1. INTRODUCTION

The study of middle-aged supernova remnants (SNRs) in the X-ray band is traditionally considered a powerful diagnostic tool for obtaining information about the dynamics of shock-cloud interaction and the relevant properties of the interstellar and circumstellar medium. However, although the bulk of the X-ray emission in evolved remnants is associated with the postshock interstellar medium (ISM), there is emerging evidence for the presence of X-ray-emitting ejecta even in middle-aged SNRs. For example, there are claims for the presence of chemical inhomogeneities in the Cygnus Loop, observed in X-rays at both large (Miyata & Tsunemi 1999, but see Levenson et al. 2002) and small (Leahy 2004) spatial scales. The metal abundances found in the Cygnus Loop are always lower than (or consistent with) solar values, but the presence of such chemical inhomogeneities suggests that the X-ray emission cannot be completely associated with the shocked ISM.

In the Vela SNR, there are indications of X-ray-emitting ejecta. Aschenbach et al. (1995) identified six “shrapnels” (labeled shrapnels A–F), which are X-ray-emitting features (with a characteristic boomerang shape) protruding beyond the primary blast wave. Shrapnel A and shrapnel D have been recently observed with XMM-Newton. Katsuda & Tsunemi (2005) found high O, Ne, and Mg abundances in shrapnel D, thus confirming its association with a fragment of supernova ejecta. As for shrapnel A, a significant Si overabundance has been observed, while O, Ne, Mg, and Fe have solar or subsolar abundances. These results seem to indicate that shrapnel D is somehow different from shrapnel D, and Katsuda & Tsunemi (2006) conclude that the ejecta in shrapnel A are strongly mixed with the swept-up ISM.

The results obtained in the Cygnus Loop and in the Vela SNR open up the possibility to study the products of SN nucleosynthesis in large and near remnants. Because of its proximity (∼250 pc; Bocchino et al. 1999; Cha et al. 1999), the Vela SNR is an ideal target for this kind of study, since it is possible to resolve fine structures at high spatial resolution. The age of this SNR has been estimated to be ∼10⁴ yr, in good agreement with the characteristic age of the pulsar PSR B0833−45 (∼11,200 yr; Taylor et al. 1993), which is associated with the remnant, as shown by Weiler & Panagia (1980) and Weiler & Sramek (1988).

The northern rim of the Vela shell presents a patchy X-ray emission, indicating a complex interaction between the blast wave shock and several ambient inhomogeneities. In Miceli et al. (2005, 2006b, hereafter Papers I and II, respectively) we studied a small isolated X-ray knot (Vela FilD) located near the northern shock front. The spectral analysis shows that two thermal components (T₁ ∼ 10⁶ K and T₂ ∼ 3 × 10⁶ K) of an optically thin plasma in collisional ionization equilibrium (CIE) are present (Paper I). Detailed hydrodynamic modeling (Paper II) shows that in the FilD knot, the cooler component (the cloud “core”) originates in the cloud material heated by the transmitted shock front, while the hotter component (the cloud “corona”) is the result of thermal conduction between the cloud and the hotter shocked intercloud medium. Moreover, the peculiar orientation of the optical filament associated with the FilD X-ray knot is naturally explained by our model as a result of thermal instabilities.

An open issue is related to the study of the metal abundances behind the shock front. As shown in Paper I, the abundances found in the FilD region (Ne slightly overabundant, Fe underabundant, and solar O) are unusual and not expected according to models of metal depletion and grain destruction behind shock waves. It is therefore interesting to study how these abundances are distributed at different distances from the main shock front and how they are related to the abundances observed in the Vela shrapnels. There is, in fact, the concrete possibility that additional shrapnels are observed in projection inside the shell.

With this in mind, we present the analysis of two new XMM-Newton EPIC observations of the northern rim of the Vela SNR. The observations (RegNE and FilE; see Fig. 1), together with the

PHYSICAL AND CHEMICAL INHOMOGENEITIES INSIDE THE VELA SNR SHELL: INDICATIONS OF EJECTA SHRAPNELS

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ABSTRACT

We present the results of the combined analysis of three XMM-Newton EPIC observations of the northern rim of the Vela supernova remnant (SNR). The three pointings cover an area of ≥10 pc² (at 250 pc) behind the main shock front, and we aim to study with high resolution the spatial distribution of the physical and chemical properties of the X-ray-emitting plasma on this large scale. We produce count-rate images and equivalent width maps of the Ne xix and Mg xii emission blends. We also perform a spatially resolved spectral analysis of a set of physically homogeneous regions. We reveal physical and chemical inhomogeneities in the X-ray-emitting plasma. In particular, we find large variations of the O, Ne, Mg, and Fe abundances. In some bright knots, we also find unexpectedly enhanced Ne and Mg abundances, with values significantly larger than solar. Our results support a possible association of a few X-ray-emitting knots with previously undetected residuals of stellar fragments (i.e., shrapnels) observed, in projection, inside the Vela shell.

Subject headings: ISM: individual (Vela SNR) — supernova remnants — X-rays: ISM

Online material: color figures
FilD pointing, cover an area \( \geq 10 \text{ pc}^2 \) (at 250 pc) and allow us to study at high resolution the spatial distribution of the physical and chemical properties of the plasma on a large scale. RegNE was partially visible in the FilD pointing analyzed in Paper I as a previously undetected (it was not visible in the *ROSAT* PSPC observation discussed in Bocchino et al. 1999) bright X-ray knot, spectrally harder than FilD. As for FilE, the *ROSAT* All-Sky Survey indicates the presence of a large limb-brightened structure corresponding to a long (several pc) and bright H\(\alpha\) filament at a larger projected distance from the main shock front than FilD (see also Bocchino et al. 2000).

The paper is organized as follows. In § 2, we present the new data and the data analysis procedure. In § 3, we present the X-ray results in terms of image analysis (§ 3.1–3.3) and spatially resolved spectral analysis (§ 3.4). Finally, § 4 discusses the results, and our conclusions are summarized in § 5.

2. DATA PROCESSING

The *XMM-Newton* EPIC observations presented here consist of the FilD observation presented in Paper I and of two new observations: (1) Observation ID 0203960101 (PI: F. Bocchino), with pointing coordinate R.A. (J2000.0) = \(8^h36^m45^s\) and decl. (J2000.0) = \(-42^\circ55'40''\) (i.e., the FilE region). The observations were performed with the EPIC MOS (Turner et al. 2001) cameras and with the EPIC pn (Strüder et al. 2001) camera on 2004 October 31 (0203960101) and 2006 November 14 (0302190101). The location of the two pointings is indicated in Figure 1, while the relevant information about the two data sets is summarized in Table 1.

The data were processed using the Science Analysis System (SAS, ver. 7.0). Light curves, images, and spectra were created by selecting events with \(PATTERN = 12\) for the MOS cameras, \(PATTERN \leq 4\) for the pn camera, and \(FLAG = 0\) for both. To

### Table 1

| ObsID       | Camera | \(t_{exp}\) (ks)\(^a\) | Mode       | Filter |
|-------------|--------|------------------------|------------|--------|
| 0203960101  | MOS1   | 52.1/26.3              | Full Frame | medium |
| 0203960101  | MOS2   | 52.1/27.3              | Full Frame | medium |
| 0203960101  | pn     | 48.6/18.2              | Ext. Full Frame | medium |
| 0302190101  | MOS1   | 39.8/32.7              | Full Frame | medium |
| 0302190101  | MOS2   | 40.0/28.5              | Full Frame | medium |
| 0302190101  | pn     | 35.8/23.7              | Ext. Full Frame | medium |

\(^{a}\) Unscreened/screened exposure time.
eliminate contamination by soft proton flares, the data were screened by applying a count-rate limit on the light curves (binned at 100 s) at high energies (10–12 keV for MOS and 12–14 keV for pn). The count-rate limit is 0.18 counts s\(^{-1}\) for the MOS cameras, and 0.3 counts s\(^{-1}\) for the pn camera. The screened exposure times are given in Table 1.

All the images presented here are superpositions (obtained using the EMOSAIC task) of the MOS1, MOS2, and pn images of the two pointings and of the FilD pointing presented in Paper I, and are background subtracted, vignetting corrected, and adaptively smoothed (with the task ASMOOTH). The contribution of the background was derived from the high signal-to-noise background event files E1_fm0000_M1.fits, E1_00fm00_M2.fits, and E1_0000fm_PN.fits (obtained using the medium filter) described in detail by Read & Ponman (2003).

The exposure and vignetting corrections were performed by dividing the count images by the corresponding superposed exposure maps (obtained with the task EEXPMAP). Since the ratio between the MOS and pn effective area \(A_{\text{rel}}\) depends on the spectral distribution of the incoming photons, we have taken the thermal spectrum of the source into account when scaling the pn exposure maps by \(A_{\text{rel}}\) to make MOS-equivalent superposed count-rate images. In particular, since in Paper I we found that in the FilD region, the emission below 0.5 keV is associated with the soft component (at \(\sim 10^6\) K), while above 0.5 keV the hotter component (at \(\sim 3 \times 10^6\) K) dominates, we assume an incoming thermal spectrum at 10\(^6\) K for the images in the 0.3–0.5 keV band (\(A_{\text{rel}} = 0.16\)) and at 3 \times 10^6 K for the images in the 0.5–1 keV band (\(A_{\text{rel}} = 0.20\)), 0.85–0.98 keV (\(A_{\text{rel}} = 0.26\)), and 1–1.24 keV (\(A_{\text{rel}} = 0.31\)) bands. The background- and continuum-subtracted line images and the equivalent width maps presented in §3.3 were produced by following the procedure described in Miceli et al. (2006a).

Spectral analysis was performed in the energy band 0.3–1.5 keV using XSPEC. The ancillary response files were generated with the SAS ARFGEN task, and the event files were processed using the EVIGWEIGHT task (Arnaud et al. 2001) to correct vignetting effects. The background contribution was subtracted from the same region positions on the CCD (i.e., in the detector coordinates) in order to take into account the inhomogeneous response of the instruments across the field of view. Spectra were rebinned to achieve a signal-to-noise ratio (S/N) per bin of >5, and the fittings were performed simultaneously on both the MOS spectra and on the pn spectrum. Since the FilE observation was performed after the micrometeoroid damage to the MOS1 camera, we used only the pn and MOS2 spectra in region 6 (see §3.4), because this region partially covers the damaged chip 6. We also added a systematic 5% error term to reflect the estimated uncertainties in the calibration of the instrumental effective area (Kirsch 2007). All the reported errors are at 90% confidence, according to Lampton et al. (1976).

3. THE DATA ANALYSIS

3.1. The Region Morphology

Figure 2 shows the mosaicked count-rate image of the three observations of the northern rim of the Vela shell in the two bands chosen for the study of FilD in Paper I, 0.3–0.5 keV and 0.5–1 keV (hereafter referred to as “soft band” and “hard band”).

The bulk of the X-ray emission of the RegNE knot is above 0.5 keV, although its brightest part, at the northern end of the knot, is also visible in the 0.3–0.5 keV band. This bright “head” shows
a bow-shaped morphology in the 0.5–1 keV band and lies outside the field of view of the FilD observation discussed in Paper I. South of this head, there is an elongated sharp “tail,” extending for about 15′ (corresponding to ~1 pc, at 250 pc) toward the center of the remnant. North of RegNE, a different faint, diffuse region is visible in the 0.5–1 keV band. This region, labeled Hreg in Figure 2, does not present significant emission in the soft band.

In the FilE region, we instead observe significant emission both below and above 0.5 keV. In particular, in the eastern side of the field of view there is a region (labeled H FilE in Fig. 2) where the surface brightness in the 0.5–1 keV band is, on average, twice as large as that in the 0.3–0.5 keV band. The X-ray emission of this region is harder than that in the western part of the field of view (region S FilE in Fig. 2), where we observe a high surface brightness in the soft energy band.

Figure 3 shows combined optical (H α, in red) and X-ray images of RegNE and FilE in the soft (in green) and hard (in blue) X-ray bands. In RegNE (Fig. 3, left), no significant optical emission is present in the wide region corresponding to the hard X-ray-emitting knot, in contrast to the FilD knot, where both soft X-ray and optical emission are present. A couple of optical filaments seem instead to be related to Hreg. Figure 3 (right) shows the intense H α emission of the FilE region (in red). The H FilE structure with hard X-ray emission lies clearly “behind” the optical filament (in agreement with the results obtained by Bocchino et al. 2000 in the same region). This configuration seems to indicate that we are observing in X-rays the plasma behind a reflected shock front. According to this interpretation, the reflected shock was generated by the impact of the main shock with a dense cloud, where the slow transmitted shock generates the optical emission. Note, however, that (as shown in Fig. 2) the angular distance of this region from the border of the shell is quite large (~50′, corresponding to ~3.6 pc at 250 pc) and that projection effects may be present. Therefore, we cannot rule out the possibility that the optical filament E is not physically associated with the X-ray-emitting knot. The stratification between optical and X-ray emission is not visible in the S FilE region, where we observe both optical and soft X-ray emission, with narrow optical filaments that lie not behind, but “inside” the X-ray-emitting region.

3.2. Analysis of the Photon Energy Map

To obtain information about the thermal structure of the plasma, we produce a MOS median photon energy (MPE) map (i.e., an image in which each pixel holds the median energy of the detected MOS photons) in the 0.3–2 keV band. The MPE map can be considered as an indicator of the hardness of the spectrum and of the average temperature of the plasma, but it also depends on the chemical composition of the plasma and on the local value of $N_{\text{H}}$ (where the interstellar absorption is higher, we observe a hardening of the spectra). Note, however, that as shown in § 3.4, $N_{\text{H}}$ is quite uniform in the region of the Vela shell covered by our set of observations (in agreement with Lu & Aschenbach 2000). The MPE map is shown in Figure 4 and has a bin size of $12′′$, so we can examine the different structures with high spatial resolution. The map clearly shows that very soft X-ray emission originates in the FilD and S FilE regions, where we observe relatively low values of MPE (~500 eV). The H FilE region seems instead to be, on average, hotter than S FilE and FilD. We observe the maxima of the median photon energy in RegNE and Hreg (i.e., the regions where the bulk of X-ray emission is in the hard band). We then expect the plasma to be, on average, hotter in these two regions than in all the others. We can also focus on the overall trend of the MPE on a large scale. Figure 4 clearly shows that two well-separated “regimes” (the dashed line marks the separation in the figure) are present: a hard regime to the north and a softer regime from FilD to the south.

3.3. Equivalent Width Images

To study the spatial distribution of the chemical composition of the X-ray-emitting plasma, we produce equivalent width
(EW) maps. These depend linearly on the abundances, but are also influenced by the temperature, column density, and ionization age. However, since temperature, \( N_H \), and ionization age can be regarded as uniform (see § 3.4), the EW maps can be considered reliable indicators of the metal abundances. As shown in Paper I, O, Ne, and Fe lines mainly contribute to the observed X-ray emission in this region of the shell, but thanks to the good statistics of the new observations, we now also detect the presence of Mg lines. More specifically, in all spectra, the K-shell line complexes of O \( \text{vii} \) (at 0.56 keV), O \( \text{viii} \) (at 0.65 keV), Ne \( \text{ix} \) (at 0.92 keV), and Mg \( \text{xi} \) (at 1.35 keV) are clearly visible. We focus here on only the Ne \( \text{ix} \) (i.e., the 0.85–0.98 keV energy band) and Mg \( \text{xi} \) (1.29–1.45 keV energy band) emission lines, since it is possible to evaluate the continuum in an adjacent band (1–1.24 keV) and since the EW of these lines will be less affected by local variations of \( N_H \) than the low-energy O lines. The EW images were constructed by dividing the background- and continuum-subtracted line images by the corresponding underlying continuum. To estimate the continuum under the lines, we scale the continuum band adjacent to the line emission by using as a phenomenological model a thermal bremsstrahlung at \( kT = 0.2 \) keV (absorbed by a column density \( 2.3 \times 10^{20} \text{ cm}^{-2} \)) for the continuum, plus narrow Gaussian components for the lines. We have verified that this ad hoc model provides a satisfying description for the spectra in all the regions presented in § 3.4 (reduced \( \chi^2 \sim 1.1–1.8 \), with \( 150–200 \) degrees of freedom). A word of caution should be given for the Ne \( \text{ix} \) EW, since this emission line emerges over a “false continuum” generated by the blending of the Fe \( \text{xvii} \) L lines (which have energies in the range \( 0.72–1.1 \) keV). The Ne \( \text{ix} \) EW will not, therefore, depend simply on the Ne abundance, but on the ratio between the Ne and the Fe abundances. Note also that in the continuum energy band (1–1.24 keV), the emission may be contaminated by Fe and/or Ni L lines, and this may yield an overestimation of the continuum, and therefore an underestimation of our EWs.

Figure 5 shows the Ne \( \text{ix} \) and Mg \( \text{xi} \) EW maps. In both maps, huge inhomogeneities in the EW are visible. In contrast to the median photon energy map, we do not observe a north-south anisotropy, although an east-west anisotropy is present. In particular, three knots (corresponding to Hreg, RegNE, and partially H FilE) with enhanced values of EW are present in both maps. Since the EW depends linearly on the abundance, the presence of inhomogeneities in the EW maps suggests that the X-ray emission in this part of the Vela shell cannot be associated with a chemically uniform medium.

Figure 6 includes the spectra extracted from two regions with high and low Ne \( \text{ix} \) and Mg \( \text{xi} \) EW. The areas of the two regions have been chosen so as to have almost the same counts in the continuum band. Figure 6 clearly shows that the Ne \( \text{ix} \) and Mg \( \text{xi} \) emission lines are locally highly enhanced.

3.4. Spatially Resolved Spectral Analysis

To check whether the spatial variations in the EWs are due to inhomogeneities in the chemical composition of the X-ray-emitting plasma or to other effects (e.g., variations in temperature and/or in \( N_H \)), we perform a spatially resolved spectral analysis. As explained in Paper I, the poor statistics of the FilE observation did not allow us to perform an accurate study of the metal abundances, and we aim at exploiting the higher statistics of the new observations to address this issue. We analyze the spectra extracted from the nine regions shown in Figure 5. The shape and size of the spectral regions were chosen in order to extract the spectra from chemically and physically uniform regions. To this end, we select regions with fairly uniform values of the Ne \( \text{ix} \) and Mg \( \text{xi} \) EW (as shown in Fig. 5) and, at the same time, very small fluctuations of the median photon energy (\( \leq 3\% \)).

Region 1 corresponds to the region of low surface brightness immediately behind the border of the shell, region 2 to the hard X-ray-emitting Hreg knot, and region 3 to the brightest part (the “head”) of RegNE. Regions 4 and 5 are located in the H FilE structure, regions 8 and 9 in the bright, soft X-ray-emitting S FilE knot, while regions 6 and 7 are located between the two parts of FilE, where we observe large values of the Mg \( \text{xi} \) EW. We observe large EWs for both Ne \( \text{ix} \) and Mg \( \text{xi} \) in regions 2, 3, and 4. In region 5 we have large Ne \( \text{ix} \) EW and low Mg \( \text{xi} \) EW, while we observe relatively low values for both neon and magnesium in regions 1, 8, and 9.

All the extracted spectra are described well by two MEKAL components of an optically thin thermal plasma in collisional ionization equilibrium (Mewe et al. 1985, 1986, Liedahl et al. 1995), and the temperatures of the two components are quite similar to those found in Paper I for the FilD knot (i.e., \( T_1 \approx 10^6 \) K and \( T_2 \approx 3 \times 10^6 \) K, respectively). Figure 7 shows a representative spectrum (extracted from region 4 of Fig. 5) with its best-fit model and residual. As shown in Figure 7, strong O \( \text{viii} \), Ne \( \text{ix} \), Mg \( \text{xi} \), and Fe xvii line (which have energies in the range \( 0.72–1.1 \) keV) complexes are associated with the hotter component. Therefore, we leave the O, Ne, Mg, and Fe abundances free in the hotter component. Since the line emission mainly originates in the hotter component, it is not possible to determine the chemical
Fig. 5.— *Left:* Equivalent width maps of the Ne xi line emission in the 0.85–0.98 keV band. The bin size is 20", and the EW ranges between 0 and 300 eV. The points where the continuum-subtracted line emission is consistent with the background have been masked out. The nine regions selected for spatially resolved spectral analysis are also shown. *Right:* Same as left panel, but for the Mg xi line emission in the 1.29–1.45 keV band. The bin size is 1", and the EW ranges between 0 and 210 eV. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 6.— The pn spectrum (red crosses) extracted from regions with high Ne xi and Mg xi EW (regions enclosed by red shapes in the EW maps in the insets) compared with the pn spectrum (black crosses) extracted from regions with low EW (regions enclosed by black shapes). This shows the differences between metal-rich regions and ISM regions. [See the electronic edition of the Journal for a color version of this figure.]
abundances in the cold component. Therefore, the abundances of the cooler component are frozen to the solar values (Anders & Grevesse 1989). This assumption is in agreement with the results obtained in Paper II, where we showed that in the FilD knot, the cold component is associated with interstellar cloud material heated by the transmitted shock front. Except for region 3, all spectra are described significantly better by this model than by a single-temperature model (either in CIE or in nonequilibrium of ionization).

In region 3 (i.e., the head of RegNE), one component is enough. In Paper I, we showed that the spectra extracted from the tail of RegNE (regions 14 and 15 in Paper I) are also well described by a single thermal component in CIE. However, we found (Paper I, § 4.6) that a nonequilibrium of ionization (NEI) model at a higher temperature (~7 x 10^6 K) can also be appropriate to describe the spectra. We try to overcome this ambiguity by modeling the pn and MOS spectra of the head of RegNE (where the statistics are significantly better than in the tail) with a single MEKAL model and with the XSPEC NEI model. We do not obtain a significant improvement in the quality of the fits by using the NEI model (χ²_CIE = 264.8 with 243 dof, and χ²_NEI = 264.2 with 242 dof). We therefore adopt the CIE spectral model.

We find an entanglement between the best-fit values of NH and the temperature of the cooler component, T, with large error bars for both parameters. To overcome this problem, we determine the NH value in region 3 (where only the hotter component is present), thus finding N_H^{reg3} = (2.3 ± 0.8) x 10^20 cm⁻². We then fix N_H to this value for the fittings of the spectra extracted from the other regions. We checked that the assumption of a uniform NH in the whole observed part of the shell is valid. In fact, the χ² minima obtained by leaving the NH parameter free to vary are not significantly lower (according to the F-test) than those obtained by fixing it to the best-fit value obtained in region 3.

The best-fit parameters for all nine spectral regions are given in Table 2. The temperatures of the two X-ray-emitting components are quite similar to those found in the FilD region of Paper I, with nearly uniform values for both T_1 ~ 0.9–1.2 x 10^6 K and T_II ~ 2–3 x 10^6 K. We instead observe large variations (more than 1 order of magnitude) in the emission measures. This result confirms, as shown in Paper I and Paper II, neither component can originate in the intercloud medium. The emission measure per unit area (EM) of the cold component shows low values (~10^18 cm⁻³) to the north, in the RegNE pointing, and large values (many 10^18 cm⁻³) in the FilE region. The ratio EM/EMII ranges between EM/EMII ~ 2.5 in the regions with the hardest X-ray emission (i.e., region 2, or Hreg in Fig. 2, and regions 4 and 5, or HFiE in Fig. 2) and EM/EMII ~ 5 in the softest regions (regions 7 and 8, i.e., the brightest part of SFiE in Fig. 2). These results allow us to understand the double regime in the MPE map: the region to the north of FilD presents larger values of the median photon energy because in that region the cold component is fractionally small.

The results of the spatially resolved spectral analysis (Table 2) further confirm that the X-ray-emitting medium is not chemically homogeneous. We observe large inhomogeneities in the O, Ne, Mg, and Fe abundances, with significant overabundances both for Ne and Mg. We remark that the metal abundances do not change significantly if we adopt the NEI model. As explained in § 3.3, we expect the Ne IX EW map to depend on the Ne/Fe abundances. We indeed find a very good agreement between the Ne IX EW map shown in Figure 5 and the best-fit Ne/Fe abundances shown in Table 2. For example, we find the highest best-fit values of Ne/Fe (Ne/Fe > 5) in regions 3, 4, and 5, where the Ne IX EW map has three maxima, while we find Ne/Fe ≤ 2 in region 8.

For example, in region 1, the best-fit value of NH is consistent with N_H^{reg1}, and we obtain very similar values of χ² by both leaving the NH parameter free to vary (χ²_free = 222.4, with 260 dof) and by fixing it to N_H^{reg1} (χ²_fixed = 222.5, with 207 dof). Even in region 8, where we obtain a very low best-fit value of NH (consistent with 0 and lower than 1 x 10^19 cm⁻²), with χ²_free = 259.9 and 212 dof), the quality of the fit does not change significantly by setting NH = N_H^{reg1} (χ²_free = 263.0, with 213 dof).

### Table 2

| Parameter      | Region 1 | Region 2 | Region 3 | Region 4 | Region 5 | Region 6 | Region 7 | Region 8 | Region 9 |
|----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| T_1 (10^6 K)  | 1.06 ± 0.01 | 1.12 ± 0.07 | ...      | 1.05 ± 0.04 | 1.07 ± 0.01 | 0.95 ± 0.04 | 0.97 ± 0.04 | 1.06 ± 0.02 | 1.03 ± 0.05 |
| EM_1 (10^18 cm⁻²) | 1.4 ± 0.3 | 0.77 ± 0.08 | ...      | 4.1 ± 0.3 | 3.9 ± 0.3 | 9.9 ± 0.5 | 6.5 ± 0.6 | 8.3 ± 0.2 | 5.5 ± 0.4 |
| T_II (10^6 K) | 2.1 ± 0.3 | 2.9 ± 0.04 | 2.5 ± 0.08 | 2.6 ± 0.03 | 2.6 ± 0.05 | 2.1 ± 0.07 | 2.2 ± 0.01 | 2.5 ± 0.04 | 2.3 ± 0.02 |
| EM_II (10^18 cm⁻²) | 0.20 ± 0.03 | 0.33 ± 0.02 | 1.3 ± 0.07 | 1.45 ± 0.09 | 1.64 ± 0.15 | 3.4 ± 0.17 | 1.3 ± 0.1 | 1.48 ± 0.07 | 2.4 ± 0.04 |
| O/O_III | 0.74 ± 0.06 | 1.1 ± 0.01 | 1.0 ± 0.1 | 0.74 ± 0.07 | 0.57 ± 0.04 | 0.40 ± 0.01 | 0.35 ± 0.02 | 0.25 ± 0.02 | 0.25 ± 0.02 |
| Ne/Ne_III | 2.6 ± 0.4 | 2.8 ± 0.3 | 3.3 ± 0.4 | 2.7 ± 0.1 | 1.7 ± 0.1 | 1.3 ± 0.1 | 0.9 ± 0.2 | 0.5 ± 0.1 | 0.5 ± 0.1 |
| Mg/Mg_III | 2 ± 2 | 3.5 ± 0.5 | 4.4 ± 1.3 | 2.9 ± 0.8 | 1.3 ± 0.5 | 2.0 ± 0.7 | 0.9 ± 0.4 | 0.8 ± 0.4 | 0.8 ± 0.4 |
| Fe/Fe_III | 1.4 ± 0.2 | 0.5 ± 0.05 | 0.49 ± 0.06 | 0.50 ± 0.05 | 0.32 ± 0.05 | 0.67 ± 0.01 | 0.43 ± 0.08 | 0.21 ± 0.02 | 0.25 ± 0.05 |
| χ² dof       | 222.5/207 | 309.9/306 | 264.8/243 | 296.2/291 | 337.2/263 | 174.9/193 | 309.0/234 | 263.0/213 | 281.4/218 |

**Note:** Spectra are described with two thermal components in collisional ionization equilibrium (only one component in region 3). The NH parameter is fixed to 2.3 ± 10²⁰ cm⁻² (as explained in § 3.4). All errors are at the 90% confidence level.
regions 1 and 9, where the Ne x EW is lower. The agreement between the Mg abundance and the Mg x EW map of Figure 5 is very good. We find significantly enhanced Mg abundances in regions 2, 3, 4, and 6, while the Mg abundances are consistent with the solar value where the Mg x EW is lower (regions 1, 5, 8, and 9; see Fig. 5 and Table 2).

4. DISCUSSION

The combined analysis of the three XMM-Newton observations of the northern rim of the Vela shell reveals the presence of physical and chemical inhomogeneities in the X-ray-emitting medium. Although all spectra are described well by the two thermal components at \( \sim 10^5 \) and \( \sim 3 \times 10^5 \) K, a wide region \( \lesssim 6 \times 10^{18} \) cm from the border of the shell presents a higher median photon energy than that observed at larger distances from the main shock front. This is due to the lower values of the emission measure of the cold component and indicates that in this region the plasma is, on average, hotter and, if we assume pressure equilibrium, also more rarefied. At larger distances, we instead observe bright optical filaments and large, dense, X-ray-emitting clouds (with larger values of the emission measure of the cold component), together with a soft diffuse and faint emission that might be associated with small, unresolved, and dense cloudlets.

Both the EW maps and the spatially resolved spectral analysis unequivocally show that the chemical composition of the X-ray-emitting plasma is not homogeneous. These results clearly rule out the possibility that the whole X-ray emission originates in the shocked ISM. Moreover, the spatially resolved spectral analysis confirms the detection of several knots with overabundant Ne and Mg. This strongly suggests that we are indeed observing ejecta. It might also be possible that we are observing clumps of wind residuals from the progenitor star shocked by the main shock front. However, stellar winds from massive stars typically show overabundances of light elements, such as He and N (Esteban & Vilchez 1992; Chu et al. 2003), and it would be difficult to explain the overabundances of Ne and Mg using this scenario. We therefore suggest that we are indeed observing SN ejecta. This indication is further supported by the fact that the regions with high EWs in Figure 5 (and high Ne and Mg abundances) are visually aligned toward the center of the shell.

The detection of X-ray-emitting ejecta associated with the evolved Vela SNR is not totally unexpected. Aschenbach et al. (1995) have observed six shrapnels of X-ray-emitting material outside the Vela shell (shrapnels A–F). Two of these have been investigated in detail (shrapnel D by Katsuda & Tsunemi 2005 and shrapnel A by Katsuda & Tsunemi 2006). In shrapnel D, large overabundances of O (O/O_\text{Fe} \sim 6.4), Ne (Ne/Ne_\text{Fe} \sim 13.7), and Mg (Mg/Mg_\text{Fe} \sim 14) have been found by Katsuda & Tsunemi (2005), who also revealed a slight Fe overabundance (Fe/Fe_\text{Fe} \sim 1.4). As shown in Katsuda & Tsunemi (2006), shrapnel A is instead very rich in Si (Si/Si_\text{Fe} \sim 2.6), while O, Ne, Mg, and Fe have solar or subsolar abundances. Note that the angular distance from the center of the remnant to shrapnel A is bigger by \( \sim 20\% \) than the angular distance to shrapnel D. The abundances in shrapnel A indicate an efficient mixing between the fast-moving shrapnel and the swept-up ISM. In both cases, however, the chemical composition suggests that the shrapnels are fast ejecta.

We note that we may be observing the first shrapnels ever detected within the Vela shell (shrapnels A–F are all outside the border of the remnant). Note, however, that although the projected position of the ejecta is behind the main shock front, it is clearly possible for these “new” shrapnels to be physically outside the border of the shell. Only shrapnels ejected approximately on the plane of the sky have been detected so far, but it is very likely that many other shrapnels have also been ejected in other directions. We therefore expect to find fragments of ejecta in other regions of the remnant. When shrapnels are observed in projection within the shell, the X-ray emission is not fully associated with the ejecta, because (since the plasma is optically thin) there is also a contribution from the shocked ISM intercepted along the line of sight. Therefore, the enhanced Ne and Mg abundances that we find in regions 2, 3, 4, 6, and 7 are indeed weighted averages of the ejecta and ISM abundances. Nevertheless, we can compare our abundances with those found in shrapnel D (Fig. 1) by Katsuda & Tsunemi (2005). In particular, we consider the relative abundances between heavy elements, which are less dependent on the spectral model than the absolute abundances. In region 2 (Hreg) and especially in region 3 (RegNE), the relative abundances (normalized to the Fe abundance) are quite similar to those observed in shrapnel D: compare O : Ne : Mg : Fe \sim 2.0 : 6.3 : 1 (region 2) and O : Ne : Mg : Fe \sim 2.0 : 9.0 : 1 (region 3) to O : Ne : Mg : Fe \sim 4.6 : 9.8 : 10.0 : 1 (shrapnel D; Katsuda & Tsunemi 2005). This result supports the association of Hreg and RegNE with “new” shrapnels. Although in region 4 the relative abundances do not decrease significantly (O : Ne : Mg : Fe \sim 1.5 : 5.4 : 5.8 : 1), to the south (especially in regions 6 and 7), where we expect to intercept more shocked ISM along the line of sight, the relative abundances become lower (O : Ne : Mg : Fe \sim 0.7 : 2.2 : 3.5 : 1 in region 6 and O : Ne : Mg : Fe \sim 0.8 : 2.1 : 4.7 : 1 in region 7). Note that the largest deviations between our shrapnels and shrapnel D occur in the O/Fe abundances. The cause of this may be that since the X-ray emission in the Vela SNR is quite soft, we expect the contribution of the postshock ISM to be stronger in the low-energy line complexes (i.e., O vii and O viii) than in the Ne ix and Mg xi lines. As for the Si-rich shrapnel A, Katsuda & Tsunemi (2006) found subsolar or solar values for O, Ne, Mg, and Fe, with lower values of the abundance ratios (O : Ne : Mg : Fe \sim 0.4 : 1.0 : 0.8 : 1). Although we cannot estimate the Si abundances in our observations, we can conclude that our new shrapnels are intrinsically different from shrapnel A.

In the regions where the emission seems to be completely associated with the ISM (regions 8 and 9), we find indications for metal depletion in the X-ray-emitting plasma, since the O, Ne, and Fe abundances are significantly lower than solar (see Table 2).

5. SUMMARY AND CONCLUSIONS

The combined analysis of the three XMM-Newton observations of the northern part of the Vela shell has allowed us to obtain a high-resolution description of a large area (\( \gtrsim 10 \text{pc}^2 \)) of the Vela SNR. We observe hard X-ray-emitting knots to the north and large, soft X-ray-emitting knots associated with bright optical filaments closer to the center of the shell. All spectra are described well with two thermal components whose temperatures are almost uniform in the whole region. The observed inhomogeneities of the emission measures confirm that, as in the case of FiID, the two components cannot be associated with the uniform intercloud medium.

We find inhomogeneous patterns of abundances of O, Ne, Mg, and Fe, and we detect different knots (RegNE, Hreg and part of FiIE) with significant overabundances of Ne and Mg. The observed pattern of abundances can hardly be attributed solely to the ISM and/or clumps of wind residuals. We conclude that these knots are previously undetected shrapnels of ejecta that appear,
in projection, to be inside the Vela shell. We expect the X-ray emission from these new shrapnels to be “contaminated” by the X-ray emission from the shocked ISM intercepted along the line of sight. Nevertheless, in the regions where we expect this effect to be less considerable (RegNE and Hreg), the relative abundances are quite similar to those found in shrapnel D by Katsuda & Tsunemi (2005).

In conclusion, we confirm the presence of two phases in the X-ray-emitting plasma (at $\sim 10^6$ and $\leq 3 \times 10^6$ K), as found in Paper I. In addition, we argue that the metal abundances in the hot component are not uniformly distributed. Regions with oversolar Ne and Mg are reasonably associated with shrapnels of ejecta similar to shrapnel D. On the other hand, the other regions are probably associated with the evaporation of shocked interstellar clouds, according to the scenario described in Paper II.

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