at various levels. (See more detailed discussion below for Fig. 17.)

Nondetections come in two basic varieties, those for which no significant evidence for O VI or C III emission lines is seen, and those observations for which significant stellar light contaminates the FUSE data and makes detection of faint emission lines difficult to impossible. Figure 17 shows the C III and O VI regions of FUSE data for SNR 0507–685, one of the nondetections without significant stellar contamination. This example shows both total and night-only data segments for comparison. No O VI lines are detected, and while some spectral structure appears
at nearly the correct wavelength for LMC C\textsc{iii} emission, the large change between the total and night-only data sets implies the observed feature is not intrinsic SNR emission. In the case of the SiC2A channel, this is an instrumental feature caused by the miscentering of low pulse-height photons from the strong airglow feature to the left. Still, the presence of such structure in the spectrum limits the ability to set a significant upper limit at C\textsc{iii} unless a significant amount of orbital-night exposure time is available.

Figure 18 shows the same spectral regions for SNR 0519–697 (N120), one of the objects with stellar contamination. This example shows that a peak near the expected O\textsc{vi} position is present at a low level, but its interpretation is uncertain. Many hot stars contain P Cygni wind features of varying strengths and shapes that could produce some O\textsc{vi} emission. On the other hand, some SNR emission could be present at an undetermined level and be masked by the variable stellar continuum. In cases such as this (indicated in Table 2), our ability to place limits on O\textsc{vi} are made inherently more difficult.

Thus, the quality of the upper limits varies based on the achieved integration times for each object and whether stellar
contamination is present. Also, the unknown velocity widths for the undetected objects makes placing a specific upper limit rather arbitrary. We choose to adopt the method of Dixon et al. (2006), who have determined upper limits for a wide range of FUSE data empirically, assuming a width appropriate for a filled LWRS aperture and the LiF1 channel, viz.,

$$U(1032) = \frac{273.1}{\sqrt{t_{\text{exp}}}}$$

where $t_{\text{exp}}$ is the night exposure time in seconds, and $U(1032)$ is a 3 $\sigma$ upper limit at $\lambda$1032 in units of 1000 Line Units$^8$ (KLU), where 1 KLU = $4.5 \times 10^{-19}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Thus, a night integration of 5 ks corresponds to $U(1032) = 3.9$ KLU or a 3 $\sigma$ LWRS upper limit of $1.56 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, assuming a filled aperture and an unresolved line width (106 km s$^{-1}$). This is more than 2 orders of magnitude below the measured $F(1032)$

\footnote{A Line Unit corresponds to 1 photon cm$^{-2}$ s$^{-1}$ sr$^{-1}$.}
in the bright LMC remnant N49 (Blair et al. 2000b), although the line width in that case was over 400 km s\(^{-1}\).

Few of the nondetections can be attributed to short integration times (see Table 2), and the inferred upper limits on emission in O\(\text{vi}\), at least at the observed locations, are quite small. Of course in many objects the region sampled by the \textit{FUSE} LWRS aperture is a tiny part of the projected surface area. A clumpy distribution of O\(\text{vi}\) emission could be present, so the absence of detected O\(\text{vi}\) does not necessarily indicate a complete absence of O\(\text{vi}\) emission from an object. For completeness, we indicate the \textit{FUSE} aperture positions on optical (MCELS) and X-ray images (when available) of all nondetections in Figures 19, 20, 21, 22, 23, and 24. Inspection of these figures relative to the detections (Figs. 2–16) demonstrates that, judging from optical and X-ray morphology alone, one would be hard pressed to determine a priori which objects will be detectable in the FUV and which will not. For instance, some large, old optical shell remnants are seen (SNR 0450–709, Fig. 2) and some are not (SNR 0453–672, Fig. 19, third panel). Perhaps more telling, several of the most solid detections with \textit{FUSE} are unimpressive optical and/or X-ray

![Fig. 13.—Same as Fig. 2, but for SNR 0534–705.](image-url)
SNRs (e.g., SNR 0454.5–6713, Fig. 4; SNR 0506–680, Fig. 6), while some nondetections are relatively strong optical and/or X-ray sources (e.g., SNR 0455–687, Fig. 20, top panel; SNR 0519–697, Fig. 21, second panel). There are several SNRs with apparent central X-ray emission consistent with ejecta in both the detected and nondetected samples, but it is not clear we are seeing FUV emission associated with the ejecta in any case, so this does not appear to be a significant factor in FUV detectability.

In Figures 25 and 26, we study some systematics of the sample. In Figure 25, we show histograms of the detections and nondetections as a function of angular size. Since many objects are noncircular, we have simply adopted the average of the ranges shown in Table 2 as being representative for this purpose. There is some indication that detections tend to be smaller diameter than nondetections, but the effect is not large. In particular, in the 1′–4′ range, there are 11 detections and 15 nondetections.
Angular size does not appear to be a primary driver for FUV detectability.

However, there may be some effect at the smallest diameters. In Figure 26, we show the observed $F(\lambda 1032)$ from Table 3 against angular size for the detected SNRs. SNR 0535–660 (N63A) is exceptional, being due to an encounter of a fast shock with a dense cloud (e.g., Warren et al. 2003), and would be located at 45 on the vertical scale of this plot. However, the figure shows the next three brightest objects all below 1.5 in angular size. Between 1.5 and 4', there is significant dispersion in values, but all objects are as bright or brighter than the single detected larger object. A single upper limit is shown at the position of the one SNR detected only in C m. However, by referring back to Figure 25, there are numerous other SNRs in the midrange of angular diameter that would provide upper limits below $1.0 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, indicating an even larger dispersion than shown in Figure 26.

There are at least two objects in the nondetection list with very faint optical emission but well-formed X-ray shells (SNR 0453–685, Fig. 19, fourth panel; SNR 0534–699, Fig. 23, top panel).
These two objects are modest in size and may be dominated by nonradiative shocks (e.g., P. Ghavamian et al. 2006, in preparation, and references therein). Since most of our detections show both O VI and C III lines at relative strengths consistent with radiative shocks (Hartigan et al. 1987), it may be systematically easier to detect such objects over nonradiative cases.

Another factor in nondetections could simply be foreground extinction. Accurate optical color excesses or columns densities are not available for many of the objects we have observed. While the foreground Galactic extinction toward the MCs is generally low, some objects could be impacted by local extinction. MC extinction curves tend to show sharper upturns at short UV wavelengths than the Galactic curve (e.g., Prévot et al. 1984; Fitzpatrick 1985), so this effect cannot be ignored. Since many of the detections are quite faint, some nondetections could just be due to excessive but unknown attenuation.

Fig. 16.—Same as Fig. 2, but for SNR 0104–723. This is the only SMC SNR surveyed to date. The velocity scale of the top bar has been adjusted to that of the SMC.
TABLE 3
MEASURED PARAMETERS FOR MAGELLANIC CLOUD SNR SPECTRA

| SNR      | Object Parameter | O vi λ1032 | O vi λ1038 | C iii λ977 |
|----------|------------------|------------|------------|------------|
| 0448−669 | χ(cent) (Å)       | 1033.18    | 1038.87    | ...        |
|          | χ(cent) (km s⁻¹) | +369       | +361       | ...        |
|          | ΔχFWZI (km s⁻¹)  | 676        | ...        | ...        |
|          | F(χ) (erg cm⁻² s⁻¹) | 2.8E−14   | 9.4E−15    | ...        |
| 0450−709 | χ(cent) (Å)       | 1032.62    | 1038.32    | 978.13     |
|          | χ(cent) (km s⁻¹) | +206       | +201       | +341       |
|          | ΔχFWZI (km s⁻¹)  | 627        | ...        | 219        |
|          | F(χ) (erg cm⁻² s⁻¹) | 1.2E−14   | 3.6E−15    | 1.2E−14    |
| 0454−665 | χ(cent) (Å)       | 1032.94    | 1038.64    | 978.25     |
|          | χ(cent) (km s⁻¹) | +299       | +284       | +377       |
|          | ΔχFWZI (km s⁻¹)  | 336        | ...        | 299        |
|          | F(χ) (erg cm⁻² s⁻¹) | 3.2E−14   | 1.6E−15    | 7.8E−14    |
| 0506−680 | χ(cent) (Å)       | 1032.67    | 1038.40    | 978.28     |
|          | χ(cent) (km s⁻¹) | +220       | +225       | +377       |
|          | ΔχFWZI (km s⁻¹)  | 684        | ...        | 251        |
|          | F(χ) (erg cm⁻² s⁻¹) | 1.7E−13   | 6.5E−14    | 1.3E−13    |
| 0509−687 | χ(cent) (Å)       | 1033.01    | 1039.11    | ...        |
|          | χ(cent) (km s⁻¹) | +320       | +431       | ...        |
|          | ΔχFWZI (km s⁻¹)  | 533        | ...        | ...        |
|          | F(χ) (erg cm⁻² s⁻¹) | 1.6E−13   | 6.9E−14    | <1.0E−14   |
| 0520−694 | χ(cent) (Å)       | 1033.41    | ...        | 978.45     |
|          | χ(cent) (km s⁻¹) | +436       | ...        | +439       |
|          | ΔχFWZI (km s⁻¹)  | 490        | ...        | 391        |
|          | F(χ) (erg cm⁻² s⁻¹) | 6.7E−14   | ...        | 2.0E−13    |
| 0527−658 | χ(cent) (Å)       | ...        | ...        | 978.38     |
|          | χ(cent) (km s⁻¹) | ...        | ...        | +418       |
|          | ΔχFWZI (km s⁻¹)  | ...        | ...        | 315        |
|          | F(χ) (erg cm⁻² s⁻¹) | <1.0E−14 | ...        | 2.2E−14    |
| 0528−692 | χ(cent) (Å)       | 1033.00    | 1038.76    | ...        |
|          | χ(cent) (km s⁻¹) | +320       | +330       | ...        |
|          | ΔχFWZI (km s⁻¹)  | 453        | ...        | ...        |
|          | F(χ) (erg cm⁻² s⁻¹) | 4.8E−14   | 3.5E−14    | ...        |
| 0530−701 | χ(cent) (Å)       | 1032.97    | 1038.69    | ...        |
|          | χ(cent) (km s⁻¹) | +308       | +309       | ...        |
|          | ΔχFWZI (km s⁻¹)  | 604        | ...        | ...        |
|          | F(χ) (erg cm⁻² s⁻¹) | 1.4E−14   | 3.0E−15    | ...        |
| 0532−710 | SNR 0532−710 (D90419) | 1033.13 | 1038.90 | 978.38 |
|          | χ(cent) (Å)       | ...        | ...        | ...        |
|          | χ(cent) (km s⁻¹) | +355       | +370       | +418       |
|          | ΔχFWZI (km s⁻¹)  | 650        | ...        | 315        |
|          | F(χ) (erg cm⁻² s⁻¹) | 1.5E−14   | 1.8E−15    | 2.2E−14    |
| 0534−705 | SNR 0534−705 (D90422) | 1033.34 | 1039.04 | 978.42 |
|          | χ(cent) (Å)       | ...        | ...        | ...        |
|          | χ(cent) (km s⁻¹) | +416       | +410       | +430       |
|          | ΔχFWZI (km s⁻¹)  | 370        | ...        | 231        |
|          | F(χ) (erg cm⁻² s⁻¹) | 6.1E−14   | 2.0E−14    | 2.7E−14    |
| 0535−660 | SNR 0535−660 (D90423) | 1032.67 | 1038.42 | ...        |
|          | χ(cent) (Å)       | ...        | ...        | ...        |
|          | χ(cent) (km s⁻¹) | +221       | +231       | ...        |
|          | ΔχFWZI (km s⁻¹)  | 480        | ...        | ...        |
|          | F(χ) (erg cm⁻² s⁻¹) | 4.5E−13   | 3.5E−14    | ...        |
| 0536−706 | SNR 0536−706 (D90426) | 1033.05 | 1038.88 | 978.15 |
|          | χ(cent) (Å)       | ...        | ...        | ...        |
|          | χ(cent) (km s⁻¹) | +331       | +364       | +347       |
|          | ΔχFWZI (km s⁻¹)  | 608        | ...        | 200        |
|          | F(χ) (erg cm⁻² s⁻¹) | 3.4E−14   | 8.5E−15    | 2.7E−14    |
| 0538−723 | SNR 0538−723 (D90444) | 1032.66 | 1038.35 | 978.34 |
|          | χ(cent) (Å)       | ...        | ...        | ...        |
|          | χ(cent) (km s⁻¹) | +218       | +211       | +405       |
|          | ΔχFWZI (km s⁻¹)  | 604        | ...        | 290        |
|          | F(χ) (erg cm⁻² s⁻¹) | 2.6E−14   | 1.2E−14    | 1.6E−14    |

With the line flux information in Table 3, we can in principle calculate O vi luminosities for detected objects. However, a number of assumptions must be made, with the quality of those assumptions varying considerably from object to object. For instance, to scale an O vi flux measured through the LWRS aperture to a total O vi flux, one must assume a uniform flux across the object and scale to its projected area, an assumption that may be particularly inaccurate for the larger SNRs. Also, since many of the O vi line profiles show evidence of overlaying absorption, a correction for the missing flux must be included. A moderately good assumption involves assuming an optically thin 2:1 ratio for λ1032 : λ1038 to get a total O vi flux. Finally, a correction for overlaying extinction is required to estimate an intrinsic flux from the observed (corrected) value. Since extinction values are not known accurately for the individual objects, we choose below to assume a standard value of E(B−V) = 0.1 and a Galactic extinction curve (e.g., Cardelli et al. 1989), implying a factor of 3.5 correction at O vi. (Note that this ignores any intrinsic LMC absorption, so larger corrections may be appropriate in some cases.) Proper scaling by distance then provides an estimate of the O vi luminosity of an object. Rather than attempt this calculation for all detected objects, we choose to perform it for a few selected objects where it appears reasonable combinations of assumptions can be made to provide some insight into the importance of O vi as a source of cooling relative to, for instance, the soft X-ray emission.

SNR 0454−665 (N11L; Fig. 5) is a relatively small diameter SNR with a well-detected O vi line. Using the angular size listed in Table 2, a modest geometric correction factor (3.1) is needed...
to scale up to the whole object. If we assume from the line profile that roughly half of the actual O\textsc{vi} line is seen through the overlying absorption, a factor of 1.5 to include \( k_{\text{1038}} \), the factor of 3.5 extinction correction factor discussed above, and a distance of 50 kpc, we derive \( L(\text{O}\textsc{vi}) = 4.2 \times 10^{35} \text{ ergs s}^{-1} \). Williams et al. (1999b) used ROSAT data to estimate \( L_{X}(0.5-2 \text{ keV}) = 8.8 \times 10^{34} \text{ ergs s}^{-1} \), or nearly a factor of 5 less than our estimated \( L(\text{O}\textsc{vi}) \).

As a slightly larger object, SNR 0532/710 (N206; Fig. 12) has a geometric scaling factor from LWRS of \( /C_{24}^{27} \). However, the sampled region appears to be representative of the shell interior, and if anything the O\textsc{vi} emission might be expected to limb-brightened. From inspection of the line profile, we again estimate \( 50\% \) attenuation from overlying MC and MW absorption and assume the same \( k_{\text{1038}} \) and extinction correction factors and distance as above, yielding \( L(\text{O}\textsc{vi}) = 2.4 \times 10^{35} \text{ ergs s}^{-1} \). Williams et al. (2005) report a Chandra/XMM-Newton estimate of \( L_{X}(0.3-8 \text{ keV}) = 8(\pm 4) \times 10^{35} \text{ ergs s}^{-1} \), dependent on model spectrum assumptions, or roughly several times the estimated O\textsc{vi} luminosity in this case.

By way of contrast, we select an FUV nondetected object, SNR 0453/685 (D90403; Fig. 19, bottom panel) with a night observing time of 3.8 ks. Interestingly, this object is quite bright in X-rays but shows no obvious optical emission in the MCELS data. We determine a \( 3\sigma \) upper limit of \( 2.5 \times 10^{34} \text{ ergs cm}^{-2} \text{ s}^{-1} \) in \( \lambda_{\text{1032}} \). (This assumes an unresolved line and a filled LWRS aperture.) With a geometric correction factor of \( 16\% \) and other parameters as for N206 above, we find \( L(\text{O}\textsc{vi}) < 1.9 \times 10^{34} \text{ ergs s}^{-1} \). We are unaware of a detailed model of the X-ray emission from this SNR, but if we simply use the relative X-ray surface brightnesses for this object and N206 from Williams et al. (1999a, Table 2), scale by the projected areas, and assume the same spectral modeling as done for N206 (Williams et al. 2005), we derive an approximate X-ray luminosity of \( L_{X}(0.3-8 \text{ keV}) \approx 6 \times 10^{35} \text{ ergs s}^{-1} \), or at
least 2 orders of magnitude brighter than the O\textsc{vi} upper limit. It is unlikely that extinction alone could account for such a large depression of the $L(O\textsc{vi})$, and substantial real variations of the relative luminosities are likely present. While none of these estimates is high fidelity, clearly there is a broad range of $L(O\textsc{vi})$ : $L_X$ in the sampled objects, and the luminosity in just the O\textsc{vi} lines can rival the entire soft X-ray luminosity in some cases.

4. SUMMARY AND CONCLUSIONS

It is clear from the \textit{FUSE} survey that there are numerous SNRs in the Magellanic Clouds that are observable in the far-ultraviolet. We have detected 15 SNRs (14 previously undetected in the ultraviolet plus 0535–660 [N63A]) out of a total of 39 observed, bringing the total number of FUV-detected SNRs in the Magellanic Clouds to 22. The detected objects span a wide range of parameter space, from relatively small, bright objects to large (old) shells, and from both X-ray shells and filled-center morphologies. Almost as interesting are the nondetections, because the sensitivity of \textit{FUSE} allows significant upper limits to be placed in many cases. These objects must have substantially higher foreground columns and/or much slower shock velocities at the observed locations than the detected objects in order to escape detection. Given the likelihood of nonuniform spatial distributions of the FUV emission, nondetections at the observed positions do not necessarily indicate these objects have no FUV emission. Potential clumpiness, especially for the largest angular size SNRs, may be a significant reason for nondetection.

A significant subset of our spectra were contaminated by stellar light, making the upper limits somewhat less conclusive in these cases.

The line profiles for detected objects generally show evidence of significant overlying self-absorption by the ISM of the host galaxy (if not also the Milky Way, depending on the SNR intrinsic line widths). Although we typically looked on a sight line...
Fig. 19.—Optical and X-ray images of SNRs declared nondetections, in the same format as the top panels in Figs. 2–16. The nominal FUSE LiF1 LWRS aperture positions are superimposed and provide the scale for each panel. Shown are SNRs 0449–693, 0453.1–6655, 0453–672, and 0453–685.
Fig. 20.—Same as Fig. 19, but for SNRs 0455−687 (N86), 0500−702, 0506−657, and RX J0507−685 (see also Fig. 17).
Fig. 21.—Same as Fig. 19, but for SNRs 0513–692, 0519–697 (see also Fig. 18), 0521–657, and 0523–679.
Fig. 22.—Same as Fig. 19, but for SNRs 0524–664, 0528–672, 0532–673, and 0532–675.
Fig. 23.—Same as Fig. 19, but for SNRs 0534–699, 0536–676, 0536–692, and 0536–693.
through the center of each SNR, we tend to see emission at wave-
lengths just redward of the host galaxy rest frame, as if we are 
systematically seeing the receding side of each detected SNR. 
This is also indicative of overlying absorption, which would tend 
to impact emission from the approaching side of each SNR more 
severely. In one case, SNR 0536−706, we may be seeing front-
side/back-side shell emission, although the observed profile in 
\( \text{O} \text{ vi} \) could also represent a broader emission line with the center 
removed by \( \text{O} \text{ vi} \) self-absorption (see \( \text{xA14} \)).

All but one of the detected SNRs were seen in \( \text{O} \text{ vi} \) \( \lambda 1032 \). 
Many but not all were detected in \( \text{C} \text{ iii} \) \( \lambda 977 \) as well. A single 
SNR was seen marginally in \( \text{C} \text{ iii} \) but not in \( \text{O} \text{ vi} \). This may be due 
to a selection effect arising from SNRs with slower shocks (hence, 
no \( \text{O} \text{ vi} \)) not being visible through the more substantial ISM ab-
sorption at \( \text{C} \text{ iii} \). However, without additional observations, we 
cannot rule out the idea that \( \text{O} \text{ vi} \) emission is present but patchy in 
this object, and hence simply not seen.

Although many assumptions are involved, estimates of the 
luminosities of these objects in \( \text{O} \text{ vi} \) show a broad range relative 

to the soft X-ray luminosities (which also involve a number of 
assumptions). We have examples where the \( \text{O} \text{ vi} \) luminosity is 
considerably brighter than the inferred soft X-ray luminosity, to 
some of the FUV nondetected objects where the inferred upper 
limit on \( \text{O} \text{ vi} \) is perhaps 2 orders of magnitude or more below the 
X-ray luminosity. The reason or reasons for such diversity are not 
entirely clear, although many important parameters, such as line-
of-sight extinction and clumpiness of the FUV emission, are not 
currently well established for many of these objects.

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Fig. 24.—Same as Fig. 19, but for SNRs 0538−693, 0543−689, and 0547−697, where both “a” and “b” components (DEML316A and B) were observed separately. (See Williams et al. 1997.)
The FUSE data reported in this paper were obtained with the NASA-CNES-CSA FUSE satellite, which is operated by Johns Hopkins University with financial support through NASA contract NAS 5-32985. It is a pleasure to thank the FUSE operations team for their efforts in obtaining these data. We also thank Chris Smith, Roger Leiton Thompson, and Claudio Aguilera of the MCELS team for providing us with the optical images used in this paper. This work has been supported by NASA guest investigator grants NAG5-12423 and NNG04GJ25G, both to the Johns Hopkins University.

APPENDIX

In this Appendix, we provide brief explanatory comments on each of the detected Magellanic Cloud SNRs.

A1. SNR 0448–669 (FIG. 3)

This SNR was only recently identified, as part of ongoing analysis of the MCELS imaging survey (Smith et al. 2004). The position provided was apparently poorly centered and instead sits on the northern limb of the optical shell. No X-ray image is available. The FUSE detection of O\textsc{vi} is modest, although both lines of the doublet are present and some indication of self-absorption by LMC halo O\textsc{vi} is evident, especially for \(k_{1032}\). The C\textsc{iii} line is not detected with certainty although only 3.8 ks of the 15.7 ks integration was in orbital night. With a line width of nearly 700 km s\(^{-1}\), the blue wing of \(k_{1032}\) may be clipped by Milky Way halo absorption.

A2. SNR 0450–709 (FIG. 2)

This low surface brightness, nondescript shell SNR is one of the largest Magellanic SNRs in angular size, first reported by Mathewson et al. (1985) in the optical and radio. Williams et al. (2004) have recently provided a detailed investigation. The XMM-Newton data show only a faint enhancement above background levels with no distinct shape seen. The X-rays appear to be brighter interior to the shell, making the SNR similar to a handful of large old Galactic SNRs such as W28 and 3C 400.2 (Long et al. 1991). Despite its apparent late stage of evolution, the SNR was detected in both C\textsc{iii} and O\textsc{vi} with FUSE, although as a faint source. The detection has been aided by the relatively long (9.5 ks) orbital night integration for this object. The central velocity of the detected SNR emission appears to be just slightly redward of the LMC mean velocity. The C\textsc{iii} emission appears truncated on the blue side by LMC absorption and is artificially narrow. Both O\textsc{vi} lines appear to be broader lines impacted by overlying (mainly LMC) absorption. Intrinsic fluxes are correspondingly uncertain.

A3. SNR 0454.5–6713 (FIG. 4)

This SNR was discovered as a diffuse X-ray source and was found optically by Smith et al. (1994). It is located within the LMC H\textsc{ii} region N9. Its optical morphology is nondescript, with just a few radiative filaments embedded within faint, diffuse emission. Faint, diffuse X-ray emission fills the region of optical emission and extends somewhat farther to the south and southwest. The Chandra X-ray morphology gives the impression that this SNR is a member of the composite or “mixed morphology” class, with a faint outer shell and bright, filled center. The bright central X-ray emission in the Chandra image is probably due to ejecta, and Seward et al.
(2004) point to a likely Type Ia supernova origin. The FUSE aperture position, based on the estimated optical centroid, is clearly off-center based on the X-ray image and samples primarily the diffuse regions in X-ray and optical. The strong, relatively narrow C iii and O vi emission lines lie just longward of the LMC rest frame velocity and appear to be due to radiative shocks. The lines could be impacted by blue wing absorption, but the lack of an extended red wing on the strong, narrow lines argues for relatively low velocity dispersion within the aperture.

A4. SNR 0454−665 (N11L; FIG. 5)

This SNR is a member of the original group of SNRs identified in the LMC by Mathewson & Clarke (1973) using the optical [S ii] to Hα criterion and has been studied in detail by Williams et al. (1999b). Although it is part of the large N11 H ii region complex, it forms a well-defined and relatively isolated shell with an apparent "jet" or breakout to the NE, reminiscent of the optical jet in Cas A (Fesen & Gunderson 1996). With a relatively small angular size, the ROSAT PSPC image shows little structure and leaves the impression of filled-center emission. The FUSE spectrum with only 2.2 ks of orbital night nonetheless shows very bright and well-detected O vi λλ1032, 1038 and C iii lines with evidence for absorption on the blue sides of the profiles. In particular, the λ1032 line provides evidence of a much broader and stronger line than is actually detected. Radiative shock emission apparently dominates the line emission from material in the FUSE aperture.

A5. SNR 0506−680 (N23; FIG. 6)

Once again, the faintness of the diffuse, patchy optical emission from this SNR has caused the Mathewson et al. (1983) coordinate to be off-center in comparison with the Chandra X-ray data, which extends considerably to the north and west from the bulk of the optical emission. In this case, the FUSE aperture lies on the SE bright X-ray limb. Even with only 2.7 ks of orbital night integration, both O vi and C iii are detected, although the C iii line is quite faint. The O vi emission is quite strong and very broad relative to C iii in this object. The line shape for O vi λ1032 makes it clear that both Galactic and LMC overlying absorption are impacting the observed fluxes. The brightness of the X-ray and O vi intensity and the faintness of the optical emission and C iii line make it likely that nonradiative shocks contribute significantly to the observed emission.

A6. SNR 0509−687 (N103B; FIG. 7)

This young, small diameter SNR nearly fits within the nominal FUSE LiF1A LWRS aperture. The bright X-ray emission corresponds to the region of knotty optical emission, implicating a shock-cloud interaction on the west side, but fainter X-ray emission extends toward the east. No discernable C iii emission is present, although the small angular size of the SNR makes it possible in principle that the FUSE SiC apertures could have been misaligned enough to miss or only partially cover the SNR. (We note that the LiF2B channel, which also covers the O vi spectral region, was apparently misaligned—see main text.) The O vi λ1032 emission is quite strong and broad, and the λ1038 line is obviously impacted more severely by overlying absorption. A small amount of scattered starlight contaminates the spectrum near O vi, causing the apparent pedestal of emission.

A7. SNR 0520−694 (FIG. 8)

This relatively faint and moderately sized optical shell SNR lies in a rich star field within the bar of the LMC. Significant stellar emission contaminates the FUSE aperture position, but we feel confident in claiming detection by virtue of the strong, relatively narrow C iii emission just longward of the LMC rest velocity. Although an O vi P Cygni feature in the stellar spectrum cannot be ruled out without more information, an interpretation of the dip at λ1032 as ISM absorption would make it likely that the apparent emission just longward of the LMC rest velocity is faint, broad O vi emission from the SNR. This is the feature measured and reported in Table 3.

A8. SNR 0527−658 (DEML 204; FIG. 9)

This is one of the larger SNRs in the survey and is an apparent member of the composite class, with a large outer optical shell and filled-center X-ray emission. This is the only SNR in the survey that shows C iii emission but no detectable emission in O vi, and even the C iii detection is somewhat marginal. However, the appearance of the nominal C iii line is consistent with the hypothesis we have put forward in the main text for why there are almost no such detections: the intrinsic C iii SNR line is largely absorbed by intervening ISM. For this object, the kinematics are such that the C iii line peeks out on the red side of the LMC absorption and is just visible. The intrinsic C iii line is likely quite strong in this large (older) radiative shell-type SNR, and the absence of detectable O vi indicates few shocks remaining at velocities in excess of 160 km s⁻¹. There is a possible emission line at the position of C ii λ1037.02, the excited state component of the more well-known C ii λ1036.34 ISM absorption line, although significant overlying absorption may be present. The possible presence of this line is also consistent with the emission from this object being dominated by slow radiative shocks.

A9. SNR 0528−692 (LHG40; FIG. 10)

This SNR was first reported in X-rays by Long et al. (1981), and optical and radio detections were provided by Mathewson et al. (1984). A faint optical radiative shell is visible, but the X-ray emission is ill-defined in the ROSAT PSPC data. This is another object in
the LMC bar, and stellar contamination is nearly impossible to avoid. The \textit{FUSE} spectrum of this object includes only orbital day data, and so additional lines are due to residual dayglow, including the feature near Milky Way \textsc{c iii} rest velocity. Despite the stellar contamination, the SNR \textsc{o vi} emission is clearly seen in both lines at the LMC velocity. Interestingly, no \textsc{c iii} at LMC velocities is detected, which is surprising given the radiative shell nature of the optical emission. It may be that the receding shell is too faint to be seen and the near-side emission is lost in the ISM absorption from the LMC.

A10. SNR 0530−701 (FIG. 11)

This SNR was only recently identified, as part of ongoing analysis of the MCELS imaging survey (Smith et al. 2004), and appears to be a large, old, radiative shell-type SNR. No X-ray data are available. The supplied coordinate for this object was on the southern rim instead of the center. The \textit{FUSE} detection of \textsc{o vi} is quite weak but moderately broad. Absorption may affect the blue side of the $\lambda 1032$ line, and $\lambda 1038$ is only marginally present. The \textsc{c iii} line is not detected with certainty, although the small fraction of orbital night data for this observation (and the use of the total data set for this object) both complicate the interpretation of \textsc{c iii}.

A11. SNR 0532−710 (N206; FIG. 12)

This composite or “mixed morphology” SNR shows a classic symmetrical shell in the optical (with the shocked radiative emission showing particularly well in [S \textsc{ii}]), but a center-filled X-ray morphology. A detailed study has been published by Williams et al. (2005), with the addition of a possible pulsar wind nebula discovered in X-ray and radio data. In this moderate sized SNR, the central X-ray emission is likely due to ejecta. The \textit{FUSE} spectrum shows faint, broad \textsc{o vi} emission and a very narrow \textsc{c iii} line just longward of the LMC rest velocity. Clearly, overlying absorption is impacting these profiles, and the blue side of \textsc{c iii} could just be missing. It is likely that the observed emission is due to the radiative shell.

A12. SNR 0534−705 (DEM 238; FIG. 13)

This moderately sized faint shell-type optical SNR was reported by Mathewson et al. (1983). The \textit{Chandra} data show extended faint X-ray emission filling the optical shell, but a brighter central concentration (somewhat offset toward the southwest) that is likely due to ejecta. Even though the \textit{FUSE} aperture is filled partially with ejecta, the narrowness of the observed line profiles makes it likely that the observed lines are from the radiative shell. Both \textsc{o vi} lines are seen but $\lambda 1038$ is weak, implying overlying absorption. The \textsc{c iii} line is comparable to \textsc{o vi} $\lambda 1032$ in peak intensity but is narrower, largely attributable to ISM absorption on the blue side of the profile.

A13. SNR 0535−660 (N63A; FIG. 14)

This SNR was detected with \textit{IUE} (Benvenuti et al. 1980) but has not been observed with more modern instrumentation. The \textit{IUE} spectra only showed \textsc{c iv} $\lambda 1550$, \textsc{he ii} $\lambda 1640$, and \textsc{c iii} $\lambda 1909$ emission lines superimposed on a continuum of stellar contamination and/or dust-scattered starlight. The SNR is buried within an extended \textsc{h ii} region and OB association. The bizarre optical morphology is dominated by a shocked cloud located on the near side of the SNR from our sight line. The true size and shape of the SNR is apparent from the soft X-rays (e.g., Warren et al. 2003). The \textit{FUSE} aperture covered this shocked cloud and the spectrum is contaminated by significant continuum. Nonetheless, very strong \textsc{o vi} emission lines are detected just shortward of the LMC rest velocity. There is no clear evidence for \textsc{c iii}. Since \textit{IUE} observed \textsc{c iii} $\lambda 1909$, it is likely that the SiC channels were misaligned by enough that they missed the bright radiative shocked cloud. The strength of the \textsc{o vi} emission implies a radiative shock origin, even though \textsc{c iii} and other cooler ions are missing. Given that, it is probable that the FUV emission is dominated by radiative shocks. This is consistent with a dense, shocked cloud being hit relatively recently by the blast wave.

A14. SNR 0536−706 (DEML 249; FIG. 15)

This SNR is a large, faint optical shell SNR that is brighter on the eastern side of the shell. The X-ray emission from \textit{ROSAT} PSPC is low resolution, but rather diffuse and strongest at the center, possibly indicating it is a member of the mixed-morphology class (Williams et al. 1999a). The \textit{FUSE} spectrum shows a narrow \textsc{c iii} line centered at the LMC rest velocity and clearly double-peaked \textsc{o vi} lines that bracket the LMC rest velocity. The presence of \textsc{c iii} emission at the rest velocity argues that this object must be on the near side of the LMC, and thus suffers little overlying absorption from LMC ISM \textsc{c iii}. The \textsc{o vi} line morphology could then arise from one of two mechanisms: either \textsc{o vi} emission arises from approaching and receding sides of the shell and we are resolving this structure, or a broader \textsc{o vi} emission line is undergoing significant self-absorption from within the SNR itself. Whatever the cause, this spectral character is unique in the objects we have observed in this survey.

A15. SNR 0104−723 (FIG. 16)

This is the only SMC remnant observed to date in the \textit{FUSE} survey, and it was first reported by Mathewson et al. (1984). It is detected in \textsc{o vi}. Both \textsc{o vi} lines appear to be impacted by overlying absorption from both our Galaxy and the SMC, \textsc{c iii} may be marginally detected. The strong emission at $\lambda 977$ in the rest frame is backscattered solar emission in the \textit{FUSE} SiC channel and is not real.
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